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# Agrobiodiversity, community participation and landscapes in agroecology

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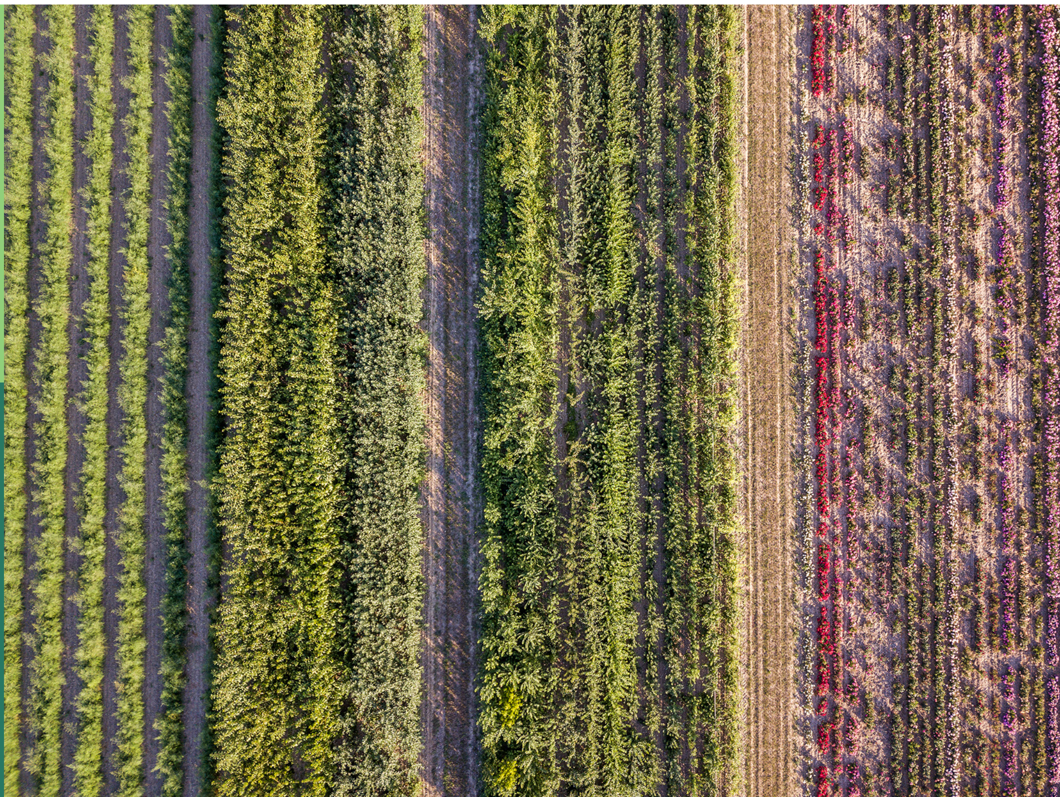

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# Agrobiodiversity, community participation and landscapes in agroecology

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# Editorial: Agrobiodiversity, community participation and landscapes in agroecology

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KEYWORDS

**farming, biodiversity, connectivity, rural community, agroecological structure**

Editorial on the Research Topic
Agrobiodiversity, community participation and landscapes in agroecology

The current model of conventional agriculture on the planet, originated in the so-called "Green Revolution" (GR), has generated positive and negative effects during its more than 80 years of application, starting in the 1940s. Among the negative effects are the accelerated loss of biodiversity and agrobiodiversity.

Different alternative farming systems propose managing the agrobiodiversity of agroecosystems (farms) to face many of the problems generated on monoculture farms (e.g., soil and genetic erosion, emergence of genetic resistance in pests and weeds, as well as public health problems associated with the use of agrochemicals), which are characteristic of the current conventional model (Vandermeer and Perfecto, 2005; Pollan, 2007).

Many positive effects are attributed to diverse crop fields. To name just a few, at the ecosystem level, beneficial effects have been proven in the preservation of the habitat for beneficial insects (pollinators, natural enemies of pests), reduction in GHG emissions, protection of soil and water, zero poisoning of human beings and nonhumans, reduction of pollutants and hazardous waste, and climate stability (Altieri, 1996; Nicholls, 2002; Letourneau et al., 2011; Gliessman, 2014; Vandermeer and Perfecto, 2018).

Agrobiodiversity is the very foundation upon which agroecology is built. It provides the mechanisms that allow agroecosystems to be managed sustainably through a set of beneficial interactions between their elements (e.g., mutualisms that occur in pollination, mycorrhizae or in crop associations).

The elements that constitute an agroecosystem are directly related to its main agroecological structure (MAS), which refers to the way in which the different sectors, patches, live fences, and vegetation corridors are arranged (spatial configuration), mixed or not with crop areas, grasslands, or agroforestry systems inside the farms and in their close surroundings. An agroecosystem structure is historically constructed by farmers because of innumerable cultural variables (symbolic, economic, social, political, and technological), in conjunction with environmental processes and its evolution configures agroecosystem matrices in the landscape (León-Sicard et al., 2018; Quintero et al., 2022). In this context, the use of the MAS approach, paired with other agroecological tools, such as the farmer-to-farmer methodology and participatory action research, can be employed as inputs into the decision-making process necessary for sustainable landscape management and conservation of agrobiodiversity in rural environments (Holt-Gimenez, 2006; Guzmán et al., 2012).

Most of the world's industrial agricultural landscapes present matrices of farms with very poorly developed agroecological structures that respond to the simplification characteristic of conventional agriculture, which has eliminated forests, corridors, patches, and live fences to make way for extensive monocultures (Vandermeer and Perfecto, 2005; León-Sicard et al., 2018). This simplification has also been the product of pesticides used to eliminate biological competitors to the main crop and to eliminate agents considered pathogenic or harmful.

In contrast, ecological- or agroecological-based agriculture proposes to maintain and reinforce agrobiodiversity in all its manifestations, both on and off the farm, as a way of achieving greater resilience, equity, autonomy, stability, and productivity through the multiple interactions that it fosters. Agroecological landscapes, therefore, will have agroecosystem matrices with more developed structures and functions favorable to agrobiodiversity.

These interactions between the different elements of agrobiodiversity are not restricted to the biological realm but are rather intricately woven into the fabric of socio-ecological systems.

These latter systems, whose central protagonists are the farmers and their cultural actions, are clearly the beneficiaries of the interactions (services) but are also responsible, in multiple ways, for the maintenance of this biodiversity. It is important to highlight that the interactions that articulate these systems manifest themselves on different scales, and in this Research Topic, we will find works that clearly show this fact.

This Research Topic collected 13 articles involving 46 authors from 36 research institutions in 14 countries on four continents (Table 1). The case studies dealing with different levels of agrobiodiversity (from crop to landscape) are based in seven countries: China, Italy, Nigeria, Colombia, Venezuela, Chile, and Uruguay.

This Research Topic includes articles that address the effects of climate change on the soil fauna of agroecosystems (Gao et al.) and how the soil microbiome can be used to adapt crops to the new climate context (Pino and Griffon). Innovative management approaches link silvopasture systems with ecosystem restoration (Durana et al.). Other contributions investigate the needs of the end users of this biodiversity (Tchokponhoué et al.), the role of entrepreneurial identity in shaping attitudes toward sustainability (Rossi et al.), and studies that address people's ecological, esthetic, and medicinal knowledge about the plants in their crops and communities (Kolze et al.; Monagas and Trujillo). Other articles address, at a larger spatial scale, the criteria for establishing community gardens in urban environments (Codato et al.), the

TABLE 1 The 13 articles in this Research Topic.

| Authors | Title | Country |
|---|---|---|
| María Puppo, Camila Gianotti, Alejandra Calvete, Alejandra Leal, Mercedes Rivas | Landscape, agrobiodiversity, and local knowledge in the protected area "Quebrada de los Cuervos y Sierras del Yerbal," Uruguay | Uruguay |
| Eleonora Sofia Rossi, Valentina C. Materia, Francesco Caracciolo, Emanuele Blasi, Stefano Pascucci | Farmers in the transition toward sustainability: what is the role of their entrepreneurial identity? | Italy |
| Carlos E. González-Orozco, Raul Alejandro Diaz-Giraldo, Catalina Rodriguez-Castañeda | An early warning for better planning of agricultural expansion and biodiversity conservation in the Orinoco high plains of Colombia | Colombia |
| Valentino Giorgio Rettore, Daniele Codato, Massimo De Marchi | How can GIS support the evaluation and design of biodiverse agroecosystems and landscapes? Applying the Main Agroecological Structure to European agroecosystems | Italy |
| Meixiang Gao, Yige Jiang, Jiahuan Sun, Tingyu Lu, Ye Zheng, Jiangshan Lai, Jinwen Liu | Open farmland is a hotspot of soil fauna community around facility farmland during a cold wave event | China |
| Dèdéou A. Tchokponhoué, Eric C. Legba, Sognigbé N'Danikou, Daniel Nyadanu, Happiness O. Oselebe, Enoch G. Achigan-Dako | Developing improvement strategies for management of the Sisrè berry plant [*Synsepalum dulcificum* (Schumach & Thonn.) Daniell] based on end-users' preferences in Southern Nigeria | Nigeria |
| Claudia Durana, Enrique Murgueitio, Bernardo Murgueitio | Sustainability of dairy farming in Colombia's High Andean region | Colombia |
| Anna Lena Kolze, Stacy M. Philpott, Leonardo F. Rivera-Pedroza, Inge Armbrecht | Campesino and indigenous women conserve floral species richness for pollinators for esthetic reasons | Colombia |
| Angel Salazar-Rojas, Ricardo Castro-Huerta, Miguel Altieri | The main agroecological structure, a methodology for the collective analysis of the Mediterranean agroecological landscape of San Clemente, Region del Maule, Chile | Chile |
| Álvaro Acevedo-Osorio, Jonathan Salas Cárdenas, Angela Maribeth Martín-Pérez | Agroecological planning of productive systems with functional connectivity to the ecological landscape matrix: two Colombian case studies | Colombia |
| Daniele Codato, Denis Grego, Francesca Peroni | Community gardens for inclusive urban planning in Padua (Italy): implementing a participatory spatial multicriteria decision-making analysis to explore the social meanings of urban agriculture | Italy |
| Carlos Pino, Diego Griffon | Scaling up: microbiome manipulation for climate change adaptation in large organic vineyards | Chile |
| Olga Monagas, Iselen Trujillo | Medicinal plants, biodiversity, and local communities. A study of a peasant community in Venezuela | Venezuela |

precautions that must be taken in terms of conservation before undertaking agricultural expansions (González-Orozco et al.), or the strategic role of managing the relations among agroecosystems and landscapes to build resilient nature matrixes (Puppo et al.; Rettore et al.) The work of Acevedo-Osorio et al. proposed an index of agroecological functionality at the landscape level in Colombia, and Rojas et al. measured the degree of connectivity of agroecosystems with the landscape, using the MAS method, in a Mediterranean environment in Chile.

In all of these works, it is clear that agrobiodiversity, through the multiple functions it fulfills, articulates, and keeps these socio-ecological systems viable. In this way, we can understand it as the glue, often invisible to our eyes, that holds these systems together and, in doing so, makes our own lives possible.

The growing competition of labels for innovative approaches to sustainable agriculture should be analyzed using the elements of agroecology (FAO, 2019), with special attention to agrobiodiversity and its plural connections with food culture and traditions, circular and solidarity economy, and responsible governance (Tittonell et al., 2022).

Agroecology, as a meeting point of plural paths between science, movements, practices, and symbolic tissues, indagates the participatory processes of the construction of agrobiodiversity, food sovereignty, and biocultural diversity (Pimbert, 2018) from a long-term perspective, weaving, often not explicitly, practices of circulation and the construction of complex nested agroecosystems and landscapes.

From an emancipatory perspective (Giraldo and Rosset, 2023), the reflections and practices deal with territorial and food policies that transform structures, do not reproduce exclusion, and cultivate autonomy based on the co-construction of knowledge at a higher level of integration among crops, animal and vegetal species, landscapes, and biomes. Agroecology has the task of revealing the ontology of agriculture itself, deepening the meanings of being, living, and remaining in the places of communities that build and transfer over time, co-evolving multiscalar matrices of nature (Giraldo, 2022).

At a cultural level, the effects of the diverse management of agroecosystems result in greater opportunities for rural employment, greater justice in the social relations of production, appreciation of indigenous, peasant, and Afro-American knowledge, fair trade, and greater opportunities for peace and reconciliation nationally and internationally, among other aspects.

## Author contributions

TL-S: Conceptualization, Writing – original draft. DG: Conceptualization, Writing – original draft. MD: Conceptualization, Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Landscape, agrobiodiversity, and local knowledge in the protected area "Quebrada de los Cuervos y Sierras del Yerbal," Uruguay

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**Introduction:** Agrobiodiversity and local knowledge are fundamental components in the domestication and structuring of rural landscapes. In a context of threats to agroecosystems resulting from changes in production systems and rural–urban migration processes, the conservation and valorization of agrobiodiversity is a pressing challenge. "Quebrada de los Cuervos and Sierras del Yerbal" is a protected landscape in Uruguay where a rural community of approximately 30 families with a long-standing tradition resides.

**Methods:** The research aimed at identifying current and abandoned (taperas) domestic contexts, and the plant genetic resources found in the area, categorizing their uses and management practices through interviews and participant observation.

**Results and discussion:** Ethnographic research revealed 185 species (121 exotic, 64 native) with diverse growth habits, 10 categories of uses, and 11 categories for management practices. The differences found between houses and taperas revealed that the abandonment of activities in rural areas is a relevant factor in the loss of agrobiodiversity. Among the 185 species, a notable group of plant genetic resources of high cultural significance is recognized due to their consensus of use, frequency of management practices, and number of uses. These include introduced fruit trees (peach, citrus, and fig) and native fruit trees (guayabo del país, pitanga, and arazá), vegetable landraces, native trees with multiple uses, yerba mate, and medicinal species such as *Aristolochia fimbriata*. For domestic contexts, a model of spatial distribution of agrobiodiversity is proposed, cultivated spaces where the plant genetic resources are located in home gardens and small plots, managed spaces where the resources are found in the surroundings of houses, and promoted and intervened wild spaces where the species are used from natural grasslands and wild environments. The obtained information reaffirms the need to conserve this biocultural landscape, placing agrobiodiversity and local knowledge as a focal point in the protected area. The management plan must be formulated with active participation from the rural community, aiming for valorization through integration into agroecological production chains, among other possibilities.

KEYWORDS

**plant genetic resources, local knowledge, *in situ* conservation, protected areas, domesticated landscape, agrobiodiversity, Pampa biome, genetic cultural erosion**

# 1. Introduction

Agrobiodiversity involves human intervention for its generation and evolution (Sthapit et al., 2016) and is defined as a dynamic network of relationships among people, living organisms, and the environment that responds to specific needs and circumstances (De Boef et al., 2013a). Agrobiodiversity encompasses biologically diverse species with relevant functional uses for humans. It is necessary for maintaining key functions within agroecosystems, and its importance lies in the fact that greater agrobiodiversity enhances agricultural systems' resilience to changes (FAO, 1999; Newton et al., 2009). Within agrobiodiversity, plant species with real or potential value for humans are referred to as Plant Genetic Resources (UN Convention on Biological diversity, 1992). This definition explicitly links plant species with specific knowledge, which can be of scientific or traditional origin, leading to the so-called Local or Traditional Ecological Knowledge, or both [see discussion in Heckler (2009)]. Local ecological knowledge refers to an accumulated body of knowledge, practices, and beliefs that evolve through adaptive processes and are culturally transmitted from generation to generation. It encompasses the relationships between living organisms and their environment, takes a holistic approach, and recognizes the complexity of the ecological system (Berkes et al., 2000; Emperaire and Peroni, 2007). The loss of agrobiodiversity, or genetic erosion, is closely associated with the loss of local knowledge, which has multiple causes, including the simplification of agricultural habitats due to industrial agriculture, the abandonment of landraces, the rapid expansion of extensive monocultures, infrastructure growth, the mining industry, and rural depopulation, among others (Achkar, 2017; Baeza et al., 2022; Gallego et al., 2023).

Rural communities play a fundamental role in generating and maintaining agrobiodiversity, as they engage primarily in non-industrial forms of nature management and possess long-standing traditional knowledge (Toledo and Barrera-Bassols, 2008). Each socioculture interacts with its own landscape and biodiversity, resulting in a complex and wide range of interactions that give rise to specific biocultural patches. These local knowledge systems exist as "historical community consciousness" and represent the reservoir of human memory that allows the species to continuously adapt to a constantly changing complex world (Toledo and Barrera-Bassols, 2008). This can also be understood as a community of practice defined by a group of individuals who interact, learn together, establish relationships, and develop a sense of belonging around a specific domain of knowledge and associated practices (Wenger et al., 2002; Dabezies and Taks, 2021).

Several authors have linked the management of agrobiodiversity to the landscape (Wiersum, 1997; Clement, 1999; Clement and Cassino, 2018; Franco-Moraes et al., 2021). This approach considers cultural diversity as the main shaping agent in the domestication of species and landscapes, involving coevolutionary processes (Casas et al., 1997; Heckenberger et al., 2003; Clement et al., 2015; Reis et al., 2018; Franco-Moraes et al., 2023). Changes in plant populations result from changes in management practices, constituting a multidimensional, dynamic, and interactive process involving plants, the environment, and humans at different scales. It encompasses the management and domestication of individual species and entire agroecosystems, transforming a wild ecosystem into a managed and domesticated one. The process of landscape domestication occurs over time through interventions and manipulations of biotic and abiotic components, leading to ecological and demographic changes in plants and animals, increased occurrence of useful species, enhanced productivity of agroecosystems, and a more habitable landscape for humans. Clement and Cassino (2018) recognizes four categories of landscapes based on the degree of human intervention, including pristine, promoted, managed, and cultivated landscapes, although the existence of pristine landscapes is widely debated by the author. Within the cultivated landscape, in addition to large-scale crops, home gardens and small plots ("chacras") can be included. These microenvironments within the agroecosystem serve as places for experimentation, species introduction, crop improvement, and refuges for unique genetic diversity (Watson and Eyzaguirre, 2001; Kumar and Nair, 2004).

Uruguay is located in the Pampa biome, the largest natural grasslands region in South America and one of the largest in the world. This region has undergone significant changes in land use/land cover in the past 20 years, primarily due to forest plantation and soybean cultivation (Baeza et al., 2022), resulting in a significant impact on biodiversity, agrobiodiversity and ecosystem services such as pollination, soil conservation, and water supply, among others, causing fragmentation and habitat loss. One of the national strategies to address these effects is the National System of Protected Areas (SNAP). In this context, the protected landscape "Quebrada de los Cuervos and Sierras del Yerbal" was established in 2008. This area is a part of the "Serranías del Este" ecoregion, characterized by its high degree of naturalness in ecosystems. It is home to a small rural community which consists of descendants of native populations, Creoles, and European colonizers. The predominant productive system is livestock farming on natural grasslands, carried out by traditional family farmers who engage in vegetable and fruit cultivation for self-consumption, while also raising poultry and pigs. They also maintain and utilize agrobiodiversity for various purposes. In this context, the protected landscape provides an exceptional opportunity to study agrobiodiversity and local knowledge.

The general objective of this study is to contribute to the understanding, valorization, and conservation of agrobiodiversity in the protected area "Quebrada de los Cuervos and Sierras del Yerbal" by delving into the study of plant genetic resources, the origin and transmission of local ecological knowledge, and their role in shaping landscape dynamics. Considering the hypothesis that there is a diverse set of species used in domestic contexts that are essential for survival, and that there is a resource management strategy by the region's inhabitants, both present and past, we propose the following objectives: (1) to identify and characterize agrobiodiversity in domestic contexts within the Protected Landscape, (2) to conduct an ethno-agronomic approach (Flora, 2001) to study the uses and management of plant genetic resources in domestic contexts, (3) to propose guidelines that contribute to conserving and valorizing agrobiodiversity in the protected area.

# 2. Materials and methods

## 2.1. Study area and rural community

The study was conducted in the protected area "Quebrada de los Cuervos y Sierras del Yerbal" (32° 55'S, 54° 27¨W), Treinta y Tres

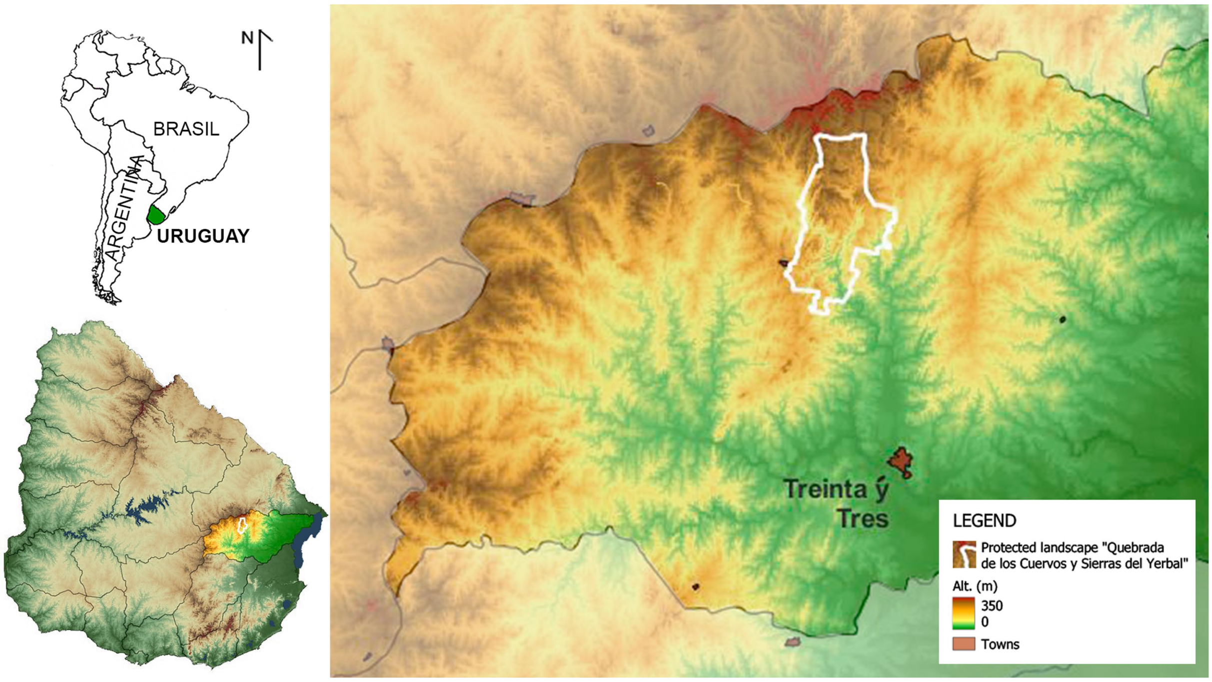


FIGURE 1
Geographic location and relief of the study area, "Quebrada de los Cuervos y Sierras del Yerbal" Protected Landscape, Treinta y Tres, Uruguay.

Department, Uruguay (Figure 1). The area is located in the Pampa biome (Allen et al., 2011; Mengue et al., 2020), within the "Serranías del Este" ecoregion (Evia and Gudynas, 2000; Achkar et al., 2016), characterized by its undulating and rugged terrain, altitudes ranging from 50 to 350 meters above sea level, slopes between 5 and 30%, and a dense hydrographic network. The climate, according to the updated Köppen-Geiger classification, is of the Cfa type (Peel et al., 2007), humid subtropical. The area experiences an average annual rainfall of 1,300 mm, distributed throughout the year; however, there is considerable irregularity and variability between years. The average annual temperature is 17.8°C, with an average maximum of 23.3°C and an average minimum of 12.3°C.[1] The predominant ecosystems are natural grasslands, hilly forests, riparian forests, and ravine forests. The protected area is part of the National System of Protected Areas, covering an area of 19,192 hectares dedicated to landscape and biodiversity conservation under the international IUCN category of "Protected Landscape" (Nudley, 2008; SNAP/DINAMA, 2010).

The protected area was inhabited by over 100 families, but currently, according to the information provided by the interviewees, only between 30 and 40 families reside in the area, indicating significant emigration forces at play (Achkar, 2017). The official rural population density is 0.34 inhabitants per square kilometer (INE, 2011). This population is primarily composed of descendants of european immigrants (Bica, 2019), with possible indigenous and/or African ancestry, resulting in a mixed population (Palermo, 2019; Clemente, 2021). The average size of properties is 350 hectares, with livestock farming as the main activity. However, the residents have recently engaged in eco and agrotourism activities.

## 2.2. Fieldwork

### 2.2.1. Field survey

Initially, a survey phase was conducted to extensively assess (Banning, 2002) the domestic contexts (DC) using satellite imagery from platforms such as Google Earth and Geoservicios IDEuy,[2] 1:50,000 cartography, field surveys, study of toponyms, and consultations with local informants. The term DC refers to inhabited locations typically comprised of one or more dispersed buildings and spaces utilized by the family for their daily activities. Abandoned locations were classified as "taperas" (traditional term used to denote abandoned houses), while inhabited ones were simply referred to as "houses." For the documentation of each DC, a form was designed to record the place's location, description, productive context, and ownership details if provided by informants. The data were organized in QGIS (v3.2) to generate a map illustrating the distribution of DCs. Subsequently, the obtained map guided a second survey phase in the field to locate and document each DC.

### 2.2.2. Primary assessment of agrobiodiversity

To gain an initial understanding of plant agrobiodiversity in the area, the species found in each visited DC were systematically identified, taking into consideration both cultivated spaces and their

1 https://www.inumet.gub.uy

2 https://visualizador.ide.uy/

surrounding areas. The environments where the species were found were categorized as home gardens, small plots, vicinity of houses or taperas, and more distant areas encompassing grasslands, forests, and hilltops or rocky outcrops. The botanical identification was performed by the authors, who collected samples for subsequent verification at the Laboratory of Botany at the Regional University Center of the East Region (Universidad de la República). The nomenclature used was verified against the Plant List.[3]

#### 2.2.3. Characterization of local knowledge

Based on the primary assessment and with the aim of obtaining detailed information regarding species, uses, and associated local knowledge, the DCs with the highest agrobiodiversity were selected, and connections were established with guardians and other key informants knowledgeable about these plant genetic resources. An ethnographic approach (Guber, 2014) was employed as a means of immersing in the context, exploring discourses, and gaining insight into the practices of the individuals (Restrepo, 2016). Techniques such as participant observation (Kawulich, 2006) and open and semi-structured interviews (Guber, 2001, 2014) were utilized, ensuring that the consent of each interviewee was obtained for the use of their provided data. A guideline was defined to cover topics such as family history and its connection to plant usage, the origin of knowledge, and the use and management of both wild and cultivated agrobiodiversity.

### 2.3. Data analysis

The data obtained from the surveys and interviews were systematically organized and analyzed both qualitatively and quantitatively. The following variables were recorded for each species: botanical family, origin (native or exotic, considering native species as those belonging to the Uruguayan flora), plant habit (annual herbaceous, perennial herbaceous, subshrub, shrub, tree, lichen), type(s) of DC (house or tapera) and environment where it is found (garden, small plots, adjacent environment, grassland, forest or rocky outcrops).

The recorded uses were classified into 11 categories: human consumption, animal feed, medicine, veterinary use, toxic and harmful use, fuel, construction, industry and crafts, environmental uses, ornamental, and social, symbolic, and ritual uses (Pardo de Santayana et al., 2014). The management practices were classified into 10 categories, based on an adapted proposal from various authors (Casas et al., 1996, 2014; Blancas et al., 2013; Furlan et al., 2017; Chamorro and Ladio, 2021): "tolerance" referring to species allowed to remain in environments where thinning, pruning, or weeding activities are carried out; "protection" implying actions taken to prevent damage caused by environmental factors to the species; "improvement" involving the favoring of individuals of the species or variety, for example, by eliminating competition, irrigation, seed dispersal, soil improvement (including soil cultivation and addition of fertilizers, among others); "propagation" referring to direct propagation of the species through seeds or vegetative methods; "transplantation" involving the moving individuals that have established naturally or were initially tolerated and then removed; "pruning" referring to the removal of parts of a plant with a specific goal; "gathering" involving direct harvesting of natural populations; "selection" referring to selecting certain phenotypes for reproduction; "community circulation" involving the exchange of plant materials among neighbors, family members, or other individuals; "care for inherited plants" involving the preservation of plants that were initially cultivated by others.

The following data were calculated: number of citations per species (NCs), understood as the number of interviews where the species was mentioned, number of uses per species (NUs), number of citations of use per species (NCUs), understood as the number of times the species was cited for a particular use, number of citations of management practices per species (NCMPs), understood as the number of times the species was cited for a specific management practice, number of management practices for each species (NMPs), and Consensus of Use index (CU%), calculated as NCs over the total number of interviewees.

To compare the agrobiodiversity of the two types of DCs, the Shannon-Wiener diversity index (H′) based on the frequency of species occurrence was estimated. Evenness was calculated as $E = H'/\ln S$, where S represents the total species richness (Magurran, 1988; Magurran and McGill, 2011). Subsequently, a Detrended Correspondence Analysis (DCA; Sokal and Rohlf, 1995) was performed to ordinate the DCs based on the assemblages of plant genetic resources found in each one.

Qualitative information about local knowledge of the species, descriptions of uses and management practices, as well as data on the origin of knowledge, its generation, and propagation, was obtained from the analysis of the interviews.

## 3. Results

### 3.1. Domestic contexts and rural communities

A total of 54 domestic contexts were surveyed, consisting of 41 taperas and 13 houses (Figure 2). In most cases, these contexts comprise more than one building, with the main constructions generally made of stone, while secondary ones may be made of mud, brick, or stone. In the DCs, there are cultivated spaces (home gardens and small plots), mostly with clear boundaries, commonly fenced with stonewalls, wire fences, or metal sheets. These spaces are located in interior courtyards, around the house, with slate walkways and raised stone beds, or near the buildings with protective measures to prevent grazing. Taperas exhibit varying degrees of deterioration, ranging from abandoned houses to remnants of foundations that outline the shapes of past constructions. The protective features of previously cultivated areas no longer fulfill their function or only partially do so.

Twelve adult individuals were interviewed, of whom 67% were women and 33% were men, ranging in age from 20 to 70 years, although 75% of the interviewees were over 50 years old. The interviewees included 10 local residents (families with several generations in the area), one non-resident owner, and one representative from a local NGO. In most cases, multiple interviews were conducted with the same person, resulting in variable quality and

3 http://www.theplantlist.org

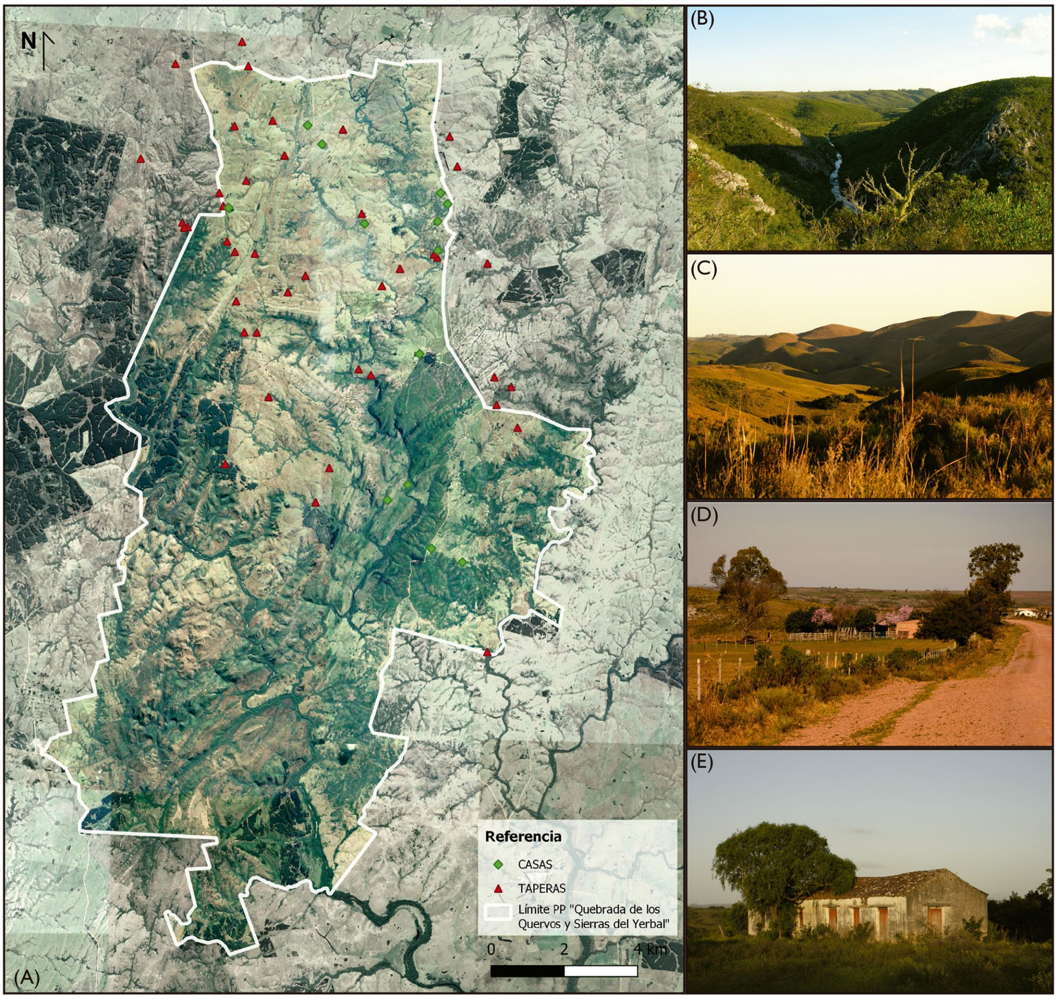


FIGURE 2
**(A)** Geographical distribution of the surveyed domestic contexts, including houses and taperas in the "Quebrada de los Cuervos and Sierras del Yerbal", Treinta y Tres, Uruguay. **(B)** Quebrada de los Cuervos. **(C)** Sierras del Yerbal. **(D)** Surveyed domestic contexts in the Quebrada de los Cuervos and Sierras del Yerbal, house with a cultivated space fenced with wire, featuring fruit tree species such as *Prunus persica* and *Citrus* spp., with *Eucalyptus* in the nearby environment. **(E)** Well-preserved tapera with a *Schinus molle* tree in the front.

depth of information, with an average of 37 species cited per informant and a range of 9 to 97.

## 3.2. Characterization and spatial distribution of agrobiodiversity

From the surveys and interviews, 185 species with associated uses were recorded, with 161 of them mentioned by the interviewees. These species belong to 66 botanical families, with 65 families of flowering plants (phanerogams) and one family represented by the lichen *Usnea densirostra* (Parmeliaceae). Seven of these families account for more than 40% of the species, namely Fabaceae (9%), Asteraceae (8%), Rosaceae (7%), Myrtaceae (5%), Rutaceae (5%), Solanaceae (5%), and Lamiaceae (4%). The Poaceae family, which along with Asteraceae has the highest number of species in Uruguay, is not well-represented in this study as it does not include forage species from natural grasslands. Figure 3A presents the distribution of families and species, including both native and exotic species, with 14 families shared between them. Figures 3C,D show the main families within each group. The distribution of growth habits among these species was as follows: 66 trees, 38 shrubs, 8 subshrubs, 44 perennial herbs, 28 annual herbs, and 1 lichen. These habits have different distributions between native and exotic species (Figure 3B).

A total of 165 and 93 plant genetic resources were recorded in houses and taperas, respectively (Table 1). The number of species in houses ranged from 9 to 91, while in taperas it ranged from 0 to 25. The shared species between houses and taperas, as well as the exclusive species in each DC, can be seen in Figure 3E. There are differences in the composition of growth habits between houses and taperas (Figure 3F). Taking into account the relative frequencies in each DC, tree species are the most represented group in both DCs, accounting for 30% in houses and 56% in taperas. The distribution of habits in houses is more balanced, with 26% perennial herbs, 21% shrubs, 17% annual herbs, and 6% other habits, while in taperas, the rest of the habits consist of 23% shrubs, 15% perennial herbs, 4% annual herbs, and 2% other habits. More than 90% of vegetable crops and 75% of aromatic species are absent in taperas. The Shannon diversity index

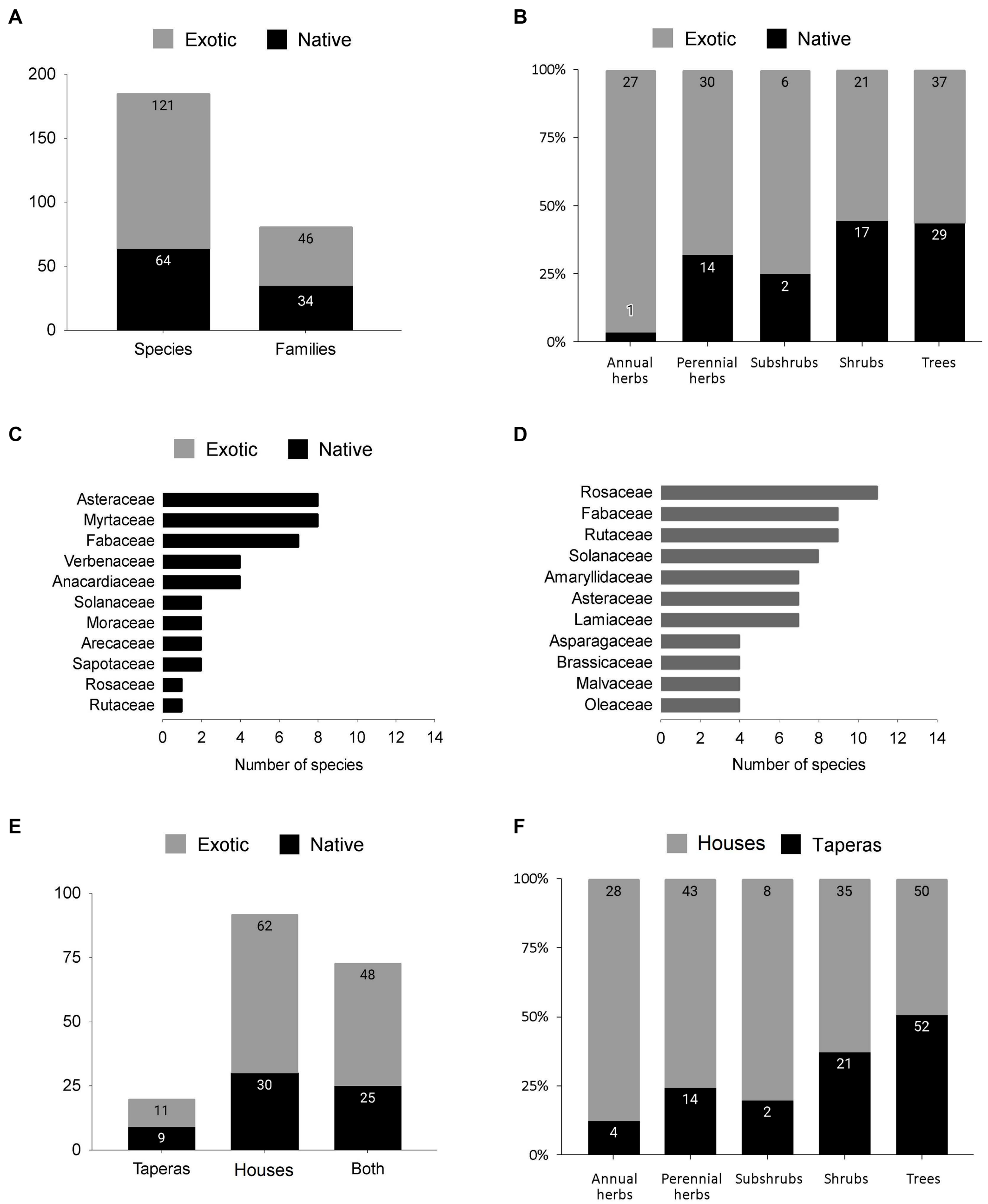


FIGURE 3
**(A)** Proportion of native to exotic plant genetic resources over a total of 185 species in 66 families of phanerogams and 1 lichen family. **(B)** Proportion of habits among exotic and native species. **(C,D)** The most important native (black) and exotic (gray) families. **(E)** Amount of species recorded exclusively in Taperas and Houses or in both, showing the exotic to native ratio (gray = exotic and black = native). **(F)** Proportion of habits in Houses (gray) and Taperas (black). Labels in bars mean the number of taxa in every category.

(H′) and evenness (E) values are shown in Table 1. Higher values are observed in houses compared to taperas, indicating higher richness and a greater number of species with comparable abundance in houses. Taperas, on the other hand, have fewer species with more extreme frequencies, resulting in lower levels of evenness.

The most frequent species and the exclusive ones in each DC are shown in Figure 4. Among the 30 most abundant species, approximately half are shared between both DCs, but their order of importance changes. Furthermore, houses and taperas are clearly separated into two groups in the DCA (Figure 5), with houses ordered toward the left and taperas toward the right of the graph. The first axis of ordination follows the reverse gradient of DC diversity. The separation into two groups was expected given the high proportion of exclusive species found in houses. Some of these species stand out in the ordination, along with other species that made a significant contribution. Species appearing in intermediate positions on the graph, such as *Schinus lentiscifolius* (Carobá) or *Eucalyptus* spp., are present in both houses and taperas.

TABLE 1 Species richness and diversity by domestic context based on the relative frequency.

| | Houses | Taperas | Total |
|---|---|---|---|
| *S* (species richness) | 165 | 93 | 185 |
| *Si* (number of exclusive species) | 92 | 20 | 112 |
| *H′* (Shannon's diversity index) | 4.86 | 3.99 | -- |
| E (Shannon's evenness) | 0.95 | 0.88 | -- |

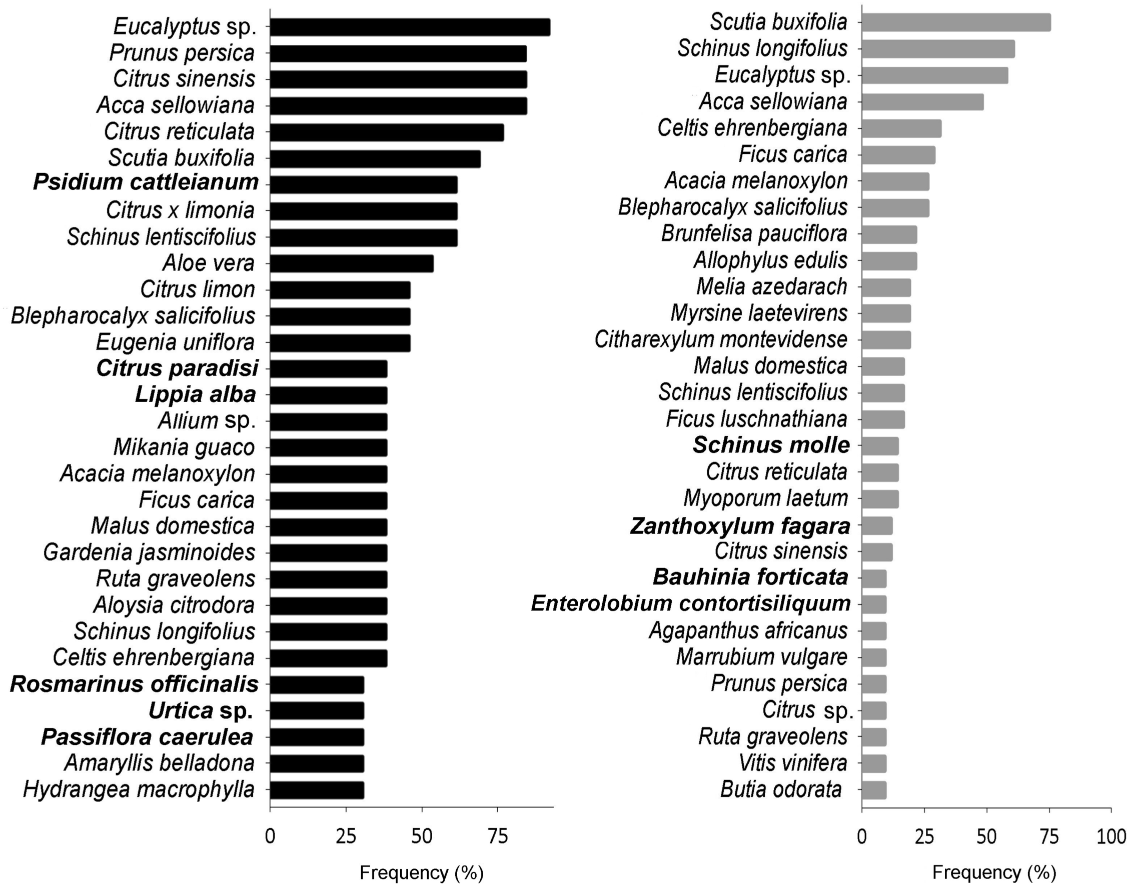


FIGURE 4
The top-30 most frequent species found in Houses (black) and Taperas (gray). In bold are shown the exclusive species in every domestic context.

Regarding the spatial distribution of plant genetic resources, the species were distributed as follows: 120 in home gardens, 17 on small plots, 82 in the surrounding area, 33 in natural grasslands, 44 in forests, and 21 on hilltops. There are 43 species present in the cultivated and non-cultivated environments, with the majority (35) being native species.

## 3.3. Uses of agrobiodiversity

From the fieldwork, 1,199 records of plant uses emerged, including inferred uses from the survey (52%) and cited uses from interviews (48%). Uses were recorded for the 11 pre-established categories, and extensive local knowledge was found regarding the ways of using numerous native and exotic plant genetic resources. Figure 6 shows the frequencies of each use category, with the most frequent being: human consumption, environmental uses, fuel, ornamental, and medicinal. The figure also indicates that native species predominate in environmental and fuel uses, while medicinal uses show an equivalent use between exotic and native species, and the other two categories are predominantly exotic. When considering the number of species, the categories are ranked differently: human consumption, ornamental, medicinal, and environmental uses with 71, 62, 58, and 49 species, respectively. Fuel use was mentioned for 28 species, while toxic and harmful use, social, symbolic uses and ritual uses, animal feed, and industry and craftsmanship were cited for 7 to 12 species each. Construction and veterinary uses registered fewer species, 3 and 2, respectively.

The species with more than one use category (NU>1) constitute 45% of the species total, with native species having the highest number of NUs: *Schinus lentiscifolius* and *Blepharocalyx salicifolius* with 5 use categories, *Scutia buxifolia*, *Acca sellowiana*, *Citharexylum*

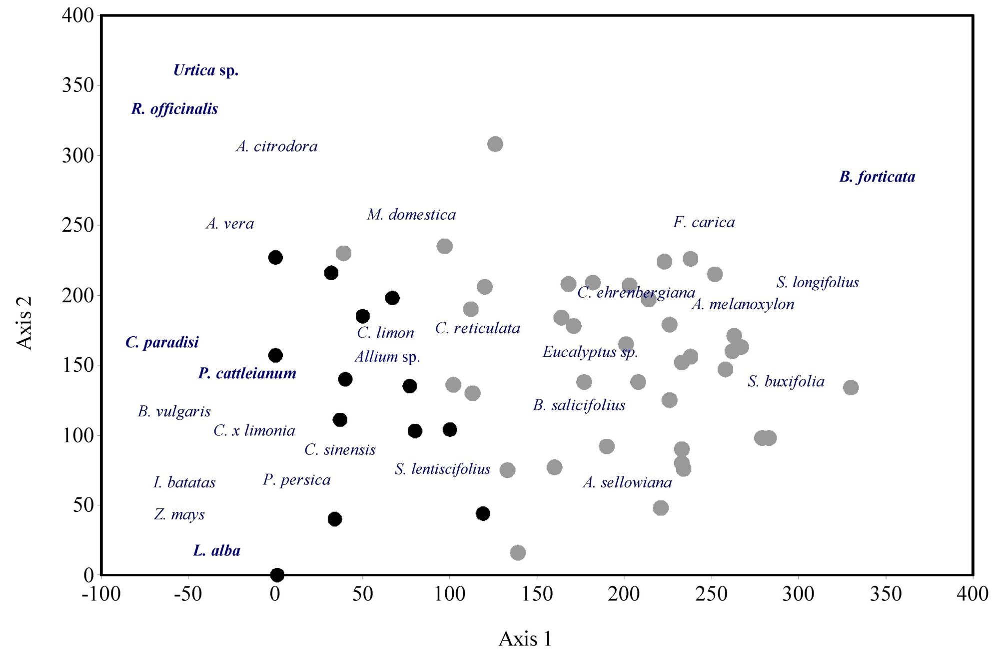


FIGURE 5
DCA ordination of Houses (black dots) and Taperas (gray dots) with respect to the frequency of species recorded. The first two eigenvalues were 0.467 and 0.316. The ordination of some of the most frequent plant genetic resources found in both domestic contexts are also shown.

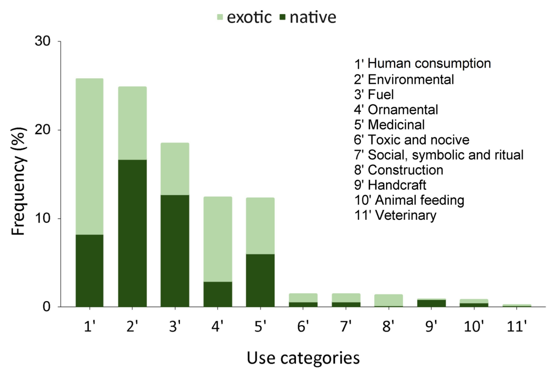


FIGURE 6
Frequency of citations of use categories in native (dark) and exotic (light) species.

*montevidense* and *Daphnopsis racemosa* with 4. It was observed that different use categories concentrate varying numbers of species with NU>1. Environmental, fuel, toxic and harmful uses practically encompass all species with more than 1 use, while medicinal uses have 64% of their species with more than 1 use, ornamental (50%), and human consumption (44%). Figure 7 provides an ordered list of species with the highest number of citations for their uses (NCUs) and the respective use categories for each species.

On the other hand, considering the Consensus of Use, the species with higher CU (>50%) are: *Prunus persica*, *Citrus sinensis*, *Acca sellowiana*, *Eucalyptus* spp., *Schinus lentiscifolius*, *Scutia buxifolia*, *Zea mays*, *Citrus reticulata*, *Citrus x limonia*, *Eugenia uniflora*, *Psidium cattleianum*, *Cucurbita* spp., *Phaseolus vulgaris*, *Ficus carica*, *Urtica urens*, and *Blepharocalyx salicifolius*. Table 2 presents the most cited species for the main use categories.

Regarding human consumption, various forms of food consumption were recorded, including fresh, cooked, or dried fruits and vegetables, alcoholic beverages (wine and liqueur), and non-alcoholic beverages (flavored water, juice, tea, and infusion), seasoning, sweets, and chewing products. Out of the 71 species cited for human consumption, 53 are exotic and are distributed among traditional productions: 27% fruit crops (19 species), 32% vegetable crops (23), and 11% aromatic plants (8). Images of some of the most relevant species for human consumption are presented in Figure 8. Among the 18 native food species, most are edible fruits that are usually consumed *in situ* when exploring forests, grasslands, or rocky outcrops. The most notable example is *Blepharocalyx salicifolius*. A.M. describes the taste and experience with the fruit: "Birds and humans feed on Arrayán, it leaves you with a refreshing sensation, like a mint candy, the aroma is very good." Other species cited with this form of consumption are *Schinus lentiscifolius*, *Celtis ehrenbergiana*, *Scutia buxifolia*, *Allophylus edulis*, *Citharexylum montevidense*, *Psidium salutare*, *Opuntia ficus-indica*, *Myrceugenia euosma*, *Passiflora caerulea*, and it also happens with *Acca sellowiana* and *Psidium cattleianum*, although these last two are also found in cultivated environments. Lastly, the preparation of infusions from different parts of the plant was recorded for 3 native species: *Ilex paraguariensis*, *Achyrocline satureioides* and *Ocimum carnosum*.

Environmental use was the second most cited use, being of equal importance as human consumption. The most common form of use was for the protection of humans and animals from extreme weather conditions, providing shade in summer and shelter from cold in winter, mainly protecting livestock from frost. Examples of some tree species in use can be observed in Figure 9. Most of the species in this

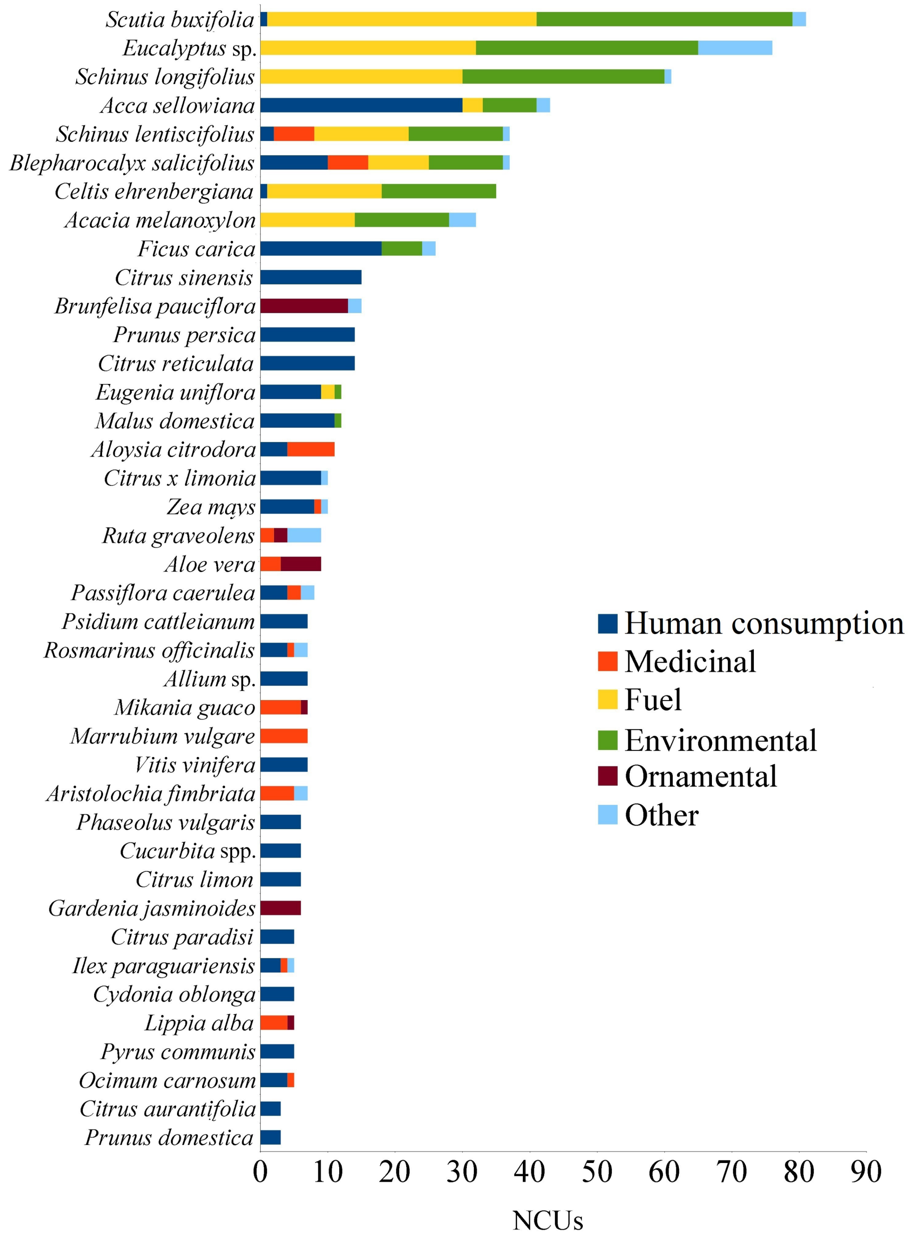


FIGURE 7
The top-40 most used species with respect to the number of cited uses (NCUs) for every use category. Minor uses are summarized as "other.

use category are trees, and although the number of species is high, the use citations are concentrated in a few species (Table 2). Fuel use has similar characteristics, with fewer species since a selection is generally made from the previous category, emphasizing the quality of firewood for fuel.

Regarding the use of ornamental plants, although it was one of the uses with the highest number of species and a significant number of citations, these are well-distributed, and few species stand out. Traditionally ornamental genera such as *Amaryllis*, *Rosa*, *Pelargonium*, and *Gardenia* are notable. The native species mentioned as ornamentals were 9, each with only 1 or 2 citations: the palms *Butia odorata* and *Syagrus romanzoffiana*, *Daphnopsis racemosa*, *Lippia alba*, *Prunus subcoriacea*, *Aspillia montevidensis*, *Cochliasanthus caracalla*, and *Phytolacca dioica*. Regarding gardens and their beauty, M.S. recounts that in Amaro's house, now in ruins, there was a "garden" framed between the buildings "that was beautiful, full of flowers, there was a huge orange tree in the middle surrounded by stones, and he cultivated plants in flowerbeds" (…) "On November 2nd, everyone would go to pick flowers for the dead." These flowerbeds still exist today, with no flowers, and they are still delimited by standing stones.

For medicinal use, citations of species used for various diseases in the respiratory, digestive, circulatory, endocrine, immune and urinary systems were recorded. As well as for the skin, subcutaneous tissue, infectious and parasitic diseases; and against poisoning, and other medicinal uses. A variety of medicine preparation methods and application forms were also documented. Fifty-eight species were found with medicinal use, 30 of which are native, exhibiting various

TABLE 2 Species with Consensus of Use greater than 25% for the main categories of use.

| | Human consumption | | Environmental uses | Used as fuel | Ornamental use | Medicinal use |
|---|---|---|---|---|---|---|
| Exotic | Durazno (*Prunus persica*)<br>Naranja (*Citrus sinensis*)<br>Maíz (*Zea mays*)<br>Mandarina (*Citrus reticulata*)<br>Limón tangerino (*Citrus x limonia*)<br>Zapallos (*Cucurbita* spp.)<br>Poroto (*Phaseolus vulgaris*)<br>Higuera (*Ficus carica*)<br>Pomelo (*Citrus paradisi*)<br>Cebolla (*Allium cepa*)<br>Boniato (*Ipomoea batatas*)<br>Romero (*Rosmarinus officinalis*)<br>Membrillo (*Cydonia oblonga*) | Manzana (*Malus domestica*)<br>Ajo (*Allium cepa*)<br>Perejil (*Petroselinum crispum*)<br>Menta (*Mentha* sp.)<br>Orégano (*Origanum vulgare*)<br>Ciruela (*Prunus domestica*)<br>Pera (*Pyrus communis*)<br>Limón (*Citrus limon*)<br>Naranjo amargo (*Citrus aurantifolia*)<br>Cedrón (*Aloysia citrodora*)<br>Uva/Parra (*Vitis vinifera*) | *Eucalyptus* spp.<br>Acacia negra (*Acacia melanoxylon*)<br>Trasparente (*Myoporum laetum*) | *Eucalyptus* spp.<br>*Acacia melanoxylon* | Azucena (*Amaryllis belladona*)<br>Aloe (*Aloe vera*)<br>Jazmín (*Gardenia jasminoides*)<br>Jazmín del Paraguay (*Brunfelsia pauciflora*)<br>Rosa (*Rosa* spp.)<br>Malvón (*Pelargonium × hortorum*) | Cedrón (*Aloysia citrodora*)<br>Marrubio (*Marrubium vulgare*)<br>Ortiga (*Urtica urens*)<br>Guaco (*Mikania guaco*)<br>Malva (*Malva sylvestris*)<br>Baldrana (*Arctium minus*)<br>Ajenjo (*Artemisia absinthium*)<br>Palma de la India (*Tanacetum vulgare*)<br>Aloe (*Aloe vera*) |
| Native | Guayabo del país (*Acca sellowiana*)<br>Pitanga (*Eugenia uniflora*)<br>Arazà (*Psidium cattleianum*)<br>Mburucuya (*Passiflora caerulea*)<br>Yerba mate (*Ilex paraguariensis*) | Butia (*Butia odorata*)<br>Anís de monte (*Ocimum carnosum*)<br>Arrayán (*Blepharocalyx salicifolius*)<br>Chal chal (*Allophylus edulis*) | Carobá (*Schinus lentiscifolius*)<br>Coronilla (*Scutia buxifolia*)<br>Molle (*Schinus longifolius*)<br>Tala (*Celtis ehrenbergiana*) | Coronilla (*Scutia buxifolia*)<br>Carobá (*Schinus lentiscifolius*)<br>Molle (*Schinus longifolius*)<br>Tala (*Celtis ehrenbergiana*) | | Coronilla (*Scutia buxifolia*)<br>Carobá (*Schinus lentiscifolius*)<br>Arrayán (*Blepharocalyx salicifolius*)<br>Cipó-Miló (*Aristolochia fimbriata*)<br>Congorosa (*Monteverdia ilicifolia*)<br>Salvia (*Lippia alba*)<br>Sauco (*Sambucus australis*) |

habits, with perennial herbs (22) being the most common, followed by shrubs (14), and finally, annual herbs, subshrubs, and trees (8, 8, and 6 respectively).

## 3.4. Agrobiodiversity management

Based on an ethnographic work, 1,338 records of management practices emerged, providing data for the 10 predefined categories of management, along with qualitative information on the application of each practice. Figure 10 shows the frequencies of management practices and their application to exotic and native species. The most frequent management practices are protection, propagation, and improvements, mainly applied to exotic species, followed by pruning, gathering, and tolerance, with the last two practices mostly applied to native species. Regarding the number of species receiving each practice, the order is as follows: protection (134), propagation (120), improvements (119), tolerance (54), gathering (45), pruning (36), community circulation (34), care for inherited plants (29), transplantation (14), and selection (11).

The recorded species with more than one management practice comprise 82% of the species total, with species ranging from 0 to 10 management practices. The species with the highest number of management practices are: *Acca sellowiana* (10), *Prunus persica* (9), *Ilex paraguariensis* (9), *Prunus domestica* (8), *Schinus lentiscifolius* (8), *Ficus carica* (7), *Citrus x limonia* (7), *Ruta graveolens* (7), *Aristolochia fimbriata* (7), *Blepharocalyx salicifolius* (7), and *Psidium cattleianum* (7). Figure 11 ranks the species according to the number of citations


FIGURE 8
**(A)** Fruit orchard: Peach (*Prunus persica*) and *Citrus* sp. **(B)** Fruit orchard: Tangerine lemon (*Citrus x limonia*) with fruit, surrounded by blooming peaches. **(C,D)** Guayabo del país (*Acca sellowiana*). **(E)** Fruit of the Tangerine lemon. **(F,J)** Ancient Fig tree (*Ficus carica*). **(J)** Detail of the Fig tree, showing a carving on the trunk, which is presumed to be the result of a healing practice. **(G)** Common bean (*Phaseolus vulgaris*). **(H)** Cidra (*Cucurbita ficifolia*). **(I)** Warted squash (*Cucurbita* spp.).

of management practices per species (NCMPs), highlighting those of greater cultural value.

Regarding protection, propagation, and improvement practices, they are mainly applied to species found in cultivated environments (gardens, small plots and holdings) and the surroundings of houses. Protection of these environments includes enclosures that prevent livestock from grazing, protect against wind and damage from other animals such as hares, parrots, and wild boars, as well as actions taken on plants to prevent insect attacks (e.g., ants). In this regard, P.R. indicates: "when there is a plague of parrots, you have to take turns scaring them away.." P.R. also mentions that after abandonment, when the previously maintained protections by the inhabitants deteriorate, livestock enter the farm or garden, breaking branches and browsing foliage, weakening and killing the specimens. As for propagation, it is carried out by sowing seeds obtained from collecting, self-production, exchange, purchased plants, or collected propagules. The recorded improvements include the addition of animal manure (chicken, horse, cow), soil preparation, sowing, irrigation, and removal of plants competing for space or light with the target plant.

Pruning was recorded in 36 species, including trees and some shrubs, mainly used for human consumption, environmental purposes, and fuel. Formation pruning is mainly performed on


FIGURE 9
**(A)** Coronilla (*Scutia buxifolia*). **(B)** Use of Coronilla in the construction category, as a post or wire rein. **(C)** Arrayán (*Blepharocalyx salicifolius*) in fruiting stage. **(D)** Carobá (*Schinus lentiscifolius*). **(E)** Carobá ancient tree managed with a single trunk.

trees that provide shade and shelter for livestock, shaping a high-crowned tree that allows circulation underneath, as is the case with *Scutia buxifolia*, *Schinus lentiscifolius*, *Schinus longifolius*, or *Celtis ehrenbergiana*. On the other hand, pruning fruit trees aims at increasing fruit production and ensuring their health. Regarding sanitary pruning, P.R. provides an example indicating an important factor leading to the death of specimens after the abandonment of the DC, namely, the parasitism of "Yerba del pajarito" (*Tripodanthus acutifolius*), a native epiphyte hemiparasitic species that germinates and parasitizes trees, weakening the specimens. According to the account, the "Yerba del pajarito" is constantly controlled by residents in their homes, and a common management practice in fruit trees is to cut the branches that support early stages of its parasitism.

Gathering and tolerance practices are applied to 45 and 54 species, respectively, of which 89 and 74% are native, primarily recorded in medicinal, human consumption, fuel, and environmental uses. Some examples of native species where these practices are applied are: *Acca sellowiana*, *Schinus lentiscifolius*, *Scutia buxifolia*, *Schinus longifolius*, *Celtis ehrenbergiana*, *Blepharocalyx salicifolius*, *Monteverdia ilicifolia*, *Ilex paraguariensis*, *Baccharis trimera*, *Baccharis articulata*, and *Passiflora caerulea*. Some examples of exotic naturalized species are *Cyclospermum leptophyllum*, *Arctium minus*, and *Urtica urens*.

The care of inherited plants was mainly recorded in old specimens of *Acca sellowiana*, *Prunus persica*, *Citrus x sinensis* and *Citrus x limonia*, indicating that they were planted by previous generations. It also includes vegetable landraces, whose seeds have been conserved

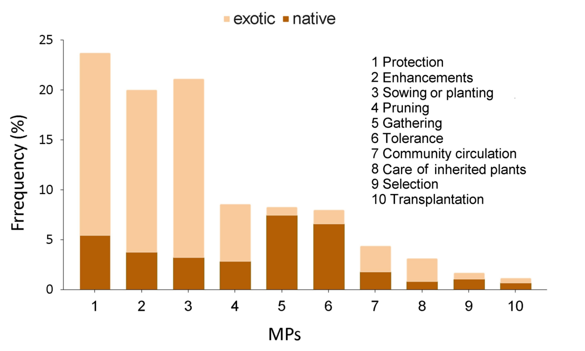


FIGURE 10
Frequency of citations of management practices (MPs) in native (dark) and exotic (light) species.

for several generations. A. states, "The squashes are from my father's house. One type has a long neck, another one grows oval."

Selection was recorded for five native species: *Acca sellowiana*, *Ilex paraguariensis*, *Achyrocline satureioides*, *Psidium cattleianum*, and *Blepharocalyx salicifolius*. In the case of Arrayán, A. indicates, "It's the white Arrayán, the one with thin leaves and a white bark. I used it to treat uric acid. I collected seeds from these plants to share seedlings with this trait." As for exotic species, selection was recorded in peach (*Prunus persica*), plum (*Prunus domestica*), fig (*Ficus carica*), as well as in landraces of maize (*Zea mays*), bean (*Phaseolus vulgaris*) and squash (*Cucurbita* spp.).

Community circulation occurs through various channels: among family members and/or neighbors, from wild plants to one or several neighbors' homes, from taperas to houses, from institutional projects to neighbors and vice versa, and from houses to the wild. A.M. comments on peaches, "They have been in the area for many years" [...] "The peach trees were brought from the plants that were at Z.'s house. They have always planted them. They had an impressive peach orchard. Z. gave me two bags of peaches, and I did not have any, so I made jam. They made dried peaches, among many other things. I made seedlings with the seeds." The same applies to native fruit trees, where seeds or seedlings are collected to be cultivated near the house, as is the case with Guayabo del país (*Acca sellowiana*) and Arazá (*Psidium cattleianum*). A.M. explains, "the ideal place for native fruit trees is to have them close to the house, so you can harvest them. Harvesting takes a long time, which I no longer have." Another example is Marcela (*Achyrocline satureioides*). A.M. states, "I used to only collect it, but now I have learned to put it back into the soil. I use scissors to cut the flowers, then I let them dry on paper. I use the flower for tea and extract the seeds. I put the seeds back into the soil. I once made a flowerbed with those seeds in the backyard." [...] "Marcela is a complicated plant to cultivate; you have to leave it alone. It prefers to live in the wild." A.M. throws the plant near the house to have it there and in the hills to maintain the species and prevent its loss. She has observed that in some enclosed fields, a different, larger species of Marcela, called "Marcelones," has grown. She is also collecting seeds from this species.

## 3.5. Prominent plant genetic resources

The cultural value of the species in this landscape can be observed in Figure 12 through the values of CU (Consensus of Use), NUs (Number of Uses), and NCPMs (Number of Citations per Mention). Qualitative information on the local knowledge gathered is presented for these species, including Yerba Mate (*Ilex paraguariensis*) and Cipo-miló (*Aristolochia fimbriata*), which are considered strategic resources by the community.

**Peach** (*P. persica*) is the most cited species by the interviewees and is highly present in households (Figures 8A,B), it is one of the species with the highest number of recorded management practices. These genetic materials have been in the area for several generations and exhibit significant variability in their fruit, skin color, pulp color, with the "white peach" being very common, along with clingstone and freestone varieties, and a wide harvest period ranging from November to February. There is local knowledge regarding its ecology and cultivation. A.M. states, "There are white-fleshed, yellow-fleshed, and red-fleshed peaches. The red one gives fruit in November, it's the first one. The latest one is in February, and I always have peaches throughout the summer." [...] "It's not big but very tasty, very aromatic, it makes excellent liqueur, exquisite." Varied ways of consumption were recorded, such as fresh fruits, dried ("orejones"), and the preparation of preserves and liqueurs. This species is found in gardens, where it receives fertilization, irrigation, training pruning, branch thinning, and sanitation pruning to eliminate the hemiparasitic plant "Yerba del pajarito" (*Tripodanthus acutifolius*). Peaches are propagated through seeds, which germinate spontaneously, and seedlings are allowed to continue their growth *in situ* or are transplanted to a definitive location. People also engage in sowing for subsequent transplantation. Seed and plant exchange and care for inherited plants was also recorded, indicating a long history of cultivation in the area. They are aware of their history: who brought the seeds, and where they came from.

The ***Citrus*** genus comprises seven fruit-bearing species in the area, and it was recorded in 92% of the surveyed households, mainly found in orchards, although there may be specimens in gardens and the surrounding area. The most used species within the genus are Orange, Mandarin, and Tangerine Lime. Some very old trees, according to accounts, could be 100 years old, and it is mentioned that there used to be orchards that sold oranges for the local industry. The "Tangerine Lime," as it is called by the local inhabitants, is a citrus not commercially cultivated in Uruguay. According to our survey, its fruit is medium-sized, orange-colored, with orange and acidic pulp (Figure 8E). It produces abundantly throughout the year without presenting alternate bearing, as reported by the interviewees. Its uses include fresh consumption, the preparation of preserves, jams, and beverages such as juices and wine. The species propagates naturally through regeneration, where plants are allowed to sprout or are transplanted to a suitable location. There is community circulation and care for inherited plants.

**Fig trees** (*Ficus carica*) are found in gardens or orchards, in protected spaces, but they are also present in the less protected surroundings (Figure 8F). They are long-lived and resilient species, and very old specimens were observed in taperas. Knowledge about the qualities and variability of its fruit was recorded, with the presence of three types of plants: A.M. "I have two fig trees, one with large white figs and another called "honey fig." Honey figs are white figs that, when ripe, release a sweet drop that resembles honey, very sweet." Black-skinned fig trees were also found during the surveys. Although its primary use is human consumption, its environmental use for shade around the house was recorded, and symbolic or ritual uses

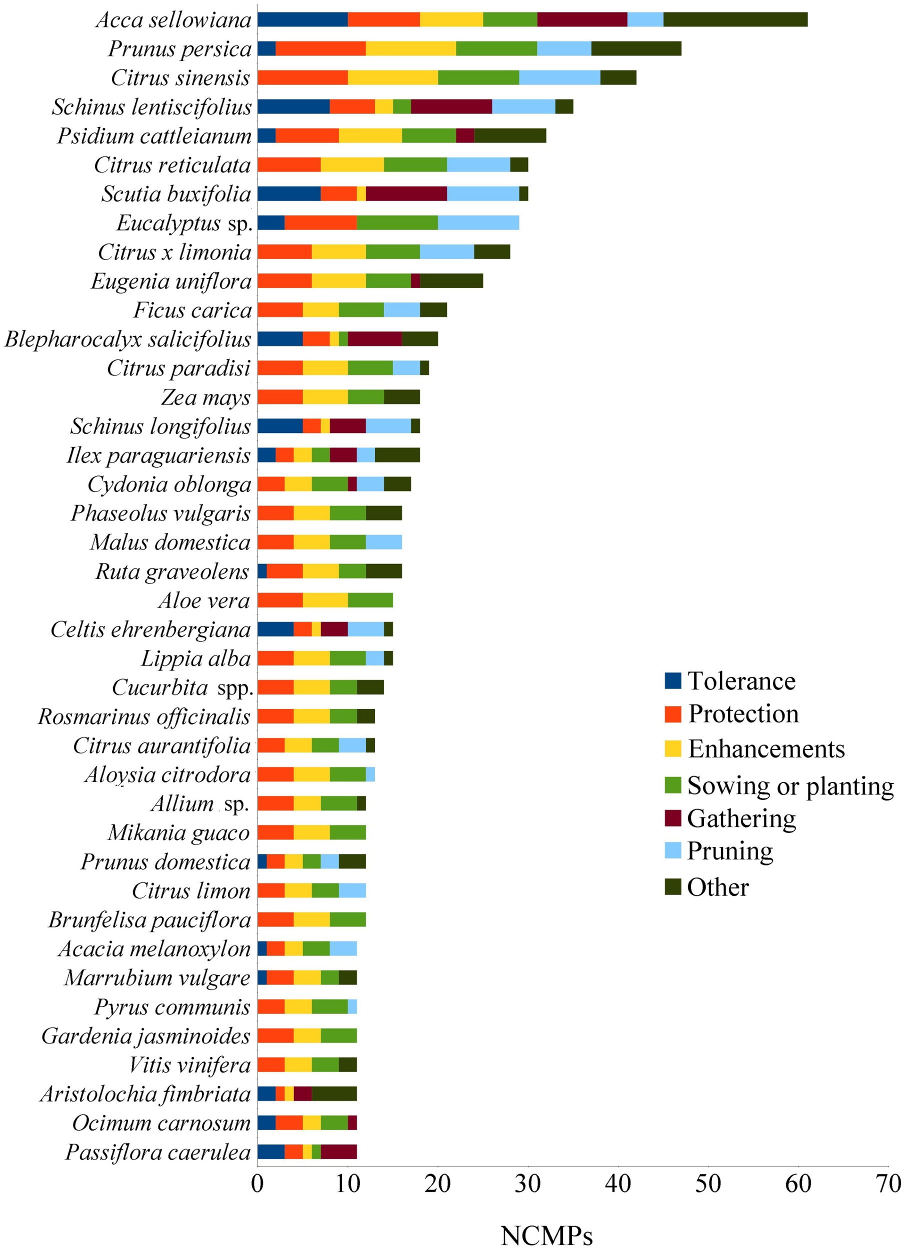


FIGURE 11
The top-40 most frequently managed species based on the NCMPs. Minor practices were summarized as "other" for better legibility.

were also mentioned, as A. recounts, "you can heal using the fig tree: you carve the sick person's foot to cure hernia. When the tree wound is healed, the person gets cured." It is worth noting that during the survey of taperas, a specimen with a carving resembling a small foot was recorded (Figure 8J). Furthermore, information about its propagation was collected, noting that root suckers emerge from the base of the tree, generate roots, and can be separated from the mother plant to generate a new identical plant.

**Guayabo del país** (*Acca sellowiana*) is a native fruit species whose fruits are consumed both fresh and processed into sweets (Figures 8C,D). In the area, there are wild specimens, specimens found in cultivated areas probably selected for their fruit, and specimens in small production plots installed by local organizations and academic groups. The interviewees shared general knowledge about the species and specific plants: A.M. said "there's a new one, in a paddock, which is growing well because it does not have any predators. That tree bears very delicious fruit, a shiny, elongated fruit with a thin skin, it's the type of Guayaba that is good to eat fresh." A.M.: "Guayaba trees do not yield the same amount every year," attributing it to climate change and noting that it can be observed in all fruit trees. P.R. comments, "Every house used to have old Guayaba trees. There was a time when Guayaba trees produced a lot, then there was a period when they stopped producing, and now the ones in the countryside are starting to produce again" [...] "When we were kids, in the afternoon, we would go out and look for Guayaba to eat." Other uses were also recorded, such as animal feed, environmental uses, and

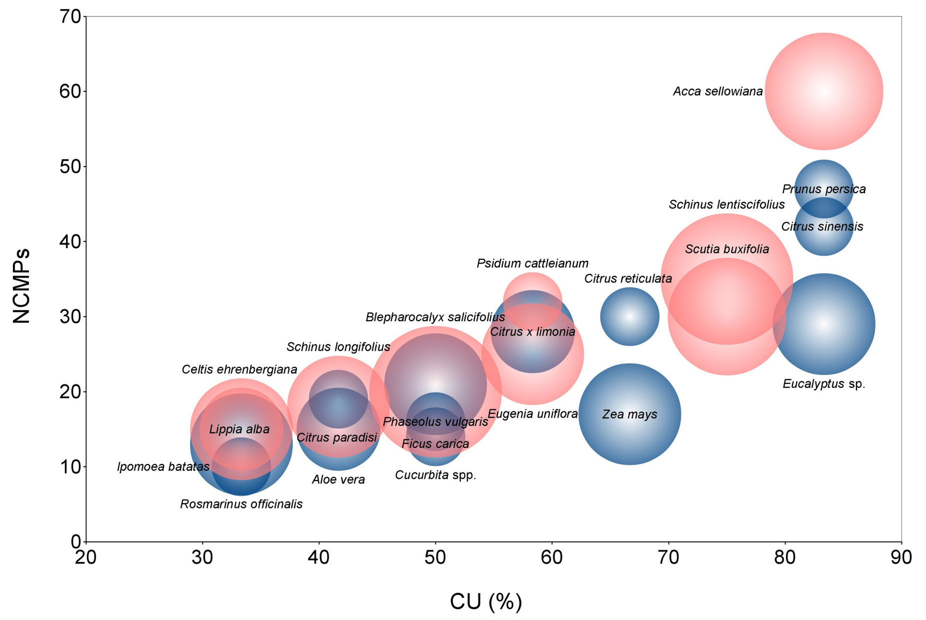


FIGURE 12
Selection of species with the highest consensus of use (CU) and NCMPs. Bubble sizes are proportional to the number of uses referred to in the interviews. Blue bubbles are exotic and pink ones are native species.

fuel. The fruit harvest is done in wild plants (gathering), which are "monitored," keeping track of their phenological status, particularly the fruit ripening stage. Local knowledge was recorded about the wild and domestic animals that eat the fruit, including sheep, wild boars, and rheas. The protection, improvement, and tolerance of plants in the immediate vicinity of the house were also noted. Improvements include measures such as removing plants of other species that compete with it, as M. comments: "I clear the area below it to make it clearer, I remove the surrounding plants." Planting, cultivation, and transplantation of specimens from the wild to the garden or farm, or from one cultivated area to another, were also observed. Z.O. states, "I plant seeds everywhere, and then, when they sprout, I move the seedlings to another place" [...] "I planted this one, I took it from the root of another plant in the garden. It had a sprout, I took it out with a small shovel and planted it in a container, and then I planted it here. It was a little trunk, it had leaves..." The care of old plants inherited from previous inhabitants or family members was also confirmed, and there was knowledge on the history of these plants.

The **Arazá** (*Psidium cattleianum*) and **Pitanga** (*Eugenia uniflora*) are two native fruit species mainly mentioned for human consumption. Both species are highly present in both gardens and small plots, and are part of current development projects managed by local NGOs. J.P., a member of an NGO, defines these species as part of the most important plant genetic resources in the area. Local knowledge about both species was recorded. One of the interviewees, M., monitors wild arazá plants near her house, in the forest along a stream, so she can eat them: "Arazá need good moisture to produce large fruits. If you plant it in the field, it produces small fruits, but next to a stream, it produces nice large fruits. One branch fell to the ground, took root, and grew into a new plant." A.M. planted Pitanga in her garden, a plant she brought from Treinta y Tres some 24 years ago. She has already harvested fruits, and made juice and wine.

The vegetable **landrace varieties** mentioned by the interviewees were maize, pumpkin and squash, beans, and sweet potato. They are usually grown in small plots and homegardens using agroecological multi-species systems. Information from the interviews reveals details about the landraces of **Squash** (*Cucurbita* spp.), their traits, and uses. Interviewee A mentions using all the landraces she has for making sweets, and some for stews: "Now I have a gray squash, white on the outside and orange on the inside. It belongs to my sister-in-law; they have had it for a long time. I like that strong color because of the color it gives the sweet." She also has warted squashes (Figure 8I). She selects the seeds by choosing "the squash closest to the stem, the first one that does not grow as much on a trellis. I choose the seeds from the tastier ones: I save the seeds, taste the squash, and if it's good, I plant it." Another cucurbit mentioned is the **Cidra** (*Cucurbita ficifolia*) (Figure 8H). A.M. says, "I plant cidra every year, a significant amount can be harvested from half a hectare, with fruits weighing up to 30 kg. The plant has always been in the area; people used to grow it and it was passed on from one person to another. It was mainly used to feed animals, and they made sweets for the house. Cows and pigs were fed with it." As for Maize, the interviews indicate its diverse uses over several generations. M.S.: "My family used to grow maize, and with the grains, they would grind them and make bread, *mazamorra*, and *gofio*." Another interviewee (A.) explains how she selects the grains for planting in the next season: "With maize, I also choose good grains that are not diseased, with even rows. I remove the tassel and the back part, which always gets crossed. About the management, she says, "The 'purple' variety pigments the others. I plant them in the same field, separated by rows of squash." Regarding the origin and circulation of the seeds, she says, "The seeds came from N's aunt and I gave them to A.M." The **Beans** included black beans (Figure 8G) and "frutilla" beans, which were the most commonly used. Interviewee A. recounted, "Black beans are delicious to eat and easy to cook. This year I harvested more than a bag of beans. I have had these seeds for 10 years; they were given to me by the husband of my daughter's teacher, who was from Treinta y Tres. We eat those beans and share them with A.M."

The species of **Eucalyptus** (*Eucalyptus* spp.) are present in most DCs, and they are among the species with the highest number of documented uses and management practices. Reports indicate that due to their rapid growth compared to native forest species, they are planted to fulfill various needs, such as livestock protection, providing shade and wind protection for homes, and serving as fuel for heating and cooking. Eucalyptus is also used in construction, particularly for posts, despite being known for its faster decay. It can be found near houses and planted as isolated stands within grasslands, forming sheltering groves. Protection is practiced in the early stages, and later they are managed through pruning. The branches and cut stems are used as fuel or for posts. In some cases, natural regeneration occurs, which is tolerated.

**Carobá** (*Schinus lentiscifolius*) (Figures 9D,E) and **Coronilla** (*Scutia buxifolia*) (Figures 9A,B) are iconic native species in this landscape, widely distributed in the "Quebrada de los Cuervos and Sierras del Yerbal." They have high cultural value and serve multiple purposes. Both species are tolerated and managed in the vicinity of DCs. However, they are generally not permitted in cultivated areas due to their space requirements. Several interviewees mentioned that their management involves pruning lateral branches and shaping the crown in a way that allows the trunk to thicken and occupy less surface area in the field. This allows animals to seek shelter underneath the trees, providing firewood and protection for livestock (Figures 9A,B,D). The interviewees also agree that felling the trees is not a good option because it encourages basal regrowth, and the tree occupies even more space. This management approach is also applied to Tala (*Celtis ehrenbergiana*) and Molle (*Schinus longifolius*). Other reported uses of Carobá include medicinal applications for stomach ailments such as acidity or heartburn, consumption of its fruit as a seasoning or chewable, and animal feed. The other uses of Coronilla include the consumption of its chewable fruit and the utilization of its trunk to build fences or enclosures. In all cases, the uses are derived from wild plants.

**Arrayán** (*Blepharocalyx salicifolius*) is another common species in the native forest of the area (Figure 9C), highly valued among local inhabitants. Four categories of use were recorded for this species, with the most cited use being medicinal as a digestive aid for stomach ailments. Local knowledge was documented, including phenotypic selection for medicinal use based on differences in bark, leaves, and fruit. One interviewee, M., mentions, "I have an Arrayán plant that I grew from a seed collected in the forest to provide plants to a neighbor who wants to take it because she says it's good for cholesterol, and the one she has there has a light yellow fruit, not red like the ones here." This statement also highlights the community circulation of the species. Other uses of Arrayán include human consumption of its fruit as candy or chewable. One of the interviewees explored the creation of processed products such as jam or liqueur. A.M. states, "I've collected and made liqueurs with Arrayán using both the fruit and the leaves." (...) "There are different plants with different fruits, more red or more orange, and they ripen at different times, so you can choose." (...) "In general, I gather the fruits, separating them by color, and make one liqueur with the orange ones and another with the red ones. The fruit is very small, though, and you have to gather a large quantity. Each tree yields a lot, but the fruits do not ripen all at once, so you spend several days collecting a large amount." It is a species that is not planted due to its abundance and is harvested from wild specimens. If Arrayán trees grow near DCs, they are tolerated.

The **Yerba mate** plant (*Ilex paraguariensis*) has three main uses: human consumption, medicinal purposes, and social, symbolic and ritual uses. It is one of the species with the highest number of management practices and the most extensive qualitative information recorded. According to P.R. 's accounts, "all these streams have Yerba mate." The interviewee does not recall the local use of this particular population, although they did participate in the harvesting and processing of Yerba mate in other nearby areas. P.R. describes the process of Yerba mate production, stating, "It used to be harvested in June and transported to the house in carts. The branches would be placed inside the shed on wire racks, a fire was made at the door using good firewood, and embers were spread throughout the shed. The leaves were gradually roasted and prepared, then ground using manual grinders or pounded with a mortar and pestle. The final product was packaged in wooden barrels weighing 60 to 70 kg. We produced a large quantity." (...) "The mate was left to age for a year. New batches were extremely bitter."

Currently, a local NGO with a farmer is implementing a development project based on the wild population present in the area and the planting of specimens in an agroforestry system. According to the accounts of P.P. and A.D, the species is propagated through locally collected seeds as well as those introduced from other locations. Seedlings are generated in containers and, upon reaching a certain height, planted in the riparian and ravine forests. The ancient plants are cared for and harvested to produce yerba for personal consumption.

The **Cipó-Miló** (*Aristolochia fimbriata*) is a species of great local importance, as indicated in the accounts. It is a native species, but it is not commonly found in wild spaces in the Quebrada de los Cuervos and Sierras del Yerbal. Instead, it is found in ruderal spaces or in some of the old taperas. It is used in cases of venomous snake bites, which were once common in rural life in the sierras. The accounts suggest that in the past, it was used to save the life of a person bitten by a snake when reaching a healthcare center in time was impossible, or even before such facilities existed. Nowadays, it is used for bitten dogs and also to treat insect bites. The plant has a reserve rhizome, known as "batata," and the remedy is prepared by chopping the rhizome and soaking it in white alcohol, sometimes with the addition of tobacco and aspirin. Locals apply this preparation to the bite or sting, and, in some cases, it is ingested while trying to reach a healthcare center. In terms of management practices for the species, if necessary, harvesting is done in the wild, and it is tolerated if found in a DC. Various cultivation practices are applied, such as transplantation, protection, and improvements. There is a sense of communal circulation, and it is one of the species where the care of inherited plants can be observed.

## 3.6. Origin, reproduction and transmission of local knowledge

The knowledge recorded in the studied rural community comes from multiple sources. While ancestral knowledge transmitted from generation to generation is present and continues to be passed down, there are other sources of information that interact and hybridize with the traditional knowledge. Among these sources are younger generations who bring knowledge acquired from agricultural schools or universities, books they acquire or receive from visitors, scholars, or government employees, who often also offer training courses or workshops. Civil society organizations promote different types of projects, and external groups bring new knowledge and share it with the community, as was the case with a Guaraní family that lived in the area for a year and shared construction techniques and knowledge about medicinal plants. Furthermore, experimentation and observation also generate knowledge on an ongoing basis, which is retained and transmitted. A.M., referring to a specific species, states, "The sheep eat it…We cleaned it up and conducted an experiment to see what would happen. We are learning from the plant; sometimes, it tells us a little about itself."

Lastly, when asked about the exchange of information among neighbors, A.M. indicates that there has always been an exchange of information in rural schools, where people would gather and frequently engage in community tasks to support the institution. The interviewee also mentions that the presence of the protected area serves as a meeting place where neighbors start to go. "These projects that involve the neighbors are very important because there is a more fluid exchange of different knowledge among the neighbors. If there are no meetings, there is no discussion about these things." [...] "Before, on a day off, you would go visit your neighbor. Now times have changed, and there is no time to visit neighbors. Many things are lost, like communication, and we do not work together on certain things anymore." [...] "Plants used to move more because when you visited your neighbor, the first thing you would talk about was the garden, and there you would see the plants you did not have and take them with you. Same thing with seeds."

# 4. Discussion

## 4.1. Agrobiodiversity and local knowledge

Our study confirms that the rural community of "Quebrada de los Cuervos and Sierras del Yerbal" utilizes and manages a wide agrobiodiversity that covers important daily life needs. Although the number of respondents is not high, it accounts for 40% of the households in the study area. Future studies may explore some age or gender limitations or biases, among other aspects. Various plant genetic resources and local knowledge intertwine in this territory to provide goods and services such as food, medicine, shaping the environment and constructions, fuel, as well as social and spiritual goods, allowing the habitability of the landscape. The hierarchy of uses for human consumption, ornamental, medicinal, environmental uses, and fuel coincides with other studies (Caballero-Serrano et al., 2016; Mariel et al., 2021; Rosero-Toro et al., 2022) highlighting the importance of provisioning, cultural, and regulatory ecosystem services provided by subsistence economies. Agrobiodiversity is part of a multiple-use strategy of resources and ecosystems (Toledo and Barrera-Bassols, 2008; Casas et al., 2014; Furlan et al., 2017) that ensures resilience, food security, and the maintenance of the needs of rural communities.

The wide documented diversity of 185 species, 121 exotic and 64 native, is a biocultural heritage of this community. Out of the 64 native species used, 51 are considered national plant genetic resources (Rivas, 2007; Vidal et al., 2018, 2021), and only four are considered priority species for conservation (Soutullo et al., 2009), including *Ilex paraguariensis* and *Psidium cattleianum* as local resources. With the indicators used, a group of 24 species with high levels of cultural significance is defined (Figure 12), including vegetable landraces, native tree species, native and exotic fruit trees, some medicinal species, in addition to *Ilex paraguariensis* and *Aristolochia fimbriata*. The most diverse environments are the home gardens and the surroundings of the house, highlighting the use of 51 native species from non-cultivated environments.

Among the 71 species recorded for human consumption, there is a high number of fruit trees, with about 33 species, predominantly from the Rosaceae, Rutaceae, and Myrtaceae families, in line with other studies (Furlan et al., 2017; Chamorro and Ladio, 2021; Mariel et al., 2021). There are important exotic fruit species at the local and national level, such as *Citrus* spp., peach, apple, plum, grape, and quince. It is likely that for some of these crops, there is secondary genetic variability generated *in situ*, adapted to the local management practices and environmental conditions. Among the native fruit species, the ones with the highest regional and international recognition are *Acca sellowiana*, *Psidium cattleianum*, *Eugenia uniflora*, and *Butia odorata* (Thorp and Bieleski, 2002; Vignale and Bisio, 2005; Vignale et al., 2016, 2018; Speroni et al., 2018). Additionally, other species were recorded that could be classified as small fruits (berries), such as *Blepharocalyx salicifolius*, *Allophylus edulis*, *Citharexylum montevidense*, *Chrysophyllum gonocarpum*, *Psidium salutare*, *Passiflora caerulea*, *Myrceugenia euosma*, and *Celtis ehrenbergiana*. Native fruits, particularly berries, have great nutritional and medicinal value and have been used by indigenous and traditional populations since ancient times (Furlan et al., 2017; Schmeda-Hirschmann et al., 2019; Rivas et al., 2020, 2023; Chamorro and Ladio, 2021).

The presence of landraces of common bean, maize, sweet potato, squash and pumpkin is traditional in family production systems (Burgueño et al., 2015; Mello et al., 2017; Pereira, 2017; Favaro and Piazza, 2019; Cuadro et al., 2024). Over time, adaptation and selection processes have resulted in a significant diversity of landraces in the Pampa biome (Almeida et al., 2020). However, these landraces are currently facing strong genetic erosion due to migration from rural to urban areas and the substitution of landraces with modern cultivars. This affects the adaptive capacity, evolutionary potential of the crops, resilience of agroecosystems, and the livelihoods of farmers and rural communities (Khoury et al., 2022). In this regard, characterizing landraces, providing *ex situ* support, and valuing them are crucial actions within a conservation and management plan for agrobiodiversity in the protected landscape.

Tree species play a fundamental role in rural communities, not only by providing non-timber forest products (NTFPs), but also for environmental and fuel uses, leading to the incorporation of multiple species in their domestic and productive systems, as observed in numerous communities (Dawson et al., 2014). Preferred species for these uses include native species such as *Scutia buxifolia*, *Schinus lentiscifolius*, *Schinus longifolius*, and *Celtis ehrenbergiana*. Additionally, the general use of native forests is cited to meet further needs. These species are generally multipurpose, consistent with other studies (Dawson et al., 2014; Caballero-Serrano et al., 2016; Morales et al., 2017). In addition, carbon sequestration, nutrient cycling, and water purification should be added to direct benefits.

Medicinal species play a fundamental role in the health and daily life of rural communities in Uruguay (Prieto and Bustamante, 1996; Castiñeira et al., 2018; Tabakian, 2019). Our study revealed a wide diversity of species with various habits and uses that people maintain in their gardens or directly collect from nature, with a 50% component of native species. Comparing our findings with comprehensive studies on medicinal species in the northern region of the country (Castiñeira et al., 2018; Tabakian, 2019) there is significant overlap in introduced and numerous native species. However, some different species are notable, such as *Schinus lentiscifolius*, *Aristolochia fimbriata*, *Anemia tomentosa*, *Ocimum carnosum*, and *Psidium salutare*. The first two species hold high cultural significance for our study area. This demonstrates that while there are widely used species, there are also territorial specificities in plant genetic resources and local knowledge.

In the set of species used, the native component is high (35%), which increases to 45% when considering species of high cultural significance or specific uses such as medicinal plants (52%), environmental uses (59%), and fuel (57%). Several authors (Caballero-Serrano et al., 2016; Tabakian, 2019) emphasize cultural factors as determinants of diversity in plant use, in addition to physical and socioeconomic factors. Chamorro and Ladio (2021) report 39% of native species in use in Patagonia, where the respondents were *mestizos* and *criollos* with some Mapuche influence. Caballero-Serrano et al. (2016) found 64% of native species in use in the Ecuadorian Amazon. Tabakian (2019) documented 70% of native medicinal plants in use in northern Uruguay, interviewing descendants of indigenous peoples. Our work confirms the use and manipulation of native species to obtain goods and services, increasing the availability of useful plants through diverse management practices; this likely triggered incipient domestication processes (Casas et al., 1997, 2014). One example is *Acca sellowiana*, which has a wild population with extensive diversity (Rivas et al., 2007; Baccino, 2011; Calvete, 2013; Puppo et al., 2014), accompanied by selected individuals managed in cultivated environments, transplanted from the wild, tolerated, or obtained from other locations. Many of the surveyed native and landraces are listed internationally as Neglected and Underutilized Species (NUS) with agri-food value. Some of the native species include *Acca sellowiana*, *Eugenia uniflora*, *Psidium cattleianum*, and *Ilex paraguariensis*, while introduced species include *Cydonia oblonga*, *Citrus reticulata*, *Citrus limon*, *Phaseolus* spp., and various species and landraces of cucurbits, among others (Hernández Bermejo et al., 2019). NUS crops, due to their limited use or cultivation abandonment, are subject to genetic erosion (Padulosi et al., 2011; Barbieri et al., 2014).

The substantial wealth of local knowledge regarding native and exotic plant genetic resources is the result of production, hybridization, and transgenerational transmission of knowledge. This legacy is a product of a cultural syncretism, incorporating knowledge from indigenous, colonial-missionary, and *criollo* populations that have converged in the area for the past 300 years (Bica, 2019; Palermo, 2019; Torres, 2019), as other authors have noted for nearby regions (Castiñeira et al., 2018; Tabakian, 2019; Vidal et al., 2021). Throughout this long process, knowledge related to specific practices flows through individuals and in relation to the environment. It is transmitted, acquired, and discarded based on trial and error, giving rise to new knowledge about introduced and local species. Currently, this entire legacy interacts with other sources of knowledge that have entered the area through academia and new ruralities (Pochettino and Lema, 2008; Toledo and Barrera-Bassols, 2008).

## 4.2. Agrobiodiversity loss and local knowledge

The high number of taperas allows us to infer that numerous families who worked the land using agrobiodiverse systems once lived in the area. Currently, only 30 to 40 families reside there, according to the provided data, highlighting the significant impact of rural population migration to urban centers, a trend that has been occurring in Uruguay for decades (Achkar, 2017; Cortés-Capano et al., 2020; Vidal et al., 2021). This migration is part of a global trend resulting from the establishment of the agro-industrial model, which jeopardizes the conservation of agrobiodiversity and biocultural heritage (Toledo and Barrera-Bassols, 2008). With the abandonment of the area, knowledge and seeds are lost as people leave, and the lack of generational turnover further endangers the conservation of cultural and biological diversity.

The difference in the number of species found in houses and taperas, the values of the Shannon index, and the ordination analysis, combined with the fact that out of 93 species recorded in the taperas only 33 are repeated in more than 10% of them, reflect the rapid loss of species and the fragility of most resources in the abandoned cultivation gardens and plots. On the other hand, several resources that are highly present in houses significantly decrease in frequency in taperas, particularly some traditional fruit crops. However, there are accounts stating that all houses had specimens of these species. The diversity of species maintained in houses is sustained by the care and management practices of the inhabitants, clearly demonstrating that the main factor contributing to the loss of diversity is the cessation of these management practices. The time it takes for species to disappear after abandonment varies (Clement, 1999), and losses are associated with the botanical habits of the species. There is a significant reduction in the number of herbaceous species from houses to taperas, with more than 90% of vegetable crops, 75% of aromatic plants, and 57% of medicinal plants lost, while species used for environmental and fuel purposes, mainly trees and shrubs, increase.

The loss of local knowledge, either due to changes in customs or the departure of knowledgeable individuals from the area, may explain the presence of 20 exclusive species in taperas. One such case is *Bauhinia forficata*, which is only found in taperas and is not mentioned in the interviews. There are national and international records of the medicinal use of this species for urinary system diseases and diabetes, among other illnesses (Prieto and Bustamante, 1996; Caffaro et al., 2015; Tabakian, 2019). Another example of knowledge loss over time is that of *Ilex paraguariensis*. Although it is not present in the taperas, it can be found in the forests and has given its name to four watercourses in the area: "Yerbal Chico," "Yerbal Grande," "Yerbalito," and "Cañada de la Yerba." Documented stories exist about the yerba mate plantations in these hills that supplied the Eastern and Río Grande Jesuitic missions (Bonetti, 2010; López Mazz et al., 2020). In our study, knowledge about this species emerged in a few interviews, and although they provided detailed descriptions of cultivation practices and the technique of harvesting and processing yerba mate, it could be inferred that there was likely an ancient knowledge that is practically extinct in the area.

## 4.3. Rural communities, knowledge and plants: interactions that transform and shape landscapes

Rural communities manage agrobiodiversity in different ways and in multiple environments, both in cultivated and wild areas, as described by Casas et al. (1997), Clement (1999), and Wiersum (1997). The qualitative and quantitative analysis of the data allows us to propose a model of organization and management of space and resources carried out by the local inhabitants. It is a complex, multi-use strategy in which plant genetic resources are found in diverse environments, at different scales, and in a variety of interactions between humans and the environment. By interpreting how different plant genetic resources are grouped in space according to their category of use, the combination of management practices and their frequency, the distance in relation to the DC, and the habits and origin of the species, we can distinguish spaces with different characteristics. Based on the classification proposed by Clement (1999) for landscapes or environments, we identify four spaces of use, with DCs and the life of the local inhabitants as the center (Table 3):

*Cultivated spaces:* These are delimited and protected areas, closely integrated with or near the house, where daily plant care takes place. Home gardens and small plots play a crucial role in species domestication, serving as repositories of germplasm and experimental sites. The resources in these spaces are intensively and consistently managed. Within the study area, the majority of exotic agrobiodiversity is cultivated, primarily for human and animal consumption, medicinal purposes, and ornamental use. High-intensity management practices, such as protection, improvement, and propagation, are performed with greater frequency; while pruning, tolerance, and gathering practices are present with medium-frequency. Lastly, community circulation, care of inherited plants, selection, and transplantation, although less frequent, occur twice as often compared to other spaces.

*Managed space:* It is a concentric area around the house, without defined boundaries or livestock protection, but with daily care and interventions. It contains a concentration of tree species, forming a small-scale agroforestry system with a 50% native component. The main uses include environmental purposes, human consumption, fuel, with some medicinal and ornamental species present. In general, trees are pruned to provide shade during summer and protection against cold in winter, or sometimes arranged to form windbreaks. The intensity of management in this space is moderate, with the most frequent management practices being protection, propagation, pruning, improvement, tolerance, and gathering. Other practices occur less frequently, including the care of inherited plants.

*Promoted spaces*: These spaces consist of the property's grasslands where livestock production takes place. Grazing with different animal loads and the burning of "maciegas" (non palatable grasses) are common practices in this pastoral system to control less efficient species for livestock, which modifies species populations and undoubtedly the landscape (Rivas and Condon, 2015). Aside from forage species, this space mainly comprises native tree species and some shrubs, primarily used for environmental purposes, medicine, and fuel. The intensity of management is lower than in the previous spaces, and the main practices are gathering and tolerance. Pruning may occur for trees that provide shelter for the livestock beneath their canopy.

*Intervened wild spaces* are areas of natural vegetation such as forests and rocky outcrops. They can be located within or outside the family farmer's property, in proximity to the house or along daily routes (school path, pasture edges, roadside, etc.). These natural formations undergo some degree of modification due to human and livestock traffic, occasional vegetation thinning for livestock shelter, and the presence of escaped or naturalized species from cultivation. Interventions may also include the cultivation of *Ilex paraguariensis* in agroforestry systems for subsequent harvesting. The species in these spaces are mostly native, with some exclusive to these environments. They are primarily used for medicinal purposes, human consumption, environmental uses, and fuel. This is also where the majority of species used for industry and craftsmanship are found, as well as a high proportion of toxic and harmful species. The intensity of management for the studied species is similar to the promoted space. The most frequent management practice is gathering, while other practices such as pruning, transplanting seedlings, selection, community circulation, and care of inherited plants occurs at a lower frequency.

The location of certain plant genetic resources and their corresponding practices is not fixed; there are movements of species from wild spaces to cultivated spaces and vice versa. Some native species are transplanted or propagated for cultivation, while a few examples of certain crops appear in wild environments, whether as a result of human activity or natural dispersal. In the same vein, the exchange of plants and seeds between neighbors and from *taperas* to cultivated spaces is part of this dynamic.

The natural dispersal of fruits and seeds is also a part of this dynamic, influencing the distribution of plant genetic resources in various spaces (Table 3). Specifically, 56 local native species (87.5% of the total native species), primarily utilized in managed, promoted, and intervened wild spaces, depend on natural dispersal, though not exclusively. Some of these species also emerge in cultivated spaces, being tolerated and protected. Most of these species are trees, predominantly exhibiting zoochory syndromes (Ramírez and Säumel, 2022). On the other hand, the herbaceous plants, mainly from the *Asteraceae* family, exhibit anemochory syndromes, while only a few species show autochory syndromes.

Although there is no research on frugivorous fauna in the protected area, some interviews conducted in this study mention birds, including the *Rhea americana*, as dispersal agents. The vertebrate fauna of Quebrada de los Cuervos and Sierras del Yerbal comprises 138 bird species, 29 species of mammals, amphibians, and reptiles (SNAP/DINAMA, 2010), to which cattle (as a potential dispersal agent) must be added. While there is no evidence to suggest that the dispersing fauna is at risk of conservation in the protected area, the crucial role these species play in landscape conservation is

TABLE 3 Characteristics of cultivated, managed, promoted, and intervened wild spaces in domestic contexts.

| | Cultivated space | Managed space | Promoted space | Intervened wild space |
|---|---|---|---|---|
| Distance to DC | Immediate | Near/concentric | Greater distance | Far |
| Reference Areas | Home garden and small plots | Adjacent area | Grassland | Forests<br>Rocky hilltops and outcrops |
| Practices frequency | High | Moderate | Low | Low |
| Main use categories | Human consumption Medicinal<br>Ornamental<br>Environmental uses | Environmental uses<br>Human consumption<br>Fuel<br>Medicinal Ornamental | Environmental uses Medicinal<br>Fuel | Medicinal<br>Human consumption<br>Environmental uses<br>Fuel |
| Main management practices | Protection, Improvements,<br>Propagation | Improvements, Propagation,<br>Pruning, Tolerance, Gathering | Gathering<br>Tolerance<br>Pruning | Gathering<br>Tolerance<br>Pruning |
| Main habits | Shrubs<br>Trees<br>Perennial herbaceous<br>Annual herbaceous | Trees | Trees<br>Shrubs<br>Perennial herbaceous<br>Trees | Trees<br>Shrubs<br>Perennial herbaceous |
| Species origin | 80% exotic | 50% exotic<br>50% native | 80% native | 100% native and some specific naturalization |
| Species propagation /dispersal | Mainly human | Human and natural | Natural and human | Mainly natural |
| Main species | *Prunus persica*<br>*Citrus reticulata*<br>*Citrus sinensis*<br>*Citrus x limonia*<br>*Zea mays*<br>*Aloe vera*<br>*Psidium cattleianum*<br>*Citrus paradisi*<br>*Schinus lentiscifolius*<br>*Acca sellowiana*<br>*Eugenia uniflora*<br>*Lippia alba*<br>*Ficus carica*<br>*Cucurbita* spp.<br>*Phaseolus vulgaris*<br>*Rosmarinus officinalis*<br>*Ipomea batatas*<br>*Aristolochia fimbriata* | *Acca sellowiana*<br>*Eucalyptus* spp.<br>*Scutia buxifolia*<br>*Schinus lentiscifolius Celtis ehrenbergiana*<br>*Schinus longifolius*<br>*Blepharocalyx salicifolius*<br>*Ficus carica*<br>*Aristolochia fimbriata* | *Acca sellowiana*<br>*Schinus lentiscifolius*<br>*Scutia buxifolia Schinus longifolius*<br>*Celtis ehrenbergiana*<br>*Blepharocalyx salicifolius*<br>*Eucalyptus* spp. | *Acca sellowiana Schinus lentiscifolius*<br>*Scutia buxifolia*<br>*Schinus longifolius*<br>*Celtis ehrenbergiana*<br>*Blepharocalyx salicifolius*<br>*Ilex paraguariensis* |

Distribution of the main plant genetic resources.

recognized (Green and Dennis, 2007; Wright, 2007), along with the need for future ethnographic and ecological research.

This spatial differentiation allows us to propose that landscape management processes are taking place in the Sierras del Yerbal. The differential human-nature interaction in different spaces is a way of extending domestic units (Stampella, 2015) and ultimately shapes what we have referred to in our work as the domestic context. The inhabitants use the territory for their daily needs, just as they use their gardens and small plots for plants that are not present in natural environments, while naturally abundant resources are directly harvested. Recognizing these assemblages of species, uses, and differential management of the territory, applied persistently, allows us to visualize the human imprint on the historical processes of landscape modification and domestication (Franco-Moraes et al., 2021). The transformation of the environment based on cultural criteria leads to the creation of specific biocultural landscapes (Peroni et al., 2013; Hong et al., 2014). The current challenge of conserving the protected landscape largely relies on recognizing these aspects and integrating them into the area's planning and management.

## 4.4. Local community, agrobiodiversity, and conservation in protected areas

Agrobiodiversity, a significant component of biodiversity, depends on human intervention for its generation, maintenance, and future evolution (Sthapit et al., 2016). It delivers valuable ecosystem services, including provisioning, cultural, and regulatory services, not only to local inhabitants but also to the global population (Wood et al., 2015; Caballero-Serrano et al., 2016). However, agrobiodiversity is often overlooked in conservation objectives and management plans of protected areas, where it is only tangentially considered through the conservation plans of "natural" ecosystems. Integrating agrobiodiversity as a focal point in *in-situ* conservation strategies for the "protected landscape" category of the IUCN would serve the purpose of conserving the human-environment interaction that shapes the observed landscapes.

Our research reveals a sustained interaction process between rural communities, plant genetic resources, and environmental conditions. The role of local communities is internationally recognized and needs to be studied locally to design appropriate guidelines for agrobiodiversity conservation and management (De Boef et al., 2013b). The power of local knowledge relies not only on keen observation but also on experiential learning (Morris, 2006; Eden, 2012). Many practical knowledge systems employed by local communities regulate species diversity, create habitat heterogeneity at the landscape scale, and adjust the intensity of use, thus increasing the diversity of available biological resources (Berkes et al., 2000; Assis et al., 2013; Reis et al., 2018; Araujo et al., 2021). The resource management practices of communities reflect a knowledge system based on cultural practices aligned with their objectives and the need for future conservation (Jackson et al., 2007), forming authentic "communities of practice" (Dabezies and Taks, 2021) that safeguard biocultural landscapes (Rivas et al., 2023).

In this regard, conservation objectives of the area cannot be pursued independently of social and rural development goals (Cortés-Capano et al., 2020). It is necessary to revise the perception of farmers as degraders of natural systems and recognize them as custodians and creators of agrobiodiversity and the landscape, as they play a key part in the solution (Cortés-Capano et al., 2020; Dawson et al., 2021). The sustainability of agroecosystems must consider environmental, social, and economic aspects. Therefore, production carried out by farmers within protected areas, integrating their local knowledge and agrobiodiversity, is crucial for landscape conservation. *In-situ* conservation, a dynamic approach that integrates biophysical, socioeconomic, and cultural components, allows for ongoing evolutionary processes in agroecosystems (Maxted et al., 1997; Rivas et al., 2010). It encompasses the concepts of conservation through use (Halffter, 2002) and community-based biodiversity management (MCB), which promotes local governance and community empowerment (Jarvis et al., 2011; De Boef et al., 2013b).

Furthermore, landscape conservation should not solely rely on farmers; it requires policymakers to generate and implement incentives that facilitate and promote *in-situ* conservation of agroecosystems while improving the quality of life for inhabitants (Rivas et al., 2010; Lacerda et al., 2020). In the current national context, protected landscape areas could play a leading role in the https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/comunicacion/publicaciones/plan-nacional-para-fomento-produccion-bases-agroecologicas/plan-nacional across its four strategic pillars: (1) promoting and facilitating the adoption of agroecological practices, increasing the number of farmers practicing this system within the area; (2) facilitating access to products, distribution, and generating consumers by emphasizing the value of agrobiodiversity, fostering local farmers' markets, establishing production networks, and agroecological certification to access national, regional, and international markets; (3) contributing to ecosystem conservation through the rescue, production, and use of native and local genetic resources while recognizing the rights of farmers, and (4) promoting training, research, and extension processes in the area.

## 5. Conclusion

The research revealed a high number of plant species used and managed by the rural community in the protected landscape of "Quebrada de los Cuervos and Sierras del Yerbal," which cover various needs of the daily life of its inhabitants. This agrobiodiversity and the local knowledge about it constitute a landscape where biological and cultural diversity intertwine. A group of native and introduced plant genetic resources of high cultural significance stands out due to their agreed-upon use, diversity of uses, and management practices.

The comparison between the agrobiodiversity of houses and old rural buildings clearly indicates that the abandonment of domestic contexts is a primary cause of agrobiodiversity loss. The *in-situ* conservation of agrobiodiversity and local knowledge is intrinsically associated with the conservation of the biocultural landscape and, therefore, the permanence of family production systems in their domestic contexts.

The proposal regarding the differential use of spaces in domestic contexts reflects the historical and ongoing management of the landscape, reaffirming the close link between agrobiodiversity and the domestication of landscapes. The challenge of current conservation in the protected landscape largely rests on recognizing these aspects and integrating them into the planning and management of the area.

The threat faced by these rural landscapes worldwide is no different from that occurring in the Pampa biome. In the protected landscape of "Quebrada de los Cuervos and Sierras del Yerbal," it is a priority to include agrobiodiversity as a relevant focal object of conservation and to generate a participatory management plan that involves the local community from the outset. The conservation and valorization strategy of plant genetic resources requires public policies that support production, commercialization, and agroecological certification as alternatives to encourage the permanence of farmers in rural areas and promote generational turnover. Academia has a relevant role to play through the deployment of transdisciplinary strategies where the generated information is taken into account by decision-makers.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

MP: study conception and design, data collection, analysis and interpretation of results, draft manuscript preparation and final edition. CG and MR: study conception and design, analysis and interpretation of results, draft manuscript preparation, and final edition. AC: data collection. AL: analysis and interpretation of results and draft manuscript preparation. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Farmers in the transition toward sustainability: what is the role of their entrepreneurial identity?

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**Introduction:** The European Union has recently prompted a shift toward Ecological Intensification (EI) practices, aiming to harmonize agricultural productivity and environmental conservation. Despite the benefits of EI, its implementation has been limited, as farmers face challenges in business reorganization and supply chain adaptation. This paper investigates the role of contract farming (*CF*) in promoting the adoption of sustainable practices among Italian wheat producers. Specifically, it analyzes the influence of farmers' entrepreneurial identity on their engagement in such initiatives.

**Methods:** Using the case study of Barilla Group's Carta del Mulino initiative, an innovative contract farming scheme incentivizing sustainable EI practices, the study explores the relationship between entrepreneurial identity and participation in *CF* schemes supporting EI. Data from a sample of 314 soft wheat farmers in four regions of Northern Italy were collected to examine the role of entrepreneurial identity in the adoption of sustainable practices and participation in *CF* schemes. To evaluate the research hypotheses, two distinct econometric models were developed.

**Results and discussion:** The findings reveal that farmers with a more developed entrepreneurial identity are more likely to adopt more sustainable agricultural practices and engage in contractual schemes involving EI practices. The study highlights the importance of fostering and supporting farmers' entrepreneurial identity while increasing their knowledge of alternative agricultural techniques to address the challenges of the agricultural sector. This integration of individual perspectives (entrepreneurial identity) with a systems view (contract farming schemes) offers valuable insights for future research, policy, and practice in agri-food systems sustainability.

KEYWORDS

**ecological intensification, soil health, entrepreneurial orientation, Barilla, contract farming, cereal farmers**

## 1. Introduction

As a result of a focus on specialized, industrialized, monoculture-based agricultural systems, current agriculture practices have significant negative impacts for the environment and the climate in terms of greenhouse gas emissions (GHG_emissions), loss of biodiversity and ecosystem services, pollution of water systems, increased risk of pests and crop diseases, and loss of soil health (Foley et al., 2005; Despotović et al., 2021; Weituschat et al., 2022). Particularly, soil health is now becoming increasingly more relevant on the agenda of the European

Union—EU—(European Commission, 2018, 2020, 2021). Crop diversification, together with agro-ecology, agroforestry, organic and biodynamic agriculture—among others—are examples of regenerative practices designed for the so-called Ecological Intensification (EI). EI has emerged in the literature as an alternative to conventional and sustainable intensification agricultural systems (Altieri and Nicholls, 2005; Pretty, 2008; Foley et al., 2011; Garnett et al., 2013; Tittonell, 2014; Wezel et al., 2014; Petersen and Snapp, 2015; Rockström et al., 2017). Although the EI agricultural practices prove to restore soil health, they are not as widely spread among farmers as expected (Pretty et al., 2018; Kleijn et al., 2019; Suvanto et al., 2020; Benitez-Altuna et al., 2021; Kernecker et al., 2021).

Implementing EI practices implies a change in farmers' business strategies. More specifically, the adoption of EI-focused practices implies reorganizing farm business models and likely changing the relationships with partners in the whole agri-food supply chains, with higher costs and longer adaptation periods (Blasi et al., 2015; Meynard et al., 2017; Rosa-Schleich et al., 2019). Among the forms of organization of agri-food supply chains that could support farmers in adopting new practices and overcoming such limitations, Contract Farming (*CF*) has proved to be an effective tool to consider (Banterle and Stranieri, 2013; Wang et al., 2014; Minot and Sawyer, 2016; Ricome et al., 2016; Pancino et al., 2019). However, extant literature has not thoroughly investigated the role that contract farming (and especially privately driven initiatives) can play in enhancing specifically the adoption of sustainable practices, particularly at value chains (Weituschat et al., 2023a). What is still in need of further investigation is how the adoption and diffusion of EI practices through contract farming are influenced by entrepreneurial attitudes. The adoption of new practices, combined with a reconfiguration of participation in contractual relations, do engage with entrepreneurial attitudes and dynamics, for instance in terms of recombination of farm assets and resources, skill development, organizational capabilities, and risk management, among others. Today, only a few studies in the domain of agricultural entrepreneurship have provided insights into the entrepreneurial processes mobilized by farmers when engaging in the adoption of sustainable practices and through supply chain participation and contracting (Weituschat et al., 2023a). These studies mainly point to how these entrepreneurs adopt more sustainable agricultural practices for mitigating the impact of their business on natural resources (Fitz-Koch et al., 2018; Mann, 2018; Bakker et al., 2021), thus revealing the presence of entrepreneurial attitudes where business and environmental aspects are strongly intertwined. Consistently, extant studies indicate that farmers' Entrepreneurial Identity (EntID), namely the set of values and attitudes behind farmers' decisions and objectives, likely plays a significant role in the choice to adopt sustainable practices (Azman et al., 2013; De Rosa et al., 2019; Dias et al., 2019; Suvanto et al., 2020). However, no study has so far analyzed whether the entrepreneurial identity of farmers triggers participation in contract farming schemes that aim at incentivizing a higher adoption of sustainable practices.

In this article, we argue that understanding at the systemic level of the value chain what role contracts play as governance mechanisms conducive to the transitions toward more sustainable food systems is necessarily connected to the understanding at the individual level of the farmers of how individuals use their entrepreneurial identity to ensure productivity is improved in quality and conditions within planetary boundaries. Therefore, this paper aims at analyzing the relationship between farmers' entrepreneurial identity and their choice to participate in a contractual scheme that aims to enhance the adoption of EI practices. In order to analyze whether a relationship exists between the entrepreneurial identity of the farmers so defined and the participation in contractual schemes for the adoption of sustainable practices, we draw on the case of a large–scale value chain-based initiative that the Italian multi-national food manufacturer Barilla Group has recently implemented in Italy. In recent years, value chain agreements and contracts are becoming more common in the cereals sector (Carillo et al., 2017; Frascarelli et al., 2021; Ciliberti et al., 2022). Barilla Group launched in 2019 the sustainability–focused Carta del Mulino initiative (CdM; Barilla, 2021a), namely a newly designed contract farming scheme, to reconfigure its value chain and to incentivize particularly farmers producing wheat to adopt sustainable EI practices (Barilla, 2018, 2021b; Pancino et al., 2019).

Implications for research, policy, and practice are provided that enhance the understanding of the potential for integrating an individual-level perspective (entrepreneurial identity) into a systems view (contract farming schemes at the industrial value chain level) when it comes to organizing sustainability in agri-food systems.

## 2. Conceptual background

### 2.1. Entrepreneurial and institutional changes for sustainable transitions

Evidence of the detrimental effect that food systems have in particular on the environment at all stages (from production to consumption and waste management) is well documented in the literature: agricultural intensification and specialization have persisted over the last decades with profound negative effects on biodiversity (Rockström et al., 2017; Kleijn et al., 2019), such as depletion of freshwater resources, soils degradation, deforestation, and loss of plants and animal species (Campbell et al., 2017; Davies, 2017; Rockström et al., 2020). Such effect has motivated the emergence of initiatives at the policy level in Europe—such as the Farm to Fork strategy, a cornerstone in the European Green Deal (European Commission, 2020)—and at the stakeholders' level globally—such as the UN Food Summit in 2021—that underlines how the overall goals of a food system's transformation should be achieved while ensuring food systems' resilience to shocks. Tensions clearly emerge when addressing at the same time these goals (Béné et al., 2018).

This calls for a radical transformation of how the agricultural sector produces commodities (Vermunt et al., 2020; Di Bene et al., 2022) to support and make sustainable use of biodiversity. At the individual level, farmers need to embrace new sustainable agricultural practices which necessarily also imply a change in their business model, but for these practices to flourish, at a more systemic level agricultural supply chains need major changes. Transforming food systems by breaking down barriers (such as structural inequalities) necessarily challenges established assumptions, mindsets, procedures, political and economic interests, and power relations (IFAD's Rural Development Report, 2021). Although new technologies, governance modes, economic deregulation, and changes in consumer patterns have been widely introduced to reduce barriers (Fuenfschilling and Truffer, 2014), food system transformations remain very challenging. The reason is the existence of so-called "lock-ins" which tend to reproduce the status quo and impede change (Magrini et al., 2016; Meynard et al., 2018; Geels, 2019). Several factors have been identified in the literature as relevant to lock-ins: at a systemic level, technologies, economic and institutional mechanisms and rules, and political dynamics; at the individual level, the role of social and cognitive processes and attitudes as impediments or drivers, although recognized as relevant to sustainability transitions, has only partially been explored (Geels, 2019).

However, the literature also suggests that the orientation toward sustainability and environmental protection actively influences the entrepreneurial actions of types of individuals (Munoz and Cohen, 2017; De Bernardi and Sydow, 2022). Environmental and/or sustainable entrepreneurs act by combining the creation of economic value with the creation of environmental value (Lans et al., 2014; Antolin-Lopez et al., 2019; Gregori et al., 2021). The empirical evidence seems to be strong enough to state that the cognitive and individual aspects of entrepreneurs can determine processes of change and transition toward alternative production systems (Suvanto et al., 2020; De Bernardi and Sydow, 2022; Weituschat et al., 2023a).

In this framework, we propose that the entrepreneurial identity concept can be mobilized to understand the role that attitudes of individual agricultural producers play in their decision to accept supply chain governance mechanisms that explicitly require the adoption of sustainable agricultural practices. Among the organizational mechanisms widely studied in the literature, contract farming has received much attention and proved to be a useful tool in opposing existing lock-in toward more sustainable production systems transition (Banterle and Stranieri, 2013; Ricome et al., 2016; Pancino et al., 2019; Cholez et al., 2020; Weituschat et al., 2023a,b). In particular, contract farming schemes regulating crop cultivation processes build on creating a relationship of trust between suppliers and buyers on the premise that risk is shared (Key, 2005; Weituschat et al., 2023a,b). Participation in value chain contracts involves overcoming problems of access to markets by stabilizing the prices and costs incurred by agricultural producers, generating a higher income (Dubbert et al., 2021). The adoption of cultivation contracts that support the adoption of EI practices often requires the use of incentive tools though, to encourage the choice of this type of agreement (Banterle and Stranieri, 2013; Bonjean, 2019; Grandori and Furlotti, 2019; Pancino et al., 2019).

## 2.2. Entrepreneurial identity as a driver of sustainable transitions

A move toward a more sustainable food production at a systemic level necessarily builds on how—at the individual level—farmers as entrepreneurs embrace change, and at a multiple level (Fitz-Koch et al., 2018; De Rosa et al., 2019; Suvanto et al., 2020). During the last few decades, and particularly in the European Union context, farmer's roles have changed from being merely producers of raw materials to being entrepreneurs who, with their businesses, are at the center stage for the sustainability transition to happen in agricultural systems (European Commission, 2018; Fitz-Koch et al., 2018; Dias et al., 2019). Pivotal concept for understanding entrepreneurship as a social and economic phenomenon (Radu-Lefebvre et al., 2021), entrepreneurial identity emerges as a concept that informs about entrepreneurs' decisions, actions, and feelings as they run their business and commit to it in terms of acquiring resources, adopting practices and being passionate about it.

Scientific evidence suggests that entrepreneurial identity actively affects farmers' cultivation choices (Verhees et al., 2011; McElwee and Smith, 2012; Suvanto et al., 2020). When investigating the concept of entrepreneurial identity, research has reported on various dimensions through which EntID is manifest. Suvanto et al. (2020) demonstrated how entrepreneurial orientation (EO)—which is proposed as a way of envisioning what it means for organizations to "be entrepreneurial" (Wales et al., 2020)—could provide farmers with a competitive advantage, particularly for innovation processes such as new crop adoption. EO is an important determinant of corporate performance as it involves strategic entrepreneurial skills to be competitive in the sector (Shane, 2003; Wiklund and Shepherd, 2005). Entrepreneurial orientation is composed of three dimensions: innovativeness, proactivity, and risk-taking (Miller, 1983; Lumpkin and Dess, 1996; Rauch et al., 2009; Wales et al., 2013; Fuentes-Fuentes et al., 2015). Innovativeness concerns the ability to adopt new techniques for new products and services development (Hurley and Hult, 1998; Miller, 2011). Risk-taking refers to the ability to take strategic and financial risks generated by the development of new products and services (Miller, 2011; Willebrands et al., 2012). Proactivity refers to the foresight an entrepreneur has in expecting changes in consumer needs (Lumpkin and Dess, 1996; Miller, 2011). These capabilities determine the possibility for entrepreneurs to reach new markets or potential changes (Miller, 2011). Furthermore, an emerging topic that the literature is looking at with growing interest in environmental entrepreneurship is environmental attitude (Fauchart and Gruber, 2011; York, 2018; De Bernardi and Sydow, 2022). In the agricultural sector, farmers' environmental attitude seems to play a fundamental role in the transition toward sustainability (De Bernardi and Sydow, 2022; Weituschat et al., 2023b). Specifically, this environmental attitude seems to be closely influenced by the context in which farmers operate, and it is also characterized by aspects that refer to how much the farmer follows a collaborative approach in his or her decision-making. Indeed, farmers often believe that their pro-environmental actions can only be successful if carried out collectively (Poteete and Ostrom, 2004; Ostrom and Ahn, 2009; Cleveland et al., 2020; Despotović et al., 2021). Entrepreneurial identity oriented toward collaboration and environmental issues have shown to be more inclined to adopt more sustainable agricultural practices (Sadati et al., 2010; Azman et al., 2013; Kyalo and Holm-Mueller, 2013). Specifically, evidence in the literature shows how the context provided by collective actions favors changes aimed at improving agricultural systems' sustainability and natural resources management (Ravnborg et al., 2000; Pretty and Ward, 2001; Swallow et al., 2002; Prokopy et al., 2019).

In this paper, we define entrepreneurial identity (EntID) as a multidimensional construct (Table 1) composed of Entrepreneurial Orientation (EO) and Collective Environmental Attitude (CEA). Following the seminal definition, we define EO through its three dimensions of innovativeness, proactiveness, and risk-taking, according to Miller (1983). The CEA will include the assessment of the context and the propensity to participate in collective pro-climate actions.

Previous research highlights that contract farming (*CF*) could be a valuable tool for supporting farmers in adopting EI practices (Weituschat et al., 2023b). Based on this and on our theorization over the entrepreneurial identity concept, we suggest the need to understand how the entrepreneurial identity of farmers figures in the choice to adopt new sustainable practices (e.g., new crops) through participation in a contract farming regime. The hypothesized effects

TABLE 1 Operationalization of entrepreneurial identity.

| Concept | Dimensions | Description |
|---|---|---|
| Entrepreneurial orientation | Innovativeness | Ability to adopt new techniques for new products and services development |
| | Pro-activity | Ability to foresight expecting changes in consumer needs. |
| | | Ability to foresight expecting changes in consumer needs |
| | Risk-taking | Ability to take strategic and financial risks generated by the development of new products and services |
| Collective environmental attitude | | Collaborative decision-making context with other farmers that drives participation in collective pro-environmental action |

are shown in Figure 1. Continuous arrows represent expected short-term relationships. Based on extant literature, it is expected that the dimensions the entrepreneurial identity is composed of in our paper (EO and CEA) guide farmers in the adoption of more sustainable agricultural practices and that in turn, this has a role in the choice to adhere to a supply chain agreement involving more sustainable practices.

Our overarching research hypothesis is therefore that both EO and CEA play a role in shaping farmers' decisions over the adoption of sustainable practices and by this over the decision to participate in contract farming. Following this approach in our attitudinal construct, we opted for simple averaging of the Likert scale items based on the assumption that all the items hold equal importance. Formally, we treated all items as equally significant, thereby assuming that each item contributes uniformly to the overall attitudinal construct. This assumption aligns with the approach of taking a simple average. The reliability of our items was assessed using Cronbach's alpha, which was found to be satisfactory overall. Such hypothesis reflects on the one hand, the exploratory nature of our study. On the other hand, we propose a conceptualization of entrepreneurial identity as constituted of the EO and CEA constructs that lack sufficient theoretical or empirical grounding. Due to this, precise *a priori* hypotheses about the role of EO and CEA in affecting farmers' decisions cannot be proposed that presuppose a specific direction of the effects.

In order to verify our overarching hypothesis, standard control variables are also considered, such as personal and structural characteristics of the farm, which the literature has indicated as influencing crop choices (Fitz-Koch et al., 2018; Suvanto et al., 2020; Weituschat et al., 2023b). Specifically, we consider variables that can proxy of farmers' knowledge of some of the aspects dealt with such as cultivation EI, and contract's standard (e.g., certification presence).

In the long run, reverse causality effects could be hypothesized between EntID and the choices of cultivation and *CF* (dashed arrow, Figure 1). Based on the knowledge acquired in the EI adoptions, required by supply chain CFs, past behaviors could influence farmers' EntID. The supply chain CFs would also act as an aggregator between the farmers, creating a context that would also strengthen the CEAs dimensions. Although these aspects are interesting, in our study, we attempted to focus on farmers new to *CF*. Based on the available information, we cannot definitively exclude the possibility of previous experience with *CF*. We consider the resulting potential bias in interpreting the results.

## 3. Materials and methods

### 3.1. Case study: "Carta del Mulino" initiative

This study draws on the "Carta del Mulino" initiative launched in 2019 by the Italian multi-national food manufacturer Barilla Group, a family-owned company with its headquarters and majority of operations in Italy. Carta del Mulino is a contract farming scheme designed by "Mulino Bianco," one of the most important Italian bakery brands owned by Barilla Group. Originating in 1975, the "Mulino Bianco" brand has shaped its communication strategy over time around principles related to the respect toward the environment and the people. Nowadays the brand relies on sustainability certifications for almost all its products made with soft wheat flour from sustainable agriculture (Barilla, 2021b). To improve its environmental performance, the company stimulates the adoption of sustainable agricultural practices in farming activities and provides information useful to educate consumers and change their food habits (Barilla, 2020). Over the years, field experiments have been conducted, the results of which have been used to suggest revisions in the agreements for the supply of raw materials. The Carta del Mulino private standard comprises 10 rules designed to bring greater quality to products, to support the work of farmers, and to restore space to nature in agroecosystems, promoting crop diversification and biodiversity, reducing the use of chemicals, and safeguarding pollinating insects (Barilla, 2021a; see Figure 2).

Some rules regulate agronomic and technical aspects to mitigate environmental issue and to biodiversity and soil fertility in cereals production specialized area (see Figure 2). Two rules (rule 2 and 3) directly involve the farmer arable land planning and promote the adoption of EI practices such as crop diversification practices. Such practices entail 5 years crop rotation with at least three different crops, one of which must be a nitrogen fixer, legumes, and/or oilseed crop; furthermore, flower strips have to be planted on at least 3% of the agricultural area dedicated to wheat (Barilla, 2021a). This implies that farmers need support to plan the crops allocation of their land for long time, being the choice of how to use differently their arable land limited and focusing therefore more on a longer-term economic perspective (deriving from a 5-year window of performances for the crop system) than on the short term (annual) benefits (Benini et al., 2023). Furthermore, the use of pesticides and herbicides is regulated in two dedicated rules (rule 5 and 7) which propose a ban on their use. The ban concerns neonicotinoid-treated seeds and/or plant protection products containing neonicotinoids for sowing "Carta del Mulino" soft wheat fields; glyphosate and/or plant protection products containing glyphosate are banned in soft wheat fields from pre-sowing to harvest phases. Other rules regulate socio-economic aspects: according to rule 10, the premium price paid for flour produced in compliance with Carta del Mulino set of rules must be distributed throughout the supply chain actors. These rules are included in a system of supply chain agreements and contracts followed by over 1,400 farmers, mostly in Italy, for about 270,000 tons of flour per year (Barilla, 2021a).

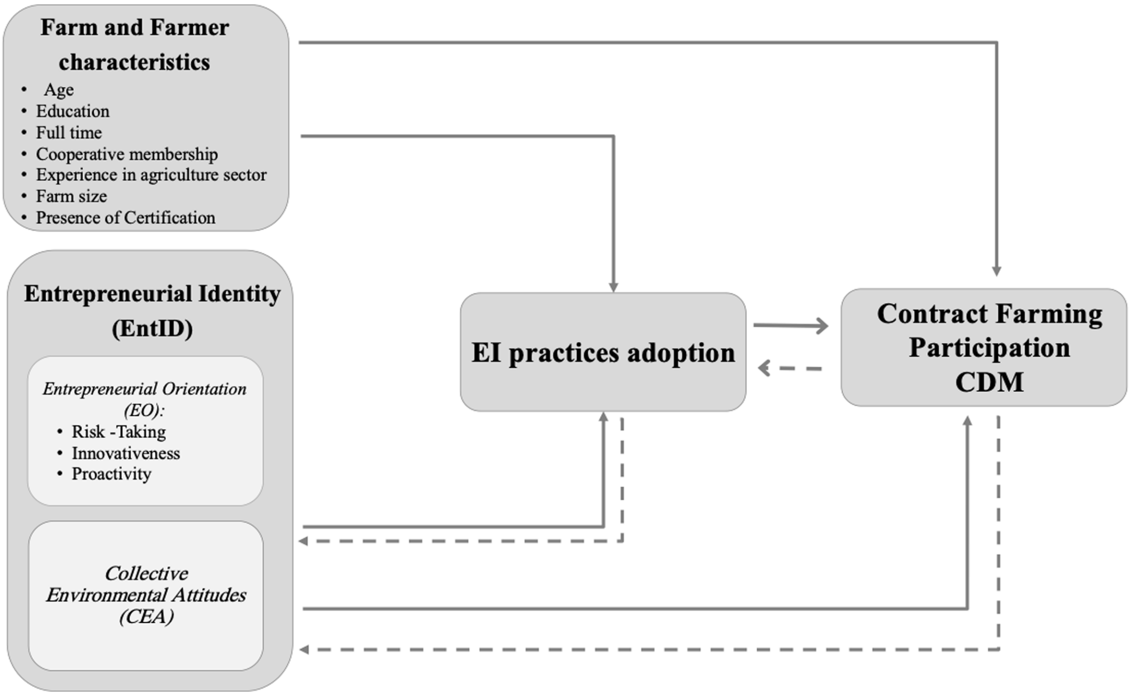


FIGURE 1
Entrepreneurial Identity (EntID) construction and effect on farm management.


FIGURE 2
The 10 rules of "Carta del Mulino" contract (source: https://www.mulinobianco.it/)—Authors elaboration.

Although the practices proposed by such a contract farming scheme and the executive certification procedures connected to their adoption are common to other certification schemes in the agri-food sector (FAO, 2014; Zezza et al., 2020), the Carta del Mulino contract scheme is original in the process that led to the definition of that set of rules and practices. The proposed agro-ecological practices resulted from a participatory process that engaged soft wheat flour value chain actors and third parties, such as environmental NGOs, universities, high-tech start-up, and agricultural extension services companies. Furthermore, the rules are periodically reviewed to embrace new practices as long as an increase in their effectiveness regarding the achievement of Carta del Mulino objectives is demonstrable. The Carta del Mulino definition process, as a contract farming regime, adapts an experimental socio-ecological approach (as described by Gaba and Bretagnolle, 2020) to the case of an agro-industrial supply chain. Indeed, the agricultural EI practices technical features (crop rotations, flower strips) and the definition of technical limits (ban on pesticides and herbicides) were shared with groups of suppliers to translate agro-ecological principles into solutions capable of responding to the needs of farmers operating in very different areas. The specific formulation of the Carta del Mulino contract practices therefore considered the actual impacts that these generated both in the environmental sphere and in the social and economic one in the areas where the raw materials were procured.

## 3.2. Methodology

Understanding the factors that influence farmers' adoption of sustainable practices as well their participation in the "Carta del Mulino" contract farming requires the application of multiple methodologies. More specifically, two separate analyses are carried out to analyze whether cognitive and psychological aspects related to entrepreneurial attitudes might play a relevant role on farmer's adoption of EI practices by means of participating in a contractual scheme. Firstly, a count data model is implemented to identify factors affecting farmers' adoption of sustainable practices in the past, under the assumption that the more practices adopted, the greater the farmer's engagement in the EI process.

Traditionally, to analyze the adoption of sustainable practices, count data models are estimated that use Poisson or negative binomial regressions (Winkelmann, 2003). For instance, Park and Lohr (2005) use negative binomial models to estimate the adopted integrated pest management strategies in the United States; Jara-Rojas et al. (2012) use a Poisson model to estimate the number of water conservation practices implemented by farmers in Chile, while similarly Bellon et al. (2016) explained the counts of plant species grown by smallholders in Southern Benin with a Poisson-based specification. The EI practices considered in our analysis include: (1) Minimum or zero tillage; (2) Green manure; (3) Flower strips; (4) Crop rotation; (5) Intercropping; and (6) Avoidance of using glyphosate.

Formally, we assume that the farmer's $i$-th utility associated to the adoption of $n$, $n = 0, 1, 2, \ldots, 6$, EI practices, is the sum of an unobserved random component $\varepsilon_{ij}$ and a deterministic component $V_i$. Such component depends on an $x_i$ vector which includes observable characteristics of both farmer and farm, and on a $z_i$ vector which includes individual aspects such as farmers environmental attitudes and their entrepreneurial orientation.

$$U_{in} = V_i + \varepsilon_{in} \quad (1)$$

Moreover, we assume that $i$-th farmer implements $n$ practices rather than $k$ when $U_{in} \geq U_{ik}$ and $Prob(N_i = n) \geq Prob(N_i = k)$ with $n \neq k$.

We assume that the conditional distribution of $n_i$ given $V_i$ follows a Poisson distribution:

$$n_i \mid (V_i) \sim \text{Poisson}\left[\lambda(V_i)\right] \quad (2)$$

After verifying the absence of overdispersion, and zero inflation, the $Prob(N_i = n)$ can be expressed as:

$$\frac{e^{-\lambda(V_i)}\lambda(V_i)^{n_i}}{n_i!} I = 1, \ldots, I; n = 0, 1, 2, \ldots. N \quad (3)$$

with $\lambda(V_i)$ generally parametrized as $exp(x_i'\beta + z_i'\delta)$ with $\beta$ and $\delta$ the parameter vectors measuring the effects of $x$ and $z$ on the number of EI practices.

Secondly, a Multinomial Probit Model (MNP) is used to estimate the probability of participation in a conventional contract farming scheme that does not require any sustainability related activities vs. the "Carta del Mulino" initiative which is centered around sustainability. Such model allows us to cover a gap over the role contract farming can play for sustainability. Recent examples of studies using multinomial probit model to analyze farming decisions include Zhang et al. (2019) and Ahmad et al. (2021). In this paper, we assume that the $i$-th farmer faces three mutually exclusive alternatives: $j = 1$ when the farmer is not participating to any forms of contract farming; $j = 2$ when the farmer participates to a contract farming scheme without EI obligations; and $j = 3$ when the farmer participates to "Carta del Mulino" scheme.

The utility associated by the $i$-th farmer to the alternative $j$ can be expressed as:

$$U_{ij} = F_{ij} + \eta_{in}, \text{with } F_{ij} = \mathbf{x}_i{}'\boldsymbol{\gamma}_j + \mathbf{z}_i{}'\boldsymbol{\alpha}_j \text{ and } \eta_{in} \sim \mathrm{N}[0, \Sigma] \quad (4)$$

The outcome of the decision making process of the $i$-th farmer will be $C_i = j$ when the farmer selects the $j$-th alternative rather than $k$, when the $U_{ij} \geq U_{ik}$ and $Prob(C_i = j) \geq Prob(C_i = k)$, j,k = 1,2,3, and $n \neq k$ with the probability that the alternative $j$ is chosen given as:

$$\text{Prob}(C_i = j) = \frac{\exp\left(X_i'\gamma_j + Z_i'\alpha_j\right)}{\sum_{j=1}^{3}\exp\left(x_i'\gamma_j + Z_i'\alpha_j\right)}, j = 1, \cdots 3; i = 1, \cdots I. \quad (5)$$

## 3.3. Survey design and sample

The study design involved the development of a questionnaire structured in different sections that collected information on farmers socio-demographic data, farm characteristics, value-chain relationships, cultivation choices, and farmers attitudes. Furthermore, additional information was collected on farmers' participation in associative forms, on EI practices implemented on the farm in the past, and on current adoption of cultivation contracts (with specific request to indicate whether farmers were already participating in the Carta del Mulino contractual scheme or in another contract that did not require the adoption of EI practices). In addition, in order to collect information over the entrepreneurial orientation of the farmers and their environmental and collective attitudes (necessary to construct the entrepreneurial identity variable), four attitudinal scales were included through a five-point Likert scale (1—totally disagree, 5—totally agree). As defined in Table 1, for the entrepreneurial orientation concept, we use the three-dimensional scale (innovativeness, proactivity, and risk-taking) developed by Khandwalla (1977) and improved by Miller (1983). To construct the Collective Environmental Attitudes scale (CEA), we follow the literature on collective action (Poteete and Ostrom, 2004; Cleveland et al., 2020; Cruz and Manata, 2020; Despotović et al., 2021) which informs us about the environmental orientation as defined in the context of participation in collective actions for the environment (Table 2).

TABLE 2 Dimensions of collective environmental attitude, entrepreneurial orientation, and associated items.

| Collective environmental attitude (six items) |
|---|
| 1. If I do something for the environment just as a single person, it will have no effect.* |
| 2. Since other farmers already contribute to sustainable crop productions, my contribution is not relevant.* |
| 3. The best way to solve environmental problems is to act collectively. |
| 4. Forming an association with other farmers to contribute to environmental improvement is just a waste of time.* |
| 5. For me, participating in collective actions related to the realization of a sustainable supply chain is important to help the environment. |
| 6. My family and friends would be proud of me if I contributed to the realization of a sustainable supply chain. |
| **Innovativeness (three items)** |
| 1. If I see an opportunity, I am always willing to try new practices and techniques. |
| 2. I always look for opportunities to try something new. |
| 3. I am not willing to experiment with new crops.* |
| **Risk taking (three items)** |
| 1. If I see an opportunity to increase profits, I am always willing to take risks. |
| 2. I would rather maintain current crops than replace them with ones I do not know. |
| 3. If I cannot be sure of the benefits, I am not willing to invest in my business. |
| **Proactiveness (three items)** |
| 1. I am willing to start activities that other farmers are not yet doing. |
| 2. I am always looking for new connections to access inputs, funding, and new markets. |
| 3. It is hard to analyze market trends and therefore set my business strategies.* |

*Reversed in code.

TABLE 3 Descriptive statistics of the sample ($n = 314$).

| Qualitative variables | Categories | | |
|---|---|---|---|
| Gender | *Male* | *Female* | |
| | 95.54% | 4.46% | |
| Contract's adoption | *None* | *Contract farming* | *Carta del Mulino* |
| | 35.08% | *35.69%* | *29.23%* |
| Education | *No degree* | *High school degree* | *University degree* |
| | 23.25% | 70.06% | 6.69% |
| | *Yes* | *No* | |
| Full time farmer | 86.62% | 13.38% | |
| Cooperative membership | 71.97% | 28.03% | |
| Presence of certification | 36.94% | 45.54% | |
| Quantitative variables | Mean | Std.dev | |
| Age (years) | 51.24 | 12.97 | |
| Experience in agriculture (years) | 28.78 | 13.43 | |
| Farm size, UAA (ha) | 77.89 | 286.67 | |
| *n.* Practices | 1.55 | 1.44 | |
| *Entrepreneurial identity* | | | |
| [a]Collective environmental attitudes | 0.945 | 0.588 | |
| EO—[a]Innovativeness | 1.367 | 0.758 | |
| EO—[a]Risk-taking | 1.275 | 0.636 | |
| EO—[a]Proactiveness | 3.465 | 0.688 | |

[a]Cronbach α: CEA: 0.68; IN: 0.65; RT: 0.41; and PRA: 0.62.

In order to include in the sample farmers' who work on farming activities as a hobby rather than main occupation, the data also include information related to the time spent on the farm (i.e., full-time is equivalent to a 5-day work week); finally, in order to understand to what extent farmers are familiar with the adoption of standards that are comparable to those required by some cultivation contracts such as the analyzed CdM, information is collected over the adoption of certification schemes at the farm level (e.g., GlobalGAP, organic, or similar).

The survey was administered to soft wheat farmers in four regions of Northern Italy: Emilia Romagna, Veneto, Lombardy, and Piedmont. Specifically, they were selected within the Po Valley, the area most intensely suited to agricultural production in Italy wherein many farmers already joined the novel Carta del Mulino *CF* program. The survey was distributed through Qualtrics Survey Software in the period December 2019 and February 2021. The extension of this period is due to an adjustment in the data collection strategy because of the COVID-19 Pandemic. The final sample contains 314 complete observations.

## 4. Results

### 4.1. Descriptive statistics

Table 3 shows the percentages of the sample by gender, education level, farm management (full-time or part-time), participation in associative forms (organization of producers, cooperatives, consortium, or association of farmers), and adherence to a certification standard. It also shows the average values for the sample by age, years of experience in the agricultural sector, and company UAA. For all the scales required for our research (Innovativeness, Proactiveness, risk-taking, and Collective Environmental Attitudes), Cronbach alphas supplied satisfactory reliability coefficients (in Table 2; mean value, standard deviation, and Cronbach alphas). Cronbach's α analysis revealed that the scales of Innovativeness, Proactivity, and Collective Environmental attitude show a good internal consistency (respectively CEA $\alpha = 0.68$, IN $\alpha = 0.65$, and PRA $\alpha = 0.62$). The risk-taking scale α shows uncertain reliability (RT $\alpha = 0.41$). The final sample considers 314 farmers, most of them male (95.54%) with a high school degree (70.06%), and full time farmers (86.62%). The vast majority of farmers is member of a cooperative (71.97%) and many do not adhere to any certification scheme (45.54%). The interviewees have an average of 51 years and approximately 28 years of farming experience. Considering the UAA, the average farm size is about 80 ha.

Figure 3 shows the number of EI agricultural practices implemented at the farm in the past and before to being potentially involved in CdM schemes. In detail, of the six practices analyzed, crop

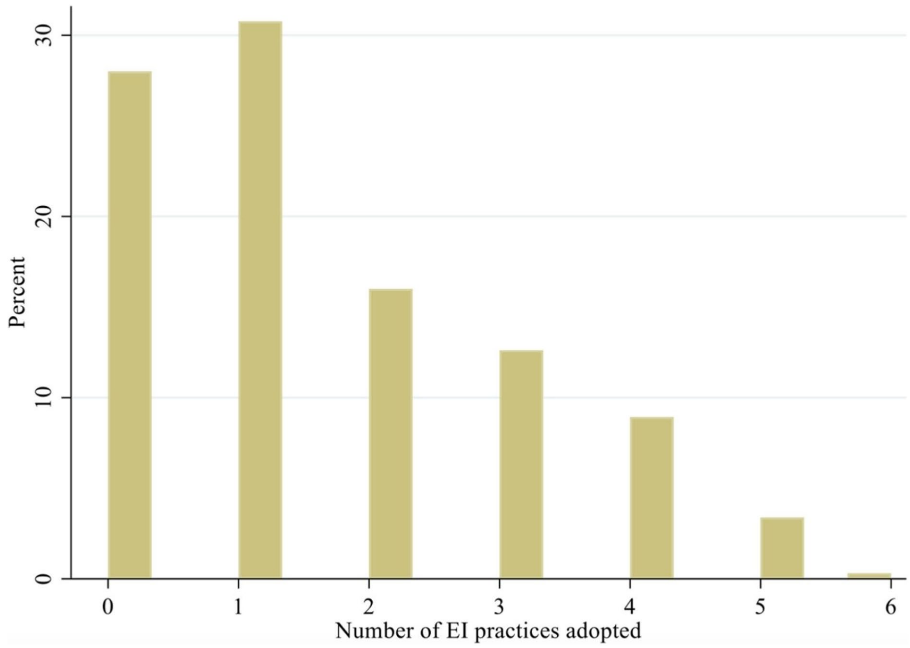


FIGURE 3
Number of EI practices adopted by farmers in the past.

rotation seems to be the most widely adopted by about 43% of farmers, followed by flower strips (32%).

Figure 4 shows as a percentage how the sample is distributed in the contract's adoption and how this variable is linked to the number of EI practices previously implemented on the farm. About 29% of the sample signed the CdM contract and it is also the part of the sample that has the highest percentage of EI practices adopted in the past. There are values above 20% from 2 to 4 practices.

## 4.2. Farmers' entrepreneurial identity analysis

To verify whether farmers with a stronger Entrepreneurial Identity have a greater propensity to adopt more EI practices and sign a contractual scheme as CdM, as hypothesized in our study, we have run two sets of models. The results are reported in Table 4.

First, the count data referring to the number of EI practices adopted by each farmer was estimated through a Poisson regression model. The results of this model seem to confirm that the EntID concept plays overall an important role in farmers' choice to implement EI practices (first part of our overarching hypothesis). Such role is led predominantly by the environmental and collective action attitudes (CEA) and the EO dimension of innovativeness. A collective environmental attitude seems to positively relate to the choice to implement sustainable practices, but it is especially the entrepreneur's innovativeness that plays a relatively stronger positive role in enhancing the taking up of these practices. Being proactive does not apparently play a role in the adoption though, while risk taking shows a negative significant coefficient: this EO component might actually surprisingly hinder the adoption of EI practices. The socio-demographic and farm structural characteristics do not seem to relate to the adoption of practices either, with the exception of the full-time variable which shows a negative coefficient.

The number of practices adopted identified in the first model (Poisson regression) is then used in the second model that estimates the participation of farmers in different contract farming schemes and verifies therefore the second part of our overarching hypothesis. It is assumed that the higher the number of practices farmers implement over time increases farmers' knowledge of the technical functioning of these practices, therefore the greater the awareness of what implies EI practices adoption implies.

Specifically, the reference base for the model is the choice not to enter any sort of contract farming scheme. Results are to be interpreted as the propensity of farmers to participate in a conventional contractual agricultural regime, i.e., without obligations as per the adoption of specific sustainable practices, and in the Carta del Mulino contract, which formally requires the adoption of EI practices. Table 3 indicates that some variables influence the participation on both the types of contracts. In particular, possessing a certification positively relates to the participation to a contract farming scheme in general, with a higher magnitude for the contract that provides requirements as per the adoption of sustainable practices. Conventional cultivation contracts seem to be more likely chosen by farmers that are already members of a cooperative, while such membership does not seems to relate to the participation to a contract with sustainability related formal requirements. Entrepreneurial pro-activeness and innovativeness both drive the farmers' participation to either the forms of contract farming analyzed. However, their impact is greater under a *CF* scheme with formal requirements such as CdM than with conventional *CF*. Risk-taking instead does not appear to affect participation in any cultivation contracts. The collective environmental attitudes (CEA) seem to negatively relate to the participation in any form of contract, but particularly for the CdM results indicate that such attitudes might be actually discouraging the participation in a

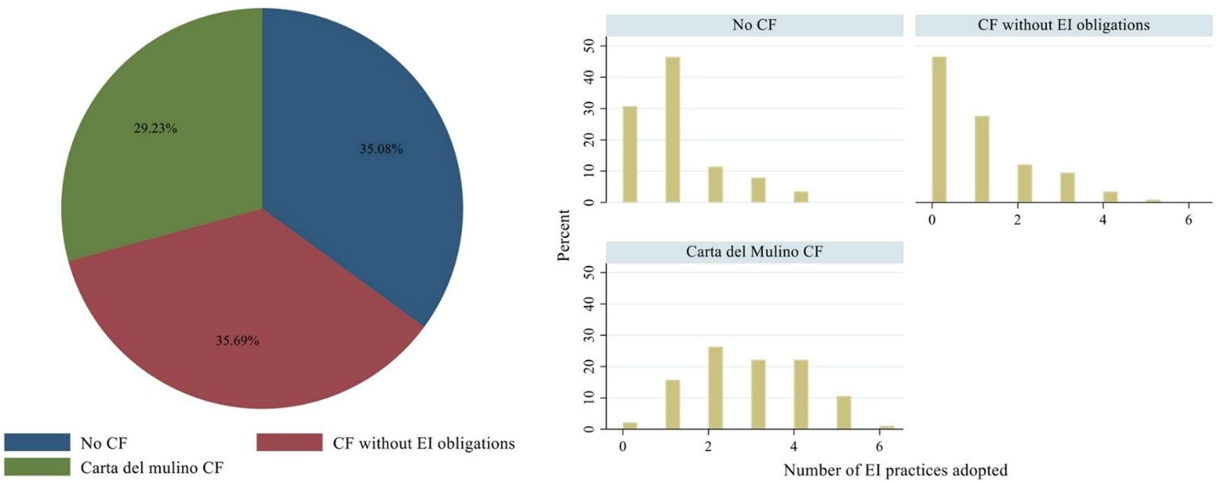


FIGURE 4
Number of EI practices adopted by farmers in the past and their present participation to *CF*.

TABLE 4 Estimates of the Poisson regression and Multinomial Probit model for adoption of EI practices and contract farming participation.

| | *n*. Practices (Poisson Regression[c]) | | | Contract farming (MNP)[b] | | | Carta del Mulino (MNP)[b] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coef | std.err[a] | *p* value | Coef | std.err[a] | *p* value | Coef | std.err[a] | *p* value |
| *n*. Practices | | | | −0.049 | 0.143 | 0.730 | **0.801** | **0.128** | **0.000** |
| Gender (male) | −0.225 | 0.205 | 0.273 | −0.735 | 0.942 | 0.435 | −0.437 | 0.796 | 0.583 |
| Age | −0.023 | 0.022 | 0.305 | 0.045 | 0.081 | 0.577 | 0.034 | 0.075 | 0.646 |
| Age (squared) | 0.000 | 0.000 | 0.348 | 0.000 | 0.001 | 0.670 | 0.000 | 0.001 | 0.932 |
| Education | −0.062 | 0.104 | 0.549 | −0.398 | 0.293 | 0.174 | **−0.816** | **0.331** | **0.014** |
| Full time | **−0.289** | **0.139** | **0.038** | 0.753 | 0.459 | 0.100 | 0.623 | 0.487 | 0.201 |
| Cooperative membership | −0.155 | 0.104 | 0.135 | **2.270** | **0.357** | **0.000** | 0.472 | 0.342 | 0.167 |
| Experience in agr. | 0.007 | 0.006 | 0.311 | −0.006 | 0.018 | 0.719 | −0.015 | 0.019 | 0.437 |
| Farm size (*ln*) | 0.036 | 0.052 | 0.494 | 0.027 | 0.172 | 0.874 | **−0.342** | **0.170** | **0.044** |
| Presence of Certification | 0.163 | 0.112 | 0.145 | **0.598** | **0.292** | **0.041** | **1.666** | **0.352** | **0.000** |
| *Entrepreneurial identity* | | | | | | | | | |
| EO—Innovativeness | **0.294** | **0.082** | **0.000** | **0.463** | **0.230** | **0.045** | **0.610** | **0.245** | **0.013** |
| EO—Risk-taking | **−0.166** | **0.075** | **0.027** | −0.012 | 0.197 | 0.951 | 0.115 | 0.232 | 0.619 |
| EO—Proactiveness | 0.068 | 0.070 | 0.335 | **0.449** | **0.223** | **0.045** | **0.660** | **0.223** | **0.003** |
| Collective environmental attitudes | **0.184** | **0.093** | **0.047** | −0.319 | 0.282 | 0.258 | **−0.644** | **0.310** | **0.038** |
| Cons. | **1.177** | **0.583** | **0.044** | −2.635 | 2.078 | 0.205 | −2.083 | 2.085 | 0.318 |

[a]Robust standard errors are reported. [b]"No contract-farming" is the base outcome category. [c]Pseudo $R^2$: 0.12; # obs: 314. In bold are reported statistically significant coefficient ($p < 0.05$). We tested for the presence of multicollinearity using the Variance Inflation Factor (VIF). The results showed an absence of significant collinearity, with all VIF values within acceptable limits.

contractual scheme that requires the adoption of EI practices. The number of practices previously implemented and therefore the awareness farmers have of how to implement such practices seems to strongly determine the choice to sign the CdM contract.

## 5. Discussion

The present research aimed to understand how farmers' entrepreneurial identity acts on the adoption choice of new sustainable practices (e.g., new crops) through participation in a *CF* scheme in Italy. In that context, we need to be mindful of the ongoing challenges facing the agricultural sector. In recent years, the strategies on which the CAP was built aim at redefining the role and position of farmers in the supply chain with a view to the sustainability of agricultural systems. However, the distribution of power within the value chain still represents an obstacle for farmers to innovate their business models and adopt new sustainable practices.

Our exploratory study hypothesizes therefore that the dimensions the entrepreneurial identity concepts build on, namely entrepreneurial orientation and collective environmental actions, play a role in shaping farmers' decisions over the adoption of sustainable practices (our first focus) and by this over the decision to participate in contract farming (our second focus).

We first analyzed what role the EntID dimensions play in the choices of adopting EI practices. As we know EI practices adoption, our first research focus, implies for farmers a change in the management of their farm and the uncertainty of the process partially slows down the innovation process (Phillipson et al., 2004; Stenholm and Hytti, 2014; Thompson et al., 2019). The traditional resistance to innovation, typical of the agricultural sector and generally explained with the amount of time and financial resources needed to engage with innovation (a deterrent for this), seems in the context analyzed to be overcome by the presence of specific skills of the farmer that actually rather than being a simple food producer consider himself/herself as an entrepreneur and thus an agent of change (Fitz-Koch et al., 2018; Dias et al., 2019; Suvanto et al., 2020). Specifically, EntID dimensions such as Innovativeness and CEA act positively in more sustainable cultivation choices. CEA results are in line with other studies that indicate that a pro-environmental context and an attitude toward collaboration are valid drivers of change toward more sustainable agricultural practices (Swallow et al., 2002; Azman et al., 2013; Abeyrathne and Jayawardena, 2014; Prokopy et al., 2019; De Bernardi and Sydow, 2022). In contrast to other studies (e.g., Suvanto et al., 2020), our results do not appear to link the choice to adopt EI practices to higher risk-taking. In our sample, this result is due to the component of entrepreneurs probably being more interested in the speculative aspect. These could prefer an even more "risky" cultivation approach than EI practices adoption.

On the other hand, innovativeness seems to be the EntID dimension capable of driving the change from the EI practices adoption up to the choice of a cultivation contract, such as CdM. Scientific evidence demonstrates that innovation is a characterizing aspect of the entrepreneurial identity of farmers more predisposed to the transition to alternative production systems (Dias et al., 2019; Suvanto et al., 2020; De Bernardi and Sydow, 2022).

Our second focus included understanding the role that EntID plays in choosing to join a contract farming scheme. Literature evidence suggests the agricultural contract (*CF*) is an effective tool in supporting farmers in the transition toward more sustainable agricultural systems (e.g., Banterle and Stranieri, 2013; Pancino et al., 2019). From our analyses, it emerges that entrepreneurial identity plays an important role also in the participation in cultivation contracts, as shown by comparison between farmers with a CdM contract and a "standard" one. Being inclined to innovate—for example being open to adopt new techniques—and being proactive in the search for new techniques and ways to improve business with foresight stimulate farmers' openness toward the cultivation arrangements proposed by contract farming schemes. As indicated in the literature, contracts might provide an opportunity to access new products or markets (Lumpkin and Dess, 1996; Woldesenbet et al., 2011; Fitz-Koch et al., 2018) and to do so in a safe or regulated environment.

Considering standard contract adoption, our results confirm what emerged from several studies (e.g., Kyalo and Holm-Mueller, 2013; Solazzo et al., 2020) on the support that cooperatives exercise for farmers in improving bargaining power and access to markets. For the CdM contract, on the other hand, these factors do not seem to override the choice but might affect the speculative aspects. Among the rules, we recall that farmers receive a price premium on production and direct access to a "privileged" supply chain. Furthermore, in the contract adoption process, knowledge seems to play an important role. We can consider certifications presence and EI practices adopted in the past as a "proxy" of this factor. On the one hand, knowledge of the standards required by a certification leads farmers to sign a contract (standard/CdM). On the other hand, the knowledge of the practices, due to the previous adoption of these, influences the choice of contracts that want to drive the transition toward sustainability. In this way, we must consider that knowledge of these aspects (certification standards and practices) has the potential to reduce the time needed to implement processes required for a transition toward more sustainable practices. Being familiar with the production techniques and the required standards reduces uncertainty and increases control over the actions that the farmer needs to implement in the process of adopting new cultivation plans (D'Silva et al., 2010; Uli et al., 2010; Lawrence et al., 2011).

Furthermore, a collective environmental attitude negatively affects participation in the Carta del Mulino contract. The explanation for this result can be 2-fold. Considering that our analyses are based on data collected at the beginning of the CdM project, we propose at least two different explanations.

First, the literature suggests that environmental farmers combine their respect and passion for nature in their entrepreneurial actions (De Bernardi and Pedrini, 2020; De Bernardi and Sydow, 2022). Those with a marked aptitude for collective environmental actions may prefer a sustainable approach to agriculture in a pioneer or early adopter perspective driven by their niche beliefs, giving more weight to the knowledge co-created within their reference system of relationships and values (Schill et al., 2019). In this approach, the farmers have a more marked environmental-value component than the entrepreneurial-market component, therefore aspects of choice outside the market, such as environmental values or social matters, could be affecting more than the profit expectations of their entrepreneurial choices (Van der Werff et al., 2013; Ratliff et al., 2017; De Bernardi and Pedrini, 2020).

Secondly, farmers may have chosen the contract looking first at the premium price guaranteed by the contract or to be recognized as reliable suppliers by one of the major leader agro-industry companies in Italy, giving less importance to the pro-environmental aspects required by the rules either the socio-environmental benefit.

Furthermore, farmers with a higher level of education and a more extensive company size appear to be more resistant to adopting the CdM contract (Weituschat et al., 2023b). Given their experience in implementing EI practices some types of farmers may feel capable of achieving certain objectives without necessarily entering contractual schemes that impose strict conditions on their business, but rather making decisions over their cultivation plans individually. In our sample, this type of farmer may be more interested in the higher opportunity costs generated by the availability of more options in the spot market. Furthermore, as Ciliberti et al. (2023) show, farmers in Italy prefer to maintain their decision-making autonomy and do not seem interested in applying sustainable practices that they perceive as more expensive than ordinary ones. As the literature indicates, a cultivation contract reduces certain risks (e.g., costs, prices) to the detriment of the farmer's autonomy (Key, 2005; Solazzo et al., 2020). The question of individualism is complex and generated both by corporate structural factors and by supply chains. To overcome this approach, in the name of environmental sustainability, policies and supply chains are acting with various tools to strengthen horizontal cooperation between farmers (Viaggi and Zanni, 2012; European Commission, 2020, 2022; Solazzo et al., 2020).

In conclusion, if we consider the transition process toward the sustainability of the supply chains, achieved through the signing of a contract that provides for EI practices adoption, aspects emerge which is important to reflect on. Entrepreneurial identity, as defined in this study, seems to be capable of some aspects of overcoming barriers to adoption but at the same time, other individual factors have a negative influence. Further future analyses could delve into these aspects and investigate the long-term aspects of reverse causality between EntID and the choices of cultivation and *CF* (dashed arrow Figure 1). CdM could be a tool capable of creating a community of farmers with strong entrepreneurial identities able to drive Italian soft wheat sector toward sustainability.

## 6. Conclusion

Soil health and the transition to more sustainable and regenerative production systems is the challenge that the agricultural sector has been facing in recent times. This transition of food systems entails a great deal of change, at multiple levels, that engage with farmers' decision and attitudes. Particularly to support food systems transitions recent scholarship has pointed to the necessity to better understand which aspects influence farmers toward change from an entrepreneurial attitude and identity perspective. Engaging in practices that represent a transition from agricultural traditional and consolidated production systems to innovative systems entails a gamble and a risk for the farmer: driven by purely economic considerations if not effectively supported by institutions, farmers' organizations or policies, agricultural producers may not be willing to take such a risk.

Based on this background, the research we present in this paper has highlighted the role that some dimensions of the entrepreneurial identity of farmers have in cultivation choices—specifically ecological intensification practices—and for the participation in a supply chain contract which requires and provides for their adoption. In this paper, one specific scheme that has the potential to drive the transition is under investigation, namely a contract farming initiative started in recent years by a multinational company based in Italy in order to achieve greater sustainability in soft wheat industrialized value chains.

The findings provided valuable empirical evidence on what factors influence these adoption processes. From this study it emerges that it is important that the entrepreneurial identity of farmers is strengthened and supported, enriched by a greater knowledge of alternative agricultural techniques and practices to the usual ones to respond to the challenges of the agricultural sector.

This study has several limitations that should be acknowledged. Primarily, while we targeted farmers who were, based on available information, in their first experience with Contract Farming (*CF*), we cannot definitively exclude the possibility of some participants having prior experiences with *CF* that we were not informed. This could introduce a potential bias when interpreting our findings. Secondly, while our theoretical framework acknowledges the presence of feedback mechanisms, it can potentially lead to endogeneity. Thus, our findings should be interpreted as highlighting statistical associations rather than definitive causal pathways. Although these associations provide valuable insights into the relationships among our variables of interest, we must be cautious about attributing causal interpretations to these associations. Future research could benefit from longitudinal data to further investigate these relationships and address potential endogeneity issues. Moreover, we adopted econometric models that led us to use the simple mean method for Likert scale items in our attitudinal construct, that means all items contribute equally. This approach could lead to a potential limitation in our findings, although Cronbach's alpha tested an overall satisfactory level of reliability. Lastly, the study refers to a specific contract farming initiative for a specific supply chain. Carta del Mulino was in its start-up phase, i.e., this initiative had not yet reached wide margins of adoption by farmers at the time the data were collected. Furthermore, it should be considered that some aspects may not be generalized to other supply chains and other countries. For this reason, we suggest that future research could compare the results of the CdM contract in the countries where it is now implemented. Despite these limitations, we believe our findings contribute valuable insights to the existing body of research.

Farmers with a more developed entrepreneurial identity and with prior knowledge of alternative agricultural techniques and practices are more likely to adopt EI practices and the CdM contract. Farmers who have a strong innovative spirit appear to be leading this transition. Making such a process affordable for all farmers requires two-pronged support from brands and policies.

In recent years, industry and private brands have taken the field proposing tools, such as contract farming, capable of pushing the most industrialized agricultural supply chains (e.g., cereals) toward sustainability also through horizontal agreements between brands. On the other hand, policies such as CAP have been addressing these challenges across the last 20 years.

The recent approval of the CAP in Europe has led in many European states to the approval of eco-schemes very similar to what is proposed in the contract scheme analyzed; in Italy flower strips for pollinators and crop rotation schemes are subsidized by land based payment (European Commission, 2022). The two dimensions (political/private) over time, with different tools, are converging toward a single goal: the sustainability of the agricultural sector.

Future research could verify if what we observe in the private sphere (CdM contract) occurs in the public one. In other words, it would be interesting to analyze the role of farmers EntID in the choice of practices adoption linked to a subsidy system based on public funds and rules of the new CAP reform and, at the same time, to investigate the choice between the subsidy of a policy (payment per hectare provided by CAP) and a price premium (per ton of product provided by sustainable *CF* private brand).

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

ESR: writing—original draft, conceptualization, and visualization. VCM: writing—original draft and conceptualization. FC: conceptualization, data curation, methodology, formal analysis, validation, and writing—review and editing. EB: conceptualization, investigation, validation, resources, writing—original draft, visualization, funding acquisition, and project administration. SP: supervision. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1196824/full#supplementary-material

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# An early warning for better planning of agricultural expansion and biodiversity conservation in the Orinoco high plains of Colombia

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The eastern high plains of the Orinoco region in Colombia are known as 'Altillanura'. They are considered the future agricultural frontier of Colombia. Unfortunately, an agricultural expansion without taking in consideration areas of high biodiversity and conservation of fragile ecosystems that are ecologically irreplaceable will likely fail in providing a sustainable grow. An orderly management planning of the territory based on scientific evidence is currently lacking for this region. Specifically, studies that combine biodiversity data and agricultural information are a major research gap. This study analyses the spatial patterns of species richness and endemism of flora and fauna at the site and subregional levels. We compared the spatial changes of biodiversity patterns with aspects related to the expansion of the agricultural frontier and its possible impacts. We found a west-to-east pattern; sites closer to the Andes were more exposed to ecological degradation than those in the east. Santa Rosalía and Puerto Lopez are the municipalities with the most remarkable species diversity. Conversely, La Primavera municipality has the most significant number of endemic species. Our spatial changes results raise the alarm showing that hotspots of diversity closer to the municipalities of Puerto Lopez and Puerto Gaitan are under more pressure than underdeveloped municipalities (La Primavera and Puerto Carreño). Our results could serve as a baseline to identify spatial changes of agrobiodiversity and a guideline for land-use planning, regional policies and local decision-makers to improve regional development in Colombia's eastern plains region.

KEYWORDS

**Altillanura, conservation, endemism, Orinoquía, richness, sustainable management**

## Introduction

Colombia is a megadiverse country, home to 314 types of ecosystems and many areas of high biological diversity [Convention on Biological Diversity (CBD), 2022]. The Orinoco eastern high plains (OHP) region is a critical area for social and economic development due to its potential for agricultural expansion. While approximately 156 types of ecosystems are found across the 34,720,853 hectares of the Colombian Orinoco basin (Bustamante, 2019), many of these ecosystems are degraded due to land clearing, with devastating consequences for biodiversity. The OHP encompasses about 10 million hectares in Meta and Vichada. The OHP is part of the savanna biome, and biogeographical studies recognise it as an independent geographic unit for plant communities [Instituto Geográfico Agustín Codazzi (IGAC), 1997; Morrone, 2014; González-Orozco, 2021].

The OHP is characterised by landscapes of well-drained natural savannas, gallery forests, rivers and lagoons that harbour a rich assemblage of species, including 144 endangered and 75 endemic species (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH [GIZ]; Correa et al., 2006; Rosselli et al., 2022). However, the biodiversity of the OHP is under threat due to large-scale and rapid transformation of ecosystems by agriculture, primarily agroindustry (Andrade et al., 2013; Baptiste et al., 2017; Etter et al., 2020). With vast areas of agricultural frontier classified as a priority for water and forest conservation, understanding the extent of usable land for sustainable human use is challenging. Thus, knowledge of the spatial relationship between biodiversity and agricultural expansion is essential for effective agricultural and environmental policy planning in Colombia's OHP.

The ecosystems of the OHP are characterised by vast grasslands, wetlands and savannas, which are suitable for livestock farming and agriculture. Cattle ranching is the most important agricultural activity in the region, with over 20 million head of cattle being raised for meat and dairy production. The region is also home to significant areas of oil palm and soybean plantations, which have been expanding rapidly in recent years. Other crops grown in the region include corn, rice, cassava and sorghum.

The OHP also known as the 'Llanos Orientales', are characterised by a unique flora and fauna that have adapted to the hot and dry climate of the region. One of the most iconic species of the Llanos is the capybara, the largest rodent in the world, which can be found living near the many rivers and lagoons that run through the region. Other common mammals include deer, jaguars and various species of monkeys. The area is also home to a variety of bird species, such as the scarlet ibis, the jabiru stork and the king vulture, making it a popular destination for birdwatchers. The vegetation of the OHP is mainly composed of grasslands, shrubs and trees that have adapted to the region's harsh climate, including species such as the Moriche palm and the Yopo tree, which are important to the local indigenous communities for their medicinal and cultural uses. The spatial distribution of many of these flora biodiverse groups are poorly understood in the OHP of Colombia. Consequently, there are profound sampling gaps due to remoteness. Therefore, we need to generate flora and fauna datasets of the OHP and analyse its spatial patterns of species richness and endemism. Richness is important because we can find out where are the greatest number of species. Endemism otherwise refers to how much range restricted are the species.

The biodiversity of the OHP is scarcely studied and under threat due to the large-scale and rapid transformation of ecosystems by agriculture, principally agroindustry (Lavelle et al., 2014; Rosselli et al., 2022; Villegas et al., 2022). In the OHP, many areas are inaccessible and remote, which is one of the main challenges regarding biological surveys and biodiversity analysis. Even the most accessible bioregions of Colombia, such as the Andean biome, experience sampling biases (Vargas et al., 2022). While the Andean bioregions are well studied, due in part to their accessibility, understanding of the more remote, OHP region is lacking. Specifically, data on species distributions and its relationship to agricultural expansion is critically needed to improve understanding of the human impacts on agrobiodiversity. Such knowledge is essential for the effective planning of agricultural and environmental policy in Colombia's eastern plains. Consequently, if this complex land-use change phenomena and the lack of biological records continue, it will likely lead to biodiversity loss and irreversible changes in the ecosystem's integrity.

We argue that biodiversity in the OHP requires a better understanding of its spatial relationships to agricultural expansion. The OHP is considered Colombia's future food basket due to its large, underutilised territories with the potential for cropping. However, a variety of classifications generate different areal estimates. According to GIZ, the agrarian land use area of underutilised crops suggests that around 16 million hectares are apt for 27 sustainable agricultural systems across the whole Orinoquía region [Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020a]. These areas are different to UPRA's classification because they use other criteria such as ecological structure. For estimates of potential agricultural areas, here we rely mainly on UPRA's classification. On the other hand, UPRA states that Meta has close to 5 million hectares and Vichada 4.7 m/h apt for developing the agricultural frontier [Unidad de Planificación Rural Agropecuaria (UPRA), 2021].

Thematic maps of crops were generated by Unidad de Planificación Rural Agropecuaria (UPRA) (2021) based on national, regional and local data census for all municipalities in the Orinoquia region. As a result, optimal, marginal and not suitable areas for agriculture were identified. They estimated that about 15.9% of all land in the Orinoquía region is suitable for livestock production and 10% (2.3 million hectares) for agroforestry and forestry systems. Of these, just 1.3 million hectares are suitable for agricultural expansion in Meta department. However, just 1.07 million hectares should be used for agricultural production. In the case of Vichada, 10 million hectares are projected for agriculture, including livestock. Of those, just 1.4 million hectares are recommended as apt for agricultural production.

The agricultural practices in the OHP of Meta and Vichada are heavily influenced by the region's climate, which is characterised by a wet season and a dry season. During the wet season, which lasts from April to November, the grasslands and wetlands provide abundant grazing for livestock, while crops are planted and harvested during the dry season. Regarding specific farming activities, cattle raising is the primary source of income for the inhabitants, and the predominant food systems are pastures, agroforestry and livestock. The problem is that land use changes caused by agriculture in the OHP are happening fast across the whole eastern plain's region degrading its native biodiversity and therefore compromising its conservation. Hence, studies investigating the spatial changes between biodiversity and the agricultural frontier are needed.

Besides agricultural expansion and biodiversity loss, the region faces several challenges, including soil erosion, deforestation and the need for improved irrigation and water management systems. Climate change is also a growing concern, as droughts and flooding events have become more frequent in recent years.

To address these challenges, the Colombian government and private sector have been working to promote sustainable agriculture practices, including the use of conservation agriculture techniques, improved water management and the expansion of agroforestry systems. These efforts aim to promote sustainable development and ensure the long-term viability of agriculture in the region. However, lack of science-based information is still a common issue in the region. Here we apply a framework that uses the distribution of existing species records of fauna and flora in the OHP areas where high levels of biodiversity (single hotspots or regions) are found, and agricultural expansion occurs. This approach aims to enable policymakers, civil society leaders and businesses to identify spatial changes of agrobiodiversity and mapped out priority areas of biodiversity to inform regional planning. Therefore, our paper will contribute to bridge the gap knowledge between biodiversity and agriculture in the OHP that could be used to improve environmental planning.

## Materials and methods

### Study region

The study region is part of Meta and Vichada. It covers the municipalities of Puerto Carreño, La Primavera, Santa Rosalía, Puerto Gaitán and Puerto López (Figure 1). The study region is rich in hydrological systems, which are essential to shaping biodiversity (Instituto Alexander von Humboldt, 2016). The elevational gradient ranges between 50 and 300 metres above sea level. A classification based on hydrological features identified four major zones and eight sub-zones in Puerto Carreño, La Primavera and Santa Rosalía [Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), 2013]. The catchments of the Meta, Orinoco, Bita and Tomo rivers form the hydrological zones. At the micro-catchment level, 31 sub-zones were identified for Puerto Carreño, La Primavera, Santa Rosalía, Puerto Gaitán and Puerto López.

Rainfall across the region has a monomodal pattern. January to March is the dry season (0–100 mm per month), and the rest of the year, it rains most of the months with an average range between 150 and 500 mm/month. There is a wet-to-dry climate pattern from west to east; Puerto Carreño is the drier and hotter municipality. In contrast, Puerto López in the far west, closer to the Andean mountain range, is cooler and wetter.

## Conceptual framework

Figure 2 summarises the variables and activities involved during the application of the proposed conceptual framework.

### Species occurrence data and distribution

Two spatial databases of species occurrences from independent sources were generated. Based on a previously published biodiversity database of Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) (2020a), we built a species-level geographic database with 2,894 occurrences, comprising 2,574 different species records of the Animalia kingdom (insects, birds, mammals, reptiles, amphibious) and 320 different species records of the Plantae kingdom (Liliopsidae and Magnoliopsida; SI Database 1).

Puerto López contain 715 occurrences, Puerto Gaitán 599, Puerto Carreño 323, La Primavera 544 and Santa Rosalía 713. The biological records were extracted from the Global Biodiversity Information Facility (GBIF) and Species Link repositories, initially gathered in the field by the Instituto Alexander von Humboldt (2019). All the occurrences in Database 1 are registered and deposited in the National Biodiversity System (SIB, for its acronym in Spanish). During field survey campaigns, local communities and scientists collected secondary information about regional species

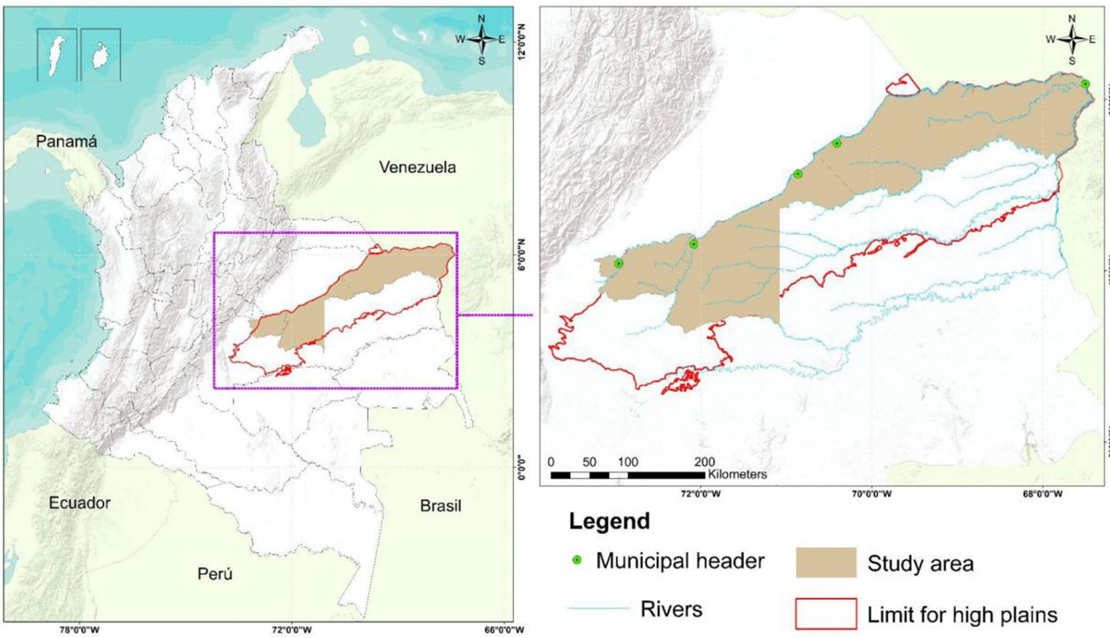


FIGURE 1
Map of the study region showing the municipalities of Puerto López, Puerto Gaitán, Santa Rosalía, La Primavera and Puerto Carreño.

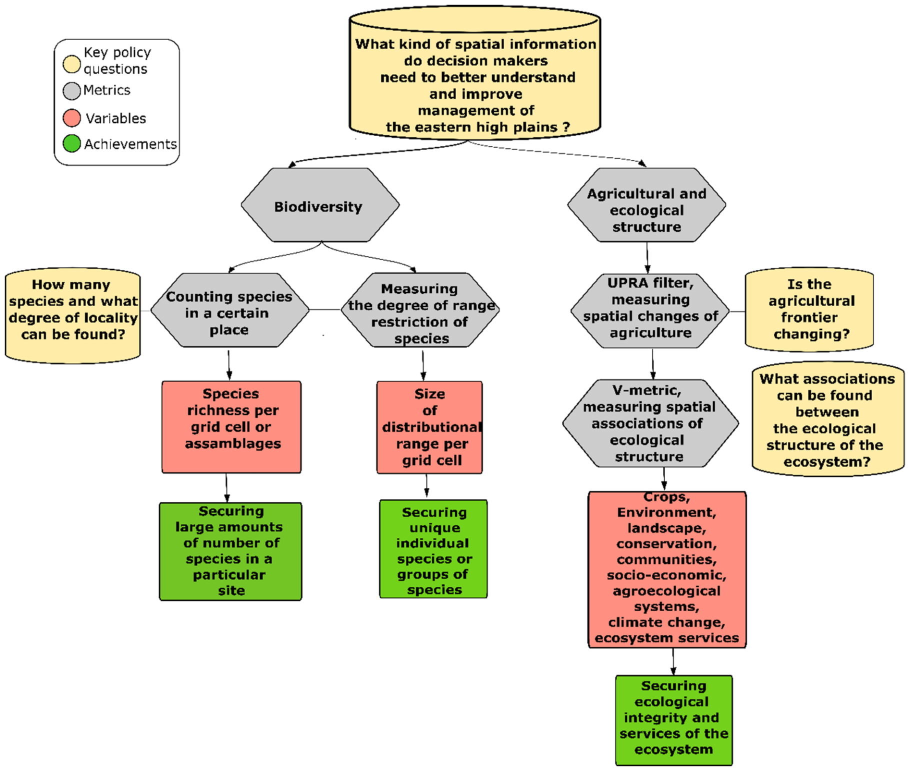


FIGURE 2
Summary of the conceptual model applied in our study.

distributions [Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020a].

The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) (2020a) database was developed under a regionally sustainable development strategy and participative community project known as Transformando la Orinoquía con la integración de los beneficios de la naturaleza en agendas sostenibles (Tonina). It can be considered more of a fauna database because 75% of the occurrences are for fauna. This regional classification was proposed by the National Bureau of Meteorology [IDEAM, for its acronym in Spanish, 2013, the physiography classification of the Orinoquía-Amazon (ORAM) developed by the Instituto Geográfico Agustín Codazzi (IGAC) (1999)].

Due to having more fauna records than any other biological group, the second dataset of plant distribution was developed using the Botanical Information and Ecology Network (BIEN) version 4.1 database. The RBIEN package (Maitner et al., 2018) extracted 8,406 occurrences comprising 3,358 species records from BIEN (SI Database 2). The BIEN database provides standardised plant observations from herbarium specimens. The total number of occurrences reported in both datasets was 11,301, comprising 6,254 species.

## Sampling completeness

We calculated the sampling completeness indicator known as redundancy using the software BIODIVERSE version 3.1 (Laffan et al., 2010). Redundancy measures the occurrence data density calculated as 1-richness/occurrences (Garcillán et al., 2003). Redundancy ranges between 0 and 1. The closer to 1, the number of samples per grid cell is better represented, suggesting fewer sampling biases in the spatial datasets. The redundancy metric was applied to Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) (2020a) and plant diversity datasets. The degree of sampling completeness is low for most of the study region but moderate to high in the main centres of diversity (Supplementary Figure 2).

## Species richness and endemism

A grid-based meta-analysis (multiple biological groups) was performed on both databases across the study region. Species richness (SR) and corrected weighted endemism (CWE) were calculated using the BIODIVERSE software version 0.18 (Crisp et al., 2001) for each $5 \times 5$ km grid cell. SR is the number of species present in a single grid cell. CWE is a relative measure of endemism and is essentially a function of range restriction (Laffan et al., 2010). CWE can be interpreted as the degree to which species ranges are restricted to a particular location. Areas of high SR or CWE are referred here as centres of diversity. These areas are sites (single or group of grid cells) with high concentration of biodiversity.

## Geographic regions

A Range Weighted Turnover (RWT) index was applied using the BIODIVERSE software version 0.18 (Laffan et al., 2016). RWT was applied to both the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) (2020a) and the BIEN databases independently. Calculating RWT, each species is weighted by the fraction of its geographic range across two locations. A dissimilarity matrix was then created in BIODIVERSE. An RWT score of zero means that the species composition of the two cell pairs is identical,

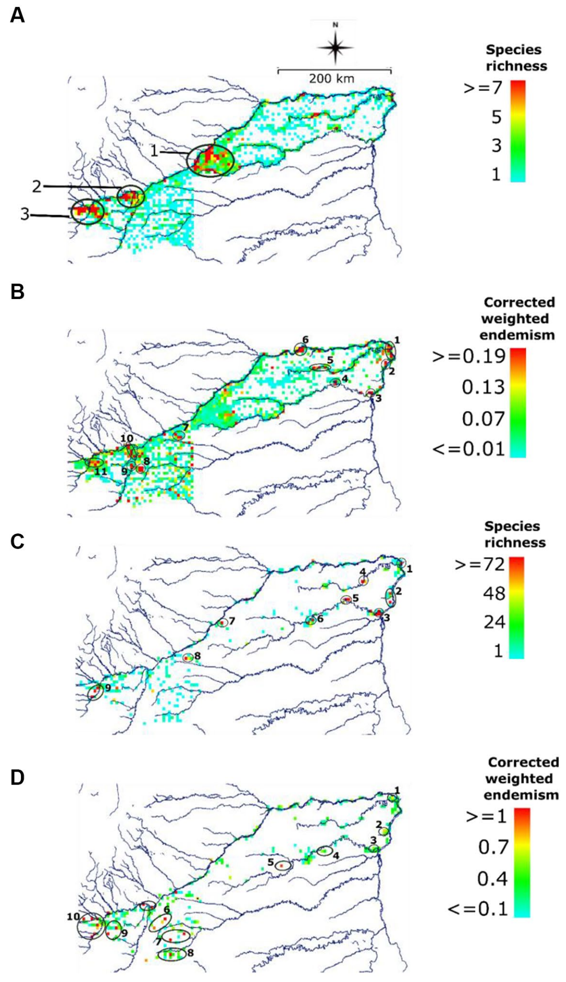


FIGURE 3
Spatial distribution of biodiversity for fauna **(A,B)** and plants **(C,D)** in the Orinoco high plains of Colombia. White areas have no data available. Colour at a threshold of 5–95%.

whereas a score of 1 means that the cell pairs are most dissimilar. The endemism-weighted dissimilarity matrix was converted into clusters of distinct species proportional to their range. The range-weighted metric provides better discrimination of the distributional break than the non-range-weighted metrics. The results of the RWT metric are displayed in a coloured map and a dendrogram. The clusters in the dendrogram reflect regions of endemism separated according to geographic distances.

### Linking biodiversity and agriculture

An integrated methodological framework that contains GIS layers of management strategies for conserving biodiversity, indicators of the benefits of nature and environmental use and management were used as the baseline information to feed our spatial changes analyses [Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020a]. This framework will map out and quantify the spatial changes of ecological structure based on their level of association across the region.

The inputs of the analyses were the layer of agricultural frontier generated by the Unidad de Planificación Rural Agropecuaria (UPRA) (2021) and the proposal for a Principal Ecological Structure [PES hereafter; Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020b]. Access to the UPRA[1] and Humboldt Institute biological databases is granted.[2] Note that each municipality has a different source in the previously mentioned sites. This framework considers Puerto Carreño, La Primavera and Santa Rosalia; Puerto Lopez and Puerto Gaitan were not included in this analysis because no PES layer was available.

The PES proposal is a database of cartographic information on ecological infrastructure and its ecosystem services that interconnect the environment, conservation, communities and socio-economic and agroecological systems. The components of the PES are hydrological units, landscape classification, identification of regional priorities and indicators of critical elements across ecosystems, land cover type, participative communal prioritisation of areas of importance, flooding and climate change risk analysis, liability assessment and finally ecosystem services of the three municipalities.

We applied the spatial statistics information-theoretical V-measure to quantify the degree of spatial changes and association between agriculture and biodiversity (Nowosad and Stepinski, 2018). This measure was calculated using ArcGIS Pro geoprocessing tools [Environmental Systems Research Institute (ESRI), 2021]. This index measures the degree of spatial association and changes between two categorical classifications. A high association is when a category is more spatially correlated with another category. The output of this measure is a spatial degree of changes and association between the variables of the categories. This measure generates a scale with values between 0 and 1. One means highly associated, and zero means a low degree of association. This analysis was applied separately for each municipality (Santa Rosalía, La Primavera and Puerto Carreño). However, a mosaic was built to facilitate the visual interpretation. The V-metric output was superposed to the layers of SR and CWE biodiversity hotspots. This way, we could compare the layers of hotspots' spatial location and agricultural information generated by the V-measure. The areas with a low degree of association suggest less exposure to changes among the agrobiodiversity inputs. In contrast, high degree of association suggests areas potentially exposed to a greater level of changes among inputs causing more spatial overlap of factors that affect biodiversity.

## Results

### Species richness

We identified three fauna SR centres (1, 2 and 3 in Figure 3A). As ordered in Figure 3, they are (1) the Santa Rosalía Gap, (2) the Manacías, Yucao and Meta rivers and (3) the Guacavia, Guatiquía and upper Meta rivers. Centres 2 and 3 are geographically part of the eastern range foothills tributaries, whereas Centre 1 relates more to the Orinoco system. The highest scores of the main fauna SR centres range between 15 and 17 species, but a single grid cell found an SR maximum value of seven at a threshold of 5–95%. There are several scattered richness grid

1 https://sipra.upra.gov.co/nacional
2 http://geonetwork.humboldt.org.co/geonetwork

cells in Puerto Carreño. In the case of plant SR (Figure 3C), the Puerto Carreño region shows the highest values with a maximum of 72 species in a grid cell. There is another centre of plant SR in Puerto Lopez and a few single cells scattered in La Primavera and Santa Rosalía.

## Endemism

We identified 11 centres of fauna endemism (Figure 3B). There are three centres of fauna endemism; the largest ones are on the east (1–6 in Figure 3B) and west (Puerto López and Puerto Gaitán; 7–11 in Figure 3B). We confirm that Puerto Carreño has the most endemic fauna locations closely related to the river systems, followed by Puerto López and Santa Rosalía. Some of the centres of fauna endemism are unevenly distributed across different regions in the high plains. The highest endemism score for fauna was 0.19 (red grid cells), meaning that these windows (individual or groups of grid cells) represent, on average, 19 per cent of the range of species they contain. The randomisation results show that all identified centres of endemism were significantly different from random at a threshold of $\alpha = 0.05$ (Supplementary Figure 1).

The spatial distribution of SR and endemism for plants show different patterns and a higher degree of endemism than the fauna dataset. The main centres of plants SR (1–6 in Figure 3C) are Puerto Carreño. In contrast, the western regions of Puerto Lopez and Puerto Gaitán showed the most significant number of sites with high endemism (6–11 in Figure 3D). However, a few scattered areas of high endemism are present in Puerto Carreño.

## Geographic regions

A strategy to improve the interpretation of endemism was to identify the turnover regions based on the degree of distributional range (Figure 4). This analysis helped to validate the spatial endemism patterns found at the individual grid cell level. Two major biogeographical fauna regions were identified in the OHP (Figure 4A). Region 1 in Figure 4A and the transition between the high plains and the systems of foothills on the eastern Andean mountain range (Region 2 in Figure 4A). Region 1 has widespread fauna. In contrast, Region 2 shows a greater degree of narrowly distributed fauna.

We propose the Santa Rosalía Gap as a strategic biodiversity region of the OHP (Figure 4B). To the northwest, it borders on the Meta River banks between the confluence of the Cusiana and Carare rivers, and to the southeast, on the lower ends of the Tomo and Elvita rivers. The Santa Rosalía Gap is a vital corridor between the eastern Orinoco savannas and the western Andean transitional savannas because it contains biodiversity elements from both ecoregions while acting as a hotspot of SR. Because of its strategic location, the Santa Rosalía Gap is a region of geographic overlap for multiple biodiversity elements that are dissimilar from each other and, at the same time, geographically restricted, likely due to the unique structure of the micro catchments comprising the Santa Rosalía region.

## Linking agriculture and biodiversity

The V-metric shows that Puerto Carreño has the lowest spatial association between the agricultural frontier and the PES (Figure 5). Santa Rosalia shows the highest values of spatial association, whereas La Primavera has an intermediate value. Hotspots of fauna SR overlapped with areas of high spatial association in the Santa Rosalía's Gap. CWE hotspots, on the other hand, overlap with areas of low to intermediate association in Puerto Carreño. Santa Rosalía shows high spatial association between agriculture and biodiversity likely due to be a highly developed region with complex hydrological networks that promote fauna SR. Areas of low association in Puerto Carreño and La Primavera are potential candidates for future sustainable agriculture and biodiversity expansion because they are exposed to less degree of human development, whereas Santa Rosalía is under greater threat than other regions.

# Discussion

Our results present new evidence that could be considered an early warning that hotspots of biodiversity in the OHP are under pressure due to agricultural expansion (Figure 5). A new action plan to map out the less vulnerable areas and more suitable lands for safe and sustainable future agrarian development in Puerto López, Puerto Gaitán, Santa Rosalía, La Primavera and Puerto Carreño will be required to address this challenge.

We suggest that each municipality plan its sustainability policy and agricultural development accordingly. The Santa Rosalía region, for example, has the highest exposure V-index, offering a high ecosystem risk (Figure 5). In a relatively small area, Santa Rosalía has more water resources, which suggests a great advantage for wildlife to thrive. Biologically, it is the main centre of fauna species richness with a high density of endemic bioregions. We tentatively argue that Santa Rosalía is a priority site which will require a careful treat under the future growth of agricultural development. Considering many of these factors, it will require a more hands-on sustainability plan to reduce the impacts of unplanned agriculture. Being the smallest of the five municipalities in the OHP provides a managerial advantage, so this region should become an exemplary case of friendly and effective agrobiodiversity development. Other external pressures, such as its proximity to Puerto Gaitán by road and fluvial connectivity with other agro-hubs, suggest this area should be prioritised for further intervention by the national government and local actors.

On the other hand, Puerto López and Puerto Gaitán are more developed in agricultural growth than other regions in the OHP of Colombia. Although the V-index was not calculated for these two municipalities, we assume the exposure value could be even higher than the one in Santa Rosalía. Some rules should be established to develop a friendly agricultural expansion towards the east of the OHP using lessons learned from these two large municipalities. In this region, the government should establish a land care centre where a multisector partnership units and proposes actions that mitigate adverse impacts on the ecosystem's health. In terms of biodiversity, the confluence of the upper Meta River and other tributaries such as Guatiquía, Yucao and Manacacías in Puerto López and the western boundaries of Puerto Gaitán makes this region vital for the conservation of unique elements of biodiversity. For instance, these regions have many secondary centres of endemism for fauna and flora (Figures 4B,D) that should be protected to reduce the risk of losing range-restricted species. Regional planning programmes in Puerto

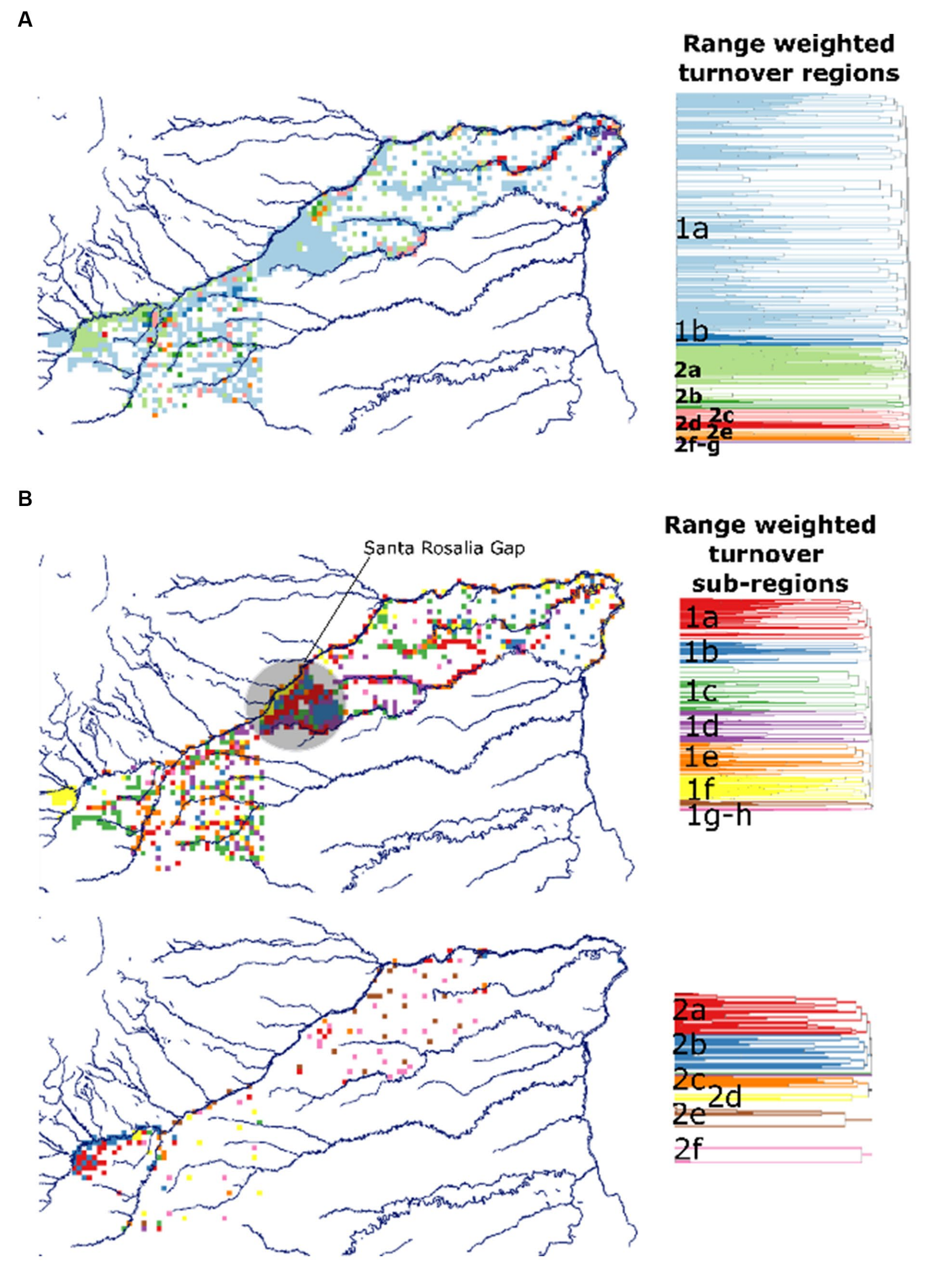


FIGURE 4
Biogeographic regions of fauna in OHP based on range-weighted turnover: **(A)** major regions; **(B)** sub-regions. Dendrograms of geographic distance showing clusters of endemic regions. White areas have no data available.

López and Puerto Gaitán municipalities should focus on *landscape recovery and agronomical remediation*; for example, implementing conservation zones based on soil carbon information (Hyman et al., 2022).

As expected, our V-index proved that a lower degree of spatial changes and association is found further east in the OHP suggesting a lower risk of environmental degradation. However, the spatial patterns of biodiversity highlight that La Primavera and Puerto Carreño were of high biological importance in terms of endemism associated with river ecosystems and outcrops. Remoteness and lack of road access in these municipalities maintain biodiversity less exposed to human impacts. These regions should be highly protected, and agricultural development should be even more carefully planned than any other region in the OHP. A solid effort to implement systems designed under a *conservation agriculture* and *biodiversity* vision is fundamental in these two agricultural frontiers.

## Agrosavias´ tools to help small farmers in the Orinoco eastern high plains

Some possible strategies to mitigate impacts on biodiversity and generate more sustainable development in agriculture for the OHP are summarised in the 12 technological offers (OTs; Table 1). The OTs were developed under a research scheme of the Corporación

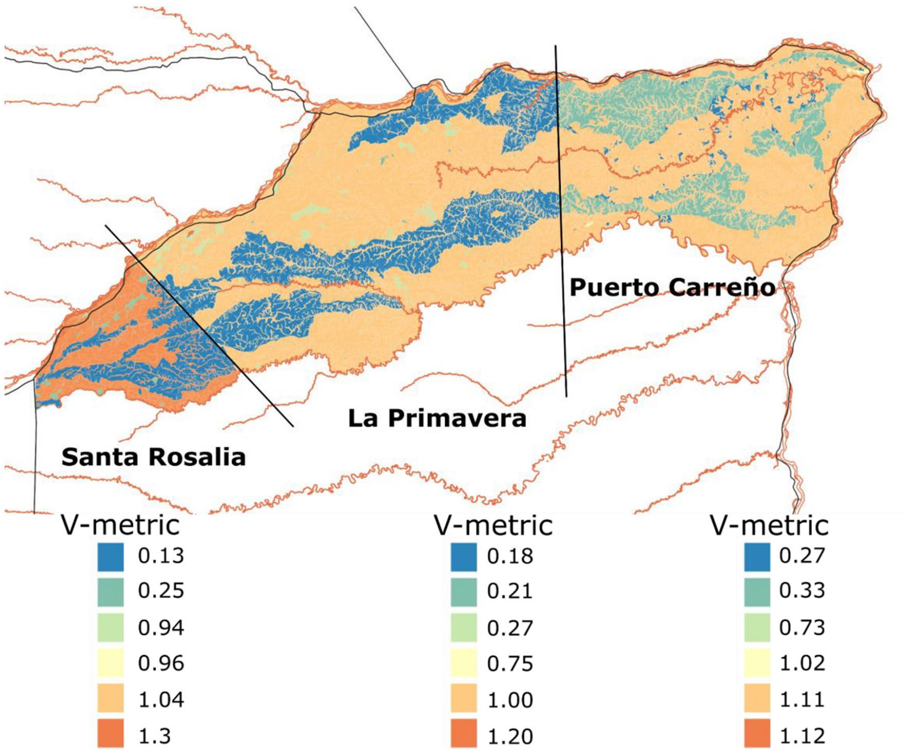


FIGURE 5
Map of the spatial changes and associations between the Agricultural Frontier [Unidad de Planificación Rural Agropecuaria (UPRA), 2021] and the Principal Ecological Structure [Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), 2020a] for Santa Rosalía, La Primavera and Puerto Carreño in the Orinoco high plains of Colombia.

Colombiana de Investigación Agropecuaria (Agrosavia). OT's technical packages have been designed for farmers (available).[3] For instance, the case of Carimagua's field station.

Within these OTs, there are several management recommendations that farmers could apply to different work areas and varieties, such as grasses and legumes that adapt to the climate and soil conditions of the OHP region (Examples 1 and 2 below). Example 1 is related to the management of pastures based on good practices of sustainable systems, which could be applied across the most impacted areas in the OHP to reduce exposure to landscape degradation.

1. This OT was designed to establish the integrated crop, forage and forestry systems for livestock. It provides recommendations to improve the productivity of livestock systems on farms in the Colombian Orinoquía region. Its application has the potential to double the carrying capacity and increase the weight gain per animal from 300 to 700 grams/animal per day, which could reflect an increase of 120 to 550 kg of meat/ha per year. The silage of transient crops such as soybeans and corn is a viable solution for feeding cattle in critical times of drought, and the establishment of trees in livestock systems contributes to animal welfare and the system's biodiversity.

3 http://bitly.ws/wAAu

Example 2 is an ecologically important strategy that could be implemented in degraded pastures. This aspect will provide more resilience to the agricultural livestock systems that, for years, have been mismanaged. For instance, the proposed legume species could be planted in small areas under a rotational system for more sustainable cattle grazing.

2. The *Arachis pintoi* (*cv*. Centauro) OT is based on a legume species. It is used for forage that typically feeds cattle. Centauro peanuts adapt well to acid, poorly drained and low-fertility soils. It can improve the nutritional quality of pastures associated with native grasses used for cattle feeding. On the other hand, the large amount of crude protein content is a feature that helps the nutrition of livestock, mainly where milk production in dual-purpose cows grazing *cv*. Centauro + *Urochloa humidicola* occurs (before *Brachiaria humidicola*). This practice could increase productivity by 95% (Rincón Castillo, 2013; Rincón et al., 2020; Díaz-Giraldo et al., 2021; Rincón Castillo et al., 2022).

## Lessons learned

A science-based strategy for the regional planning of biodiversity and agriculture is crucial for decision-making and land-use planning. Combining information from different sources (UPRA, SIB Col, EPP) adds value to the current knowledge of the high plains' exposure to

TABLE 1 Technological packages of agriculture or OTs for the OHP region in Colombia.

| Technological offer | Thematic area | Category | Description | Source |
|---|---|---|---|---|
| Forage legume *Arachis pintoi* cv Centauro | Livestock | Reproductive material | Legume for grazing and plant cover in forestry crops with adaptation to poorly drained soils | Rincón et al. (2020) |
| Protocol of Good Beekeeping Practices and genetic improvement of *Apis mellifera* | Livestock | Recommendations, protocols and methodologies | This protocol responds to the essential principles of management, hygiene and safety that ensure the quality of hive products such as honey and pollen | Camargo Sánchez et al. (2015) |
| Recommendation to recover and manage grasslands in the Orinoquía | Livestock | Recommendations, protocols and methodologies | It contributes to improving the physical properties of the soil, especially porosity and increases the supply of forage and, in turn, animal production in fattening cattle | Rincón Castillo (1999, 2010) |
| Recommendations to establish integrated crop, forage and forestry systems for livestock | Livestock | Recommendations, protocols and methodologies | They improve the productivity of livestock systems in the Colombian Orinoquia, double the carrying capacity and increase the weight gain per animal | Flórez Díaz and Rincón Castillo (2013a); Rincón Castillo (2013) |
| Recommendations for the shrubby legume *Cratylia argentea* cv Veranera to feed cattle | Livestock | Recommendations, protocols and methodologies | Shrub legume adapted to well-drained acid soils with high forage production under drought conditions | Pardo Barbosa et al. (2007) |
| Grazing recommendations to produce quality beef in Orinoquía bovines | Livestock | Recommendations, protocols and methodologies | Technological recommendations oriented to produce quality meat in livestock systems, considering grazing management | Flórez Díaz and Rincón Castillo (2013b) |
| Recommendations to use and manage Toledo grass *Brachiaria brizantha* CIAT 26110 | Livestock | Recommendations, protocols and methodologies | The objective of this OT is to intensify bovine production by increasing the forage supply from one animal per hectare to a stocking rate of 2 to 3 animal units per hectare | Lascano et al. (2002); Pérez León (2006) |
| Recommendations for cattle breeding rates | Livestock | Recommendations, protocols and methodologies | OT for cattle reproduction and management | Prieto et al. (2000); Velásquez-Penagos and Velásquez-Penagos (2018) |
| Strategic supplementation recommendations for breeding, fattening, and dual-purpose cattle in Orinoquia | Livestock | Recommendations, protocols and methodologies | Technological recommendations for strategic supplementation by supplying a balanced diet with silage and agroindustry by-products to improve meat and milk production | Diaz Giraldo et al. (2023) |
| Cashew clones (*Anacardium occidentale*): CORPOICA MAPIRIA Ao1, CORPOICA YOPARE Ao2 and CORPOICA YUCAO Ao3 for Orinoquía | Agricultural | Reproductive material | Varieties adapted to the region of the flat high plains of the Orinoquia, with high productions of nuts per hectare and tolerant to the anthracnose disease. | Clímaco Hio et al. (2016) |
| Sweet Sorghum CORPOICA JJT-18 *Sorghum bicolor L* | Agricultural | Reproductive material | Forage alternative for livestock production systems, offering fresh silage mixed with other grasses and legumes | Rincón Castillo et al. (2013) |
| Soybean varieties (*Glycine max*): CORPOICA ACHAGUA 8 and CORPOICA GUAYURIBA 9 for Piedmont and flat high plains | Agricultural | Reproductive material | Varieties with high yield and adapted to the *vegas* and *vegones* of Piedmont and high plains | |
| Rice variety CORPOICA LLANURA 11 *Oryza sativa* | Agricultural | Reproductive material | Rice variety that tolerates aluminium saturation (≥ 70%) and resistance to diseases, mainly *Pyricularia* spp. | Tapiero et al. (2003) |
| Cassava variety CORPOICA MELÚA-31 *Manihot esculenta Crant* | Agricultural | Reproductive material | The white colour of the root pulp guarantees its quality as a raw material for the industry, especially in the cassava flour production market | Rosero Alpala et al. (2019) |
| Management recommendations for the mite vector of citrus leprosis | Agricultural | Recommendations, protocols and methodologies | Management practices aimed at controlling the mite vector of citrus leprosis (*Brevipalpus phoenicis Geijskes*) | Kitajima et al. (2006); León and Kondo (2017) |
| Chemical suitability of Oxisols from Orinoquía to establish citrus and perennial fruit trees | Agricultural | Recommendations, protocols and methodologies | Technological recommendations for the mineral nutrition of crops with the application of correctives, sources and doses of compound fertilisation plus minor elements | Pulido Castro et al. (2009) |

degradation, avoiding negative impacts, for example, through hotspot transformation and biodiversity loss. Mitigation of these impacts is possible by informing decision-makers and other key stakeholders about the hotspots of biodiversity and exposure to agriculture transformation. This information can be vital to implementing sustainable land-use planning and biodiversity conservation and choosing suitable OT for developing the territory.

Successful land-use planning and biodiversity conservation also requires other enabling conditions, including skilled people, building collective capacity, political will and information that local communities can use. The shortage of available information can be improved by using the map data viewer to make the results more accessible. However, work must be done to improve the enabling conditions for future OH management.

To contribute to better land planning of Meta and Vichada, we recognised the importance of zooming in on the critical areas and exploring in the future the Cumaribo region, which is a crucial area of Vichada. In addition, understanding the learned lessons such as previous studies developed in the Carimagua fieldstation could be another way to improve the OHP management.

Carimagua is one of Agrosavia's research stations. It is the most isolated and covers an approximate area of 22.000 hectares in the heart of Meta. Some of the OTs listed in Table 1 are closely related to the development of new species of tropical pastures adapted to the regional conditions of the eastern plains (Álvarez and Rincón, 2010; Rincón Castillo et al., 2022). These technological advances are materialised in the scientific achievements conducted in Carimagua. Since the 1970s, researchers developed a new species of grasses (i.e. scientific name) that revolutionised pasture adaptation and cattle production systems in South America. Carimagua offers the ideal conditions for scientists and regional communities to test new ideas and applied research that can help to conserve the native ecosystems of the plains. We encourage the community to visit the fascinating empirical research achievements of Carimagua and create liaisons with Agrosavia's community through Carimagua's facilities.

### Limitations

While the early warning approach is valuable in helping national and local stakeholders to develop a more sustainable vision for regional planning, there is an increasing realisation that barriers to effective communication with stakeholders are still common. To reduce such gaps, a map data viewer tool is a potential solution to engage the community with science-based solutions.

The OHP region is biologically poorly understood and sparsely documented. Therefore, data deficiencies regarding spatial coverage of species occurrences are an inevitable bias in this vast region. Small sample sizes over relatively large areas can cause spatial patterns of biodiversity to be distorted. We acknowledge this issue, but at the same we provided and used the best data available at least for some key groups of fauna and flora. Under the current circumstances, to reach a complete sample of species diversity in the whole OHP is unrealistic. Species distribution modelling could be applied to fill up the sampling gaps. For instance, the biodiversity programme in the Humboldt institute has indeed modelled the distribution of many species in the OHP region showing the potential application of such approaches in under sampled regions. Our results of spatial patterns of biodiversity should be interpreted with care and used as indicators rather than definitive answers.

Regarding the V-metric, we acknowledge that the spatial changes and its associations just represent a snapshot in time over the history of the OHP. Hence, they should not be interpreted as a unique trend. Despite this limitation, our results provided new information about impacts of human on the agrobiodiversity of the eastern high plains of Colombia also known as ¨Altillanura¨ and considered one of the future agricultural frontiers in the region.

## Conclusion

A better scientific understanding of the effects of agricultural expansion on biodiversity is needed to shape policy and improve environmental management along this future agricultural frontier.

## Data availability statement

The distributional data for fauna and plants presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

All authors contributed to the study conception and design. Material preparation was performed by RD-G. Data analysis was performed by CG-O. Data collection of the fauna and flora species distribution was performed by GIZ under the supervision of CR-C. The first draft of the manuscript was written by CG-O and all authors commented on previous versions of the manuscript. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

CR-C was employed by the company Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), GmbH.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1192054/full#supplementary-material

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# How can GIS support the evaluation and design of biodiverse agroecosystems and landscapes? Applying the Main Agroecological Structure to European agroecosystems

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Agrobiodiversity plays a critical role in fostering the stability, resilience, and sustainability of European farming systems. Nonetheless, there is currently a lack of comprehensive methods to describe its spatial distribution within farms, its connectivity with the surrounding landscape, and, most crucially, how the perceptions and actions of human communities affect it. The Main Agroecological Structure (MAS) has recently been proposed as an environmental index aiming to tackle such challenges by promoting a dialogue between landscape ecology and agroecology, encompassing criteria that focus on both landscape parameters and cultural variables. Geographic information systems (GIS) can play a key role in the measurement of the index by leveraging public geodata and engaging with the direct participation of communities to map the territories they inhabit and cultivate. Nevertheless, their use in this context has not yet been studied. We propose here a new GIS-based approach for estimating the Main Agroecological Structure: landscape criteria are assessed through the hybrid use of free and open-source GIS tools, field samplings, and participative mapping methods; cultural parameters are evaluated through semi-structured interviews. Contextually to the definition of such methodological foundations, the present study tests the relevance of the index to European agroecological contexts by applying the proposed workflow to three Italian farms characterized by different territorial and organizational forms. Along with a few modifications to the original proposal, we highlight the relevance of GIS in making agrobiodiversity visible at a landscape level within the context of the index. We also suggest some potential future applications related to local empowerment and agroecosystem mapping.

KEYWORDS

**agroecology, community participation, geographical information systems, GIS, agrobiodiversity, European agroecosystems, landscape, community supported agriculture**

# 1. Introduction

## 1.1. Assessment of agroecological systems

The paradigm shift toward an increasingly sustainable food production system in Europe also demands the development of methodologies and tools to monitor, assess, and evaluate the complex aspects needed by the stakeholders to make better and more informed decisions at any level (Gascuel-Odoux et al., 2022).

Earlier approaches primarily monitored food production and economic performances. However, there has been an evolution in assessment techniques to address the multifaceted nature of sustainability concepts and agroecological frameworks (Sajadian et al., 2017; De Marchi et al., 2022; Gascuel-Odoux et al., 2022).

Nowadays, a varied suite of methodologies and tools has been tested in different case studies and contexts worldwide for ex-ante or ex-post evaluations and monitoring, focusing on one or more dimensions of sustainability (environmental, economic, social, and governance) and/or taking into account other related aspects such as climate change adaptation and mitigation, biodiversity, ecosystem services, resilience, and Sustainable Development Goals (SDGs), among others (Eichler Inwood et al., 2018; Córdoba et al., 2020; Berthet et al., 2022; Quintero et al., 2022a). These methodologies can vary in their qualitative and quantitative approaches, indicators used, the degree of stakeholder involvement, and their temporal and spatial application scale, spanning from farm to agro-landscape to the global food system, and in their degree of adaptability to different geographical contexts, technology, and time required (De Olde et al., 2016; Eichler Inwood et al., 2018; Chopin et al., 2021).

Well-documented tools to assess the agroecological sustainability of a system and their application in different global contexts include the Tool for Agroecology Performance Evaluation (TAPE) developed by FAO, which operationalizes the 10 elements of agroecology stated by the organization (Mottet et al., 2020; Bicksler et al., 2023), and MESMIS (from the Spanish acronym *Marco para la Evaluación de Sistemas de Manejo de recursos naturales incorporando Indicadores de Sustentabilidad*, Framework for the Evaluation of Natural Resource Management Systems incorporating Sustainability Indicators), initially developed in Mexico for the sustainability assessment of agro-socio-environmental systems using a participatory, interdisciplinary, and flexible framework (López-Ridaura et al., 2002). Recently, the Main Agroecological Structure (MAS) has been developed in Colombia and proposed as a socio-environmental index that aims to promote a dialogue between landscape ecology and agroecology, encompassing indicators that focus on both landscape parameters and in-farm agro-biodiversity and variables of sociocultural order (Quintero et al., 2022a).

## 1.2. Geographic (and participatory) information systems to support agroecological systems landscape assessment

Geographic information systems (GIS) *sensu lato*, i.e., comprising geo-technologies, geodata, geo-visualization, geographical participatory and critical approaches, and geodesign, can play a key role in supporting comprehensive assessments of agroecological systems (De Marchi and Diantini, 2022). It is worth highlighting that farms are not isolated entities but are intricately connected within even more complex landscapes; thus, they should not be considered separate from them (Quintero et al., 2022b). Investigating the multi-scalar aspects flows and relationships between the sociocultural and ecological systems within a landscape can be improved by leveraging spatial analysis and visualization, using public geodata, drones, and satellite images, and engaging with the direct participation of communities to map the territories they inhabit and cultivate. However, their use in these contexts has been relatively understudied and it is exposed to several challenges. As Eichler Inwood et al. (2018) highlighted, including landscape concepts adds complexity to the assessments and requires, among others, the definition of proper indicators, the involvement of expert and local knowledge, the collection and use of suitable data at different spatial and temporal scales, the use of mixed methods combining qualitative and quantitative approaches, and a presentation of results that is useful for decision-making.

## 1.3. Scope and structure of the Main Agroecological Structure environmental index

The origins of the Main Agroecological Structure environmental index lay in the reflection on the relationship between culture and ecosystem (León-Sicard, 2021). Specifically, the index aims to investigate how these dynamic relationships develop within agroecosystems, conceived as ecosystems that have been deliberately modified by humans to obtain products and services (Gliessman, 1990; Dalgaard et al., 2003). For this purpose, a dialogue between landscape ecology and agroecology is proposed. Agroecology is defined here as the science that explores the environmental dimension of agroecosystems while recognizing the interactions among biophysical, social, political, technological, and symbolic factors, aiming to investigate solutions to ecological and social problems through the interaction among traditional agricultural practices, scientific research, resource conservation, and promotion of farmers' autonomy (Altieri, 2002; Méndez and Gliessman, 2002). The elaboration of MAS is based on the observation that, in several global regions, ancient forest or grassland matrices have been replaced by new anthropic ones, in which residues of the former - patches and corridors - are studied by landscape ecology. The dichotomy between *land sparing* and *land sharing* is rejected, expanding the scope and linking the state of agroecosystems to biodiversity conservation. The way in which agriculture is carried out is considered to be more significant than the mere presence of agriculture itself when it comes to creating landscapes capable of fostering biodiversity conservation and ecosystem services (*matrix quality approach*) (Perfecto and Vandermeer, 2010; Perfecto et al., 2019). Agricultural intensification is thus deemed inadequate to solve ecological and social problems (McIntyre et al., 2009) that should instead be tackled by supporting local small-scale agroecological food systems. These are considered capable of creating agricultural matrices that can preserve biodiversity in the long term while simultaneously providing stable and accessible food. This leads the authors to link the dimension of ecological conservation with that of food sovereignty (Perfecto and Vandermeer, 2010; Perfecto et al., 2019). Building upon this theoretical basis, MAS tries to go beyond the sole consideration of landscape biophysical factors, taking into consideration the cultural, social, political, and economic factors transforming it. The single farm is identified as the base unit in which such elements play their action (Cleves-Leguízamo et al., 2017; León-Sicard et al., 2018). MAS is defined by the authors as the "internal and external configuration or spatial arrangement of the farm and the spatial connectivity among its different sectors, patches, and corridors of vegetation or productive systems, in relation to each other and to the surrounding landscape, as historically constructed and regulated by cultural variables" (León-Sicard, 2021).

### 1.4. Aims

In this study, we propose a new GIS-based approach for estimating the Main Agroecological Structure: landscape indicators are assessed through the hybrid use of free and open-source GIS tools, field samplings, and participative mapping methods; cultural parameters are evaluated through semi-structured interviews. Contextually to the definition of such methodological foundations, the present study examines the relevance of the index, originally designed to be applied in Colombian landscapes, to European agroecological farms by testing the proposed workflow on three Italian case studies characterized by different territorial contexts and organizational forms.

## 2. Materials and methods

### 2.1. Case study selection

Three farms located in North-Eastern Italy were chosen as case studies (Figure 1): Le Terre del Fiume (Veneto region), Ca' Battistini, and Arvaia (Emilia-Romagna region). Given the nature of the index, farms were selected based on their varying degrees of commitment to agroecological farming and their different specificities. Further factors guiding the choice were the variability in territorial contexts and organizational structure.

Le Terre del Fiume was selected as an example of a neo-rural family-run farm located in a peri-urban zone, on the outskirts of the city of Padua. Its territorial context is characterized by the coexistence of residential areas, extensive crops, and infrastructure (among which is a small civil airport). Since its foundation, Le Terre del Fiume has moved toward ecological restoration of the territory, seen as one of the main tasks of agriculture. This also led the farm to actively participate in citizen networks opposing further urban development in the area and working toward the creation of an *agricultural park* in which social uses and agricultural production can coexist. Its production mainly consists of cereals, vegetable crops, and processed products directly sold to consumers on-site.

Ca' Battistini is a family-run peasant farm located in the Apennine Mountains, 40 km southwest of the city of Bologna. The surrounding area is dominated by grasslands, non-irrigated extensive crops, and oak forests. As confirmed by cadastral maps and old aerial photos, such woods result from the naturalization of abandoned wooded pastures, resulting in various other tree species (ash, alder, willow, pear, and cherry tree) interspersed among oaks. Ca' Battistini is one of the founding members of the Campi Aperti association, a 21-year-old network of farmers involved in food sovereignty struggles at the local, regional, and national levels. The association currently organizes several farmer markets in the city of Bologna on a weekly basis (Paltrinieri and Spillare, 2018; Angelis and Diesner, 2020; Diesner, 2020; Alberio and Moralli, 2021; Ferrando et al., 2021; Rossi, 2022). Vegetable and fruit crops coexist with the prevalent production of cereals, used as raw materials in the cooperative brewery hosted on the farm.

Arvaia was selected as an example of CSA (community-supported agriculture), thus differing in its organizational structure from the previous two case studies. It was founded in 2013 as a cooperative of citizens willing to be directly involved in the sustainable production of food. Its operations and political stance are based on the participation of its members in three yearly assemblies. Its budget is covered by raising shares through a solidarity-based system: the amount each member contributes is flexible, while the distribution of the products is equal and independent of the size of the share (Rossi, 2017; Paltrinieri and Spillare, 2018; Piccoli et al., 2021). This peri-urban farm is located on the outskirts of the city of Bologna, where a diverse mix of crops coexists alongside industrial and commercial areas. The farm's production is quite diverse, including cereals, small fruits, vegetables, fruit, and protein crops. Additionally, a small section of the land is occupied by a vineyard.

### 2.2. Input data sourcing and preliminary processing

The Main Agroecological Structure of the selected case studies was calculated following the methods proposed by León-Sicard (2021). It has to be noted that the index is still under development and that further modifications have been proposed in subsequent

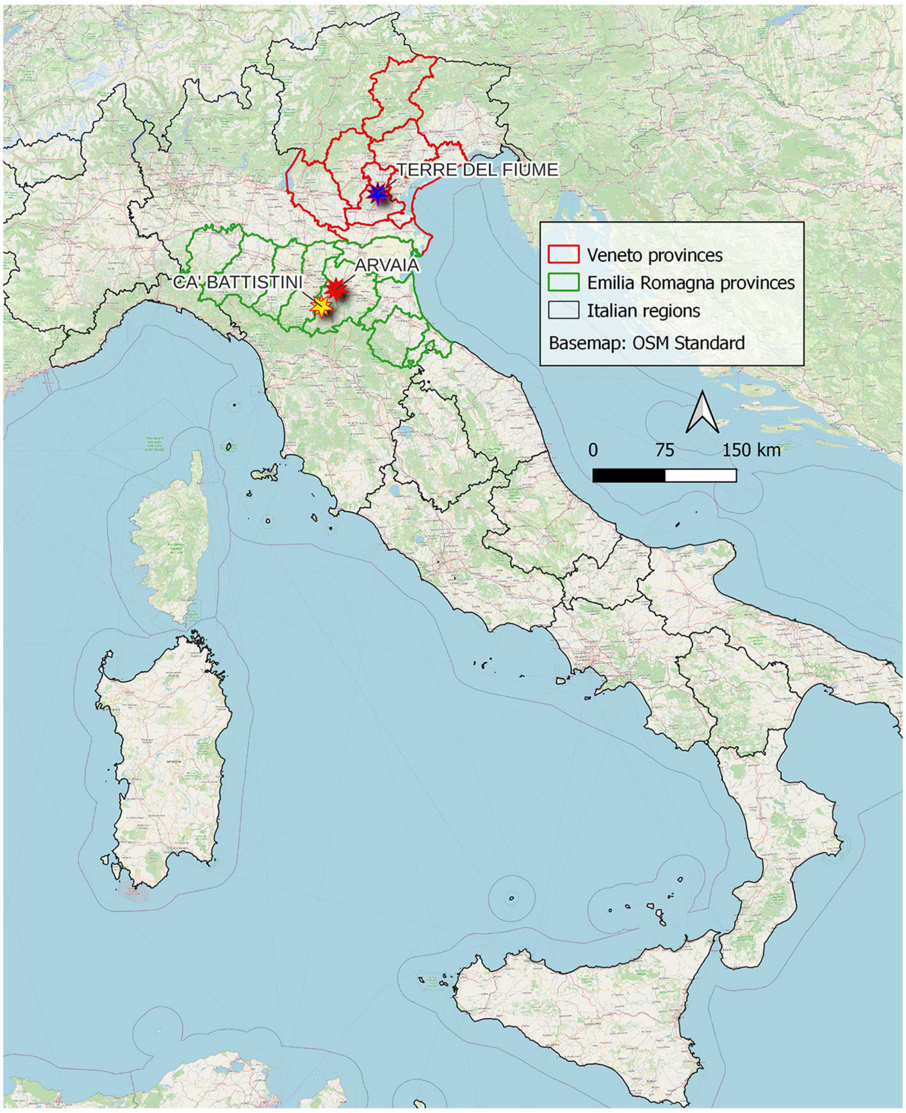


FIGURE 1
Location of the three farms under study in Italy.

works (Quintero et al., 2022a). The original structure of the index was preserved here, thus calculating 10 criteria: four dealing with landscape features and six with cultural parameters. A detailed workflow dealing with the specific geoprocesses used for adapting such an index to the territorial context of the chosen case studies is available in Supplementary material. A quick overview of the workflow is also provided in Figure 2.

Unless otherwise stated, all the processing steps were carried out in QGIS 3.16.x.

The farm boundaries were determined using a combination of different methods: pre-existing digitization of Le Terre del Fiume and Ca' Battistini boundaries were modified according to cadastral units, while in the case of Arvaia, pre-existing maps were digitized using the QGIS *Georeferencer* tool. Field visits were then carried out, during which the QField app was used to ground-truth these boundaries with the participation of farmers.

The center of each farm was calculated by using the processing algorithm *Point on the Surface*. As suggested by León-Sicard (2021), a circular area of influence (AI) with a radius proportional to the longest side of the farm was identified. Such a radius was here defined as equal to the longest side (as opposed to the original proposal, where it was suggested to measure double the longest side) to avoid taking into consideration residential zones, a problem that could particularly affect the two peri-urban farms. The *Buffer* processing algorithm was then used for calculating AI. Since Ca' Battistini is composed of two different parts located a few kilometers away, a buffer was calculated around the center of each part.

Land use/land cover (LULC) vector maps were obtained from regional geoportals (Veneto and Emilia-Romagna regions) and clipped using AI buffers as overlays. The resulting maps were further modified by manually digitizing hedgerows and forest patches (1:1,000 scale). Regional ortho-photos (*AGEA*

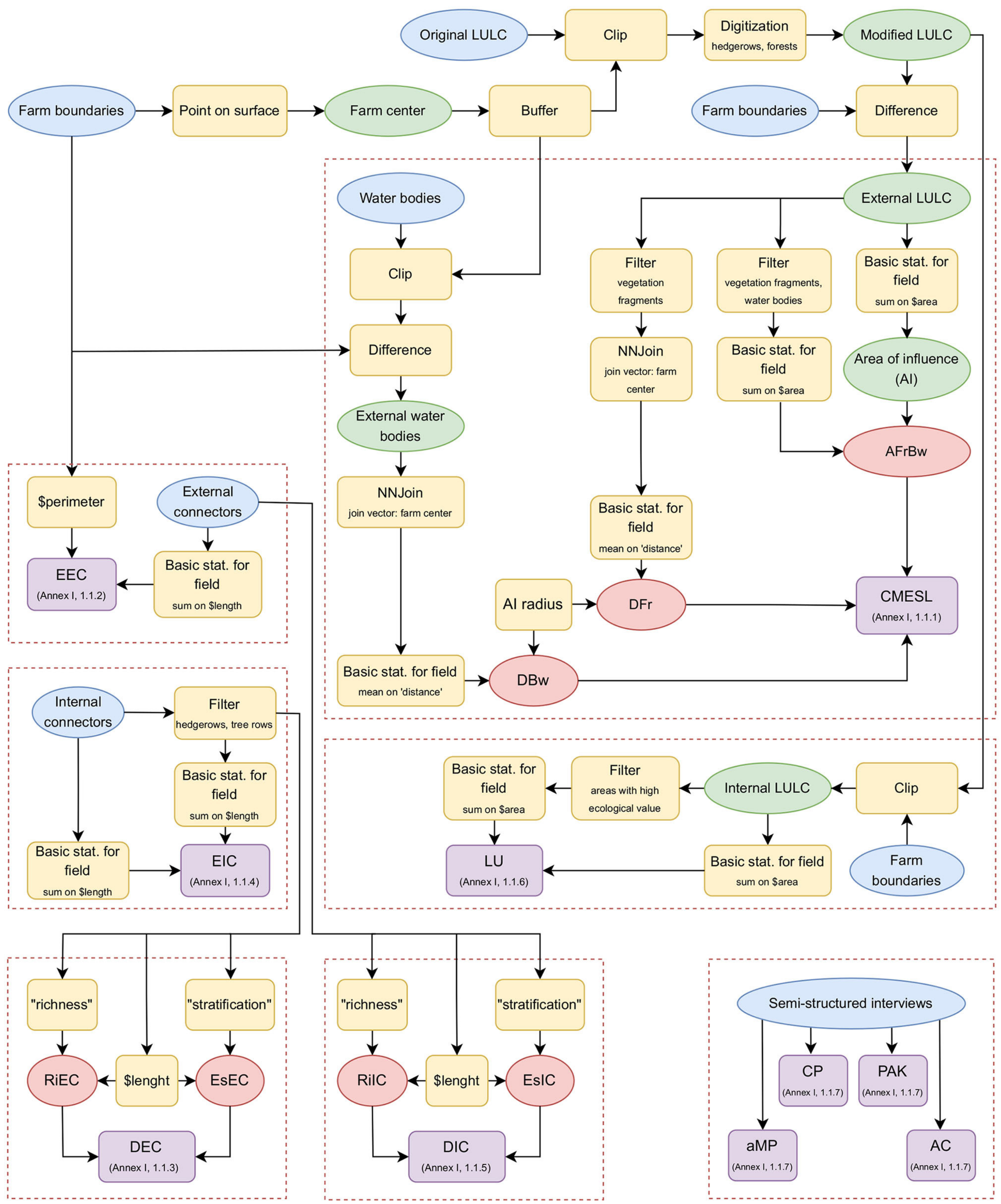


FIGURE 2
Overview of the proposed workflow. Input data are marked in blue, geoprocesses in yellow, intermediate data in green, indicators in red, and criteria in purple. Among brackets (in criteria frames) is the reference paragraph of Supplementary material detailing the workflow for each single criterion.

*2018* in the case of the Veneto region, *CGR 2018* for Emilia-Romagna) were used as base maps. LULC maps of both the AI and the area inside farm boundaries were then obtained from the modified LULC map using *Clip* and *Difference* processing algorithms. The input dataset and its links are presented in Table 1.

TABLE 1 Main input dataset used and their sources.

| Dataset | Type | Source | Link |
|---|---|---|---|
| Land use/land cover 2018, Veneto | Vector | Veneto region geoportal | Downloaded from: https://idt2.regione.veneto.it/ |
| Land use/land cover 2017, Emilia Romagna | Vector | Emilia Romagna region geoportal | Downloaded from: https://geoportale.regione.emilia-romagna.it/catalogo/dati-cartografici |
| Regional ortho-photos 2018, Veneto | WMS service | AGEA | https://idt2.regione.veneto.it/gwc/service/wmts |
| Regional ortho-photos 2018, Emilia Romagna | WMS service | CGR | http://servizigis.regione.emilia-romagna.it/wms/CGR2018_rgb?request=GetCapabilitiesandservice=WMS |
| Water bodies, Veneto | Vector | Veneto region geoportal | Downloaded from: https://idt2.regione.veneto.it/ |
| Water bodies, Emilia Romagna | Vector | Emilia Romagna region geoportal | Downloaded from: https://geoportale.regione.emilia-romagna.it/catalogo/dati-cartografici |

Vector layers representing water bodies were obtained from regional geoportals, clipped using the AI buffer as an overlay, and then divided (external or internal to the farm boundaries) using the *Clip* and *Difference* algorithms.

Two participatory mapping sessions were then carried out on each farm to incorporate farmers' knowledge into the final maps and verify the mapped data with their help (Figure 3). In the first session, paper maps (created with the QGIS *Print layout* tool) were used to identify elements of interest. Markers were used to create interpretative maps, highlighting features and covers that were not previously incorporated. In the second participatory mapping session, walking transects through the farm were carried out with farmers. The QField app was used to digitize new features and fill attribute table fields. Final maps representing LULC, internal and external connectors, and water bodies were obtained as an output of such participatory mapping sessions. These activities initiated discussions about the current conditions, past developments, and future prospects of the agroecosystems, elements that were later investigated through semi-structured interviews while evaluating qualitative criteria, as described in the following paragraphs.

## 2.3. Criteria structure and evaluation

### 2.3.1. Connection with the Main Ecological Structure of the Landscape (CMESL)

This parameter describes the spatial relationship of the agroecosystem with the elements composing the surrounding landscape, with a focus on vegetation fragments and water bodies. Such landscape features are conceived as elements preserving biodiversity, influencing the functional processes inside the agroecosystem. For this purpose, indicators DFr and DBw are calculated considering the average distance of vegetation fragments and water bodies from the center of the farm and the distance is weighed based on the radius of the calculated area of influence around the farm. A third indicator, AFrBw, represents the percentage of AI covered by such elements. The parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.1 (Supplementary material).

### 2.3.2. Extension of External Connectors (EEC)

This parameter evaluates the linear extension of vegetation connectors (hedgerows and tree rows) located on the farm perimeter. The parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.2 (Supplementary material).

### 2.3.3. Diversity of External Connectors (DEC)

The parameter DEC aims to estimate the degree of ecological function of vegetation connectors located on the farm perimeter. For this purpose, it is divided into two indicators dealing with species richness (RiEC) and vertical stratification (EsEC). Weighting factors proposed by the authors are applied to the sampled values of richness and stratification, dividing them into classes (León-Sicard, 2021). The parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.3 (Supplementary material).

### 2.3.4. Extension of Internal Connectors (EIC)

The EIC parameter measures the extension of vegetation connectors inside the farm, calculated as the percentage of interior farm divisions composed of living structures (hedgerows, tree rows). The parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.4 (Supplementary material).

### 2.3.5. Diversity of Internal Connectors (DIC)

This parameter is comparable in its aim and structure to DEC, composed of two indicators dealing with richness (RiIC) and stratification (EsIC). It differentiates from the former as its main focus is vegetation connectors located inside the farm. The parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.5 (Supplementary material).

### 2.3.6. Land Use (LU)

This parameter focuses on measuring the percentage of the farm area occupied by vegetation that benefits agrobiodiversity. The

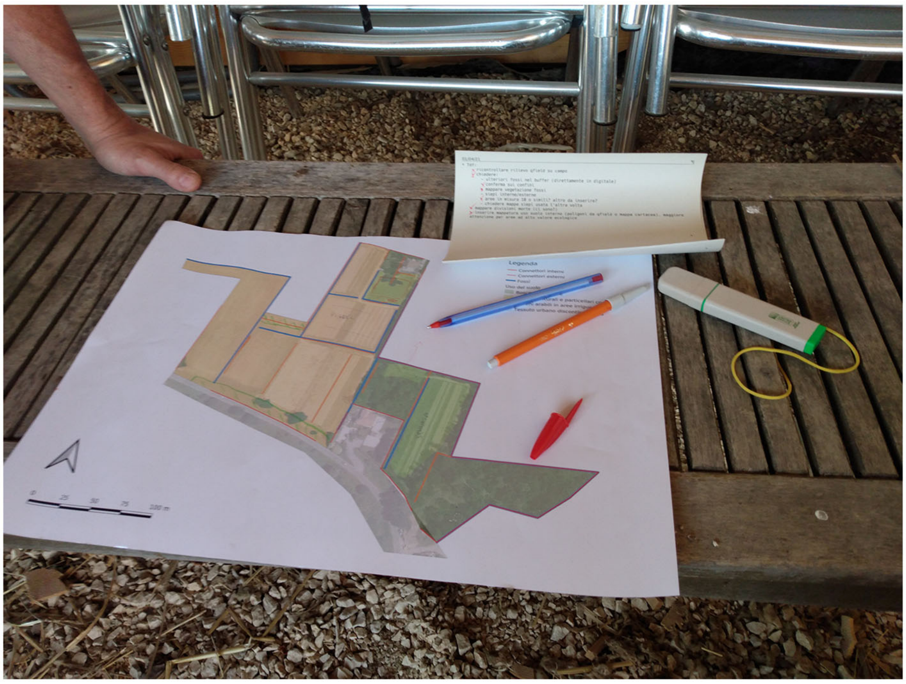

FIGURE 3
Participatory mapping: preliminary data being checked with farmers in the field.

parameter was calculated using QGIS, according to the workflow detailed in paragraph 1.1.6 (Supplementary material).

### 2.3.7. Agricultural Management Practices (aMP)

The aMP parameter aims to qualitatively investigate the approach of farmers toward agriculture, with a focus on their agricultural management practices.

Four indicators are taken into consideration:

- Seeds (S): origin, type, production, and conservation;
- Soil preparation (SP): type and intensity of tillage, use of complementary practices (green fertilization, cover crops, mulching, fallow, harvest residue management);
- Fertilization (F): fertilizer origin and type; use of rotation; use of complementary practices;
- Phytosanitary management (PM): use of complementary practices for weed management, tools, and approaches used for pest control

The single indicators were calculated through semi-structured interviews, as further detailed in paragraph 1.1.7 (Supplementary material).

### 2.3.8. Conservation Practices (CP)

This parameter aims to assess the degree of application of conservation practices on each farm.

It is composed of three indicators:

- Soil conservation practices (CsP): erosion control methods, fertility conservation;
- Water conservation practices (CwP): water body protection, water collection, use of hydric balance methods, water analysis, presence of contaminants;
- Biodiversity conservation practices (CbP): reforestation, natural area preservation, introduction of autochthonous species, introduction of beneficial plants, habitat protection or enrichment, germplasm banks.

Also in this case, the single indicators were calculated through semi-structured interviews, as further detailed in paragraph 1.1.7 (Supplementary material).

### 2.3.9. Perception, Awareness, and Knowledge (PAK)

This qualitative parameter aims to investigate the degree of environmental awareness, knowledge, and conceptual clarity on the role and importance of agrobiodiversity expressed by farmers. These factors are also assessed in their intersection with the perception of the territory and with the choice to act toward its preservation. Measuring this parameter required extensive interaction with farmers through semi-structured interviews as a starting point for in-depth discussion.

### 2.3.10. Action Capacity (AC)

This parameter aims to measure social, organizational, political, economic, and logistic external factors impacting the farmer's capacity to preserve or enrich agrobiodiversity.

Four indicators are considered:

TABLE 2 Values of the ten calculated criteria and of the final MAS.

| Farm | CMESL | EEC | EIC | DEC | DIC | LU | aMP | CP | PAK | AC | MAS value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Le Terre del Fiume | 4.67 | 10 | 10 | 5 | 6 | 4 | 8 | 9.33 | 10 | 7 | 7.4 |
| Ca' Battistini | 7 | 10 | 10 | 9 | 9 | 6 | 8.5 | 7.33 | 10 | 7.25 | 8.4 |
| Arvaia | 2 | 10 | 10 | 8 | 7 | 2 | 7.5 | 9 | 10 | 8.25 | 7.4 |

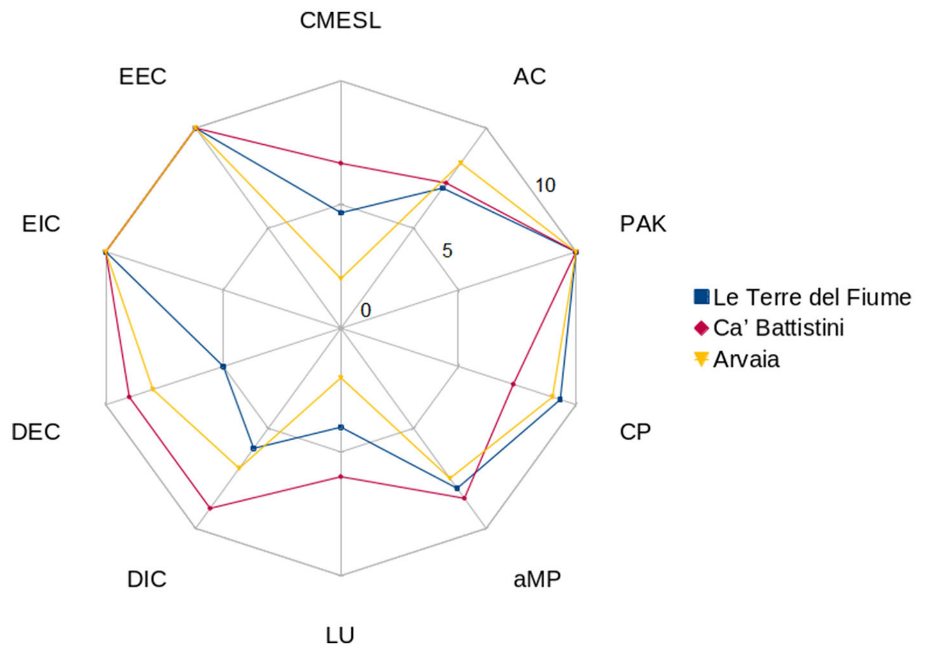


FIGURE 4
Values of the ten calculated criteria.

- Economic and Financial Capacity (EfC): economic resources, access to credit, and access to institutional support programs;
- Logistic Capacity (LC): availability of labor, tools, plant resources, access to transportation means, and infrastructure;
- Management Capacity (MC): relationships with networks and associations, alliances with the community, relationships with institutions, access to information, and planning tools;
- Technological and Technical Capacity (TTC): access to agroecological technical assistance and access to institutional programs that support the preservation and management of agrobiodiversity.

The single indicators were calculated through semi-structured interviews, as further detailed in paragraph 1.1.7 (Supplementary material).

## 2.4. Calculation of MAS value

The values of the single criteria were normalized using the tables proposed by León-Sicard (2021). The final value of the index was obtained by averaging the values of the ten criteria, as in paragraph 1.2 (Supplementary material). An overview of the calculated values is available in Table 2 and Figure 4.

## 3. Results and discussion

The CMESL value has been observed to be deeply linked to the territorial context of each farm (Figure 5). The peri-urban area surrounding Le Terre del Fiume (4.67), in which agricultural areas are mixed with residential zones, justifies the value of AFrBw (3). Forest patches are highly fragmented (AFrBw = 3) and river bodies (Bacchiglione river and canals) are close to farm boundaries (DBw = 8). A similar territorial context characterizes Arvaia (2), located in an area where extensive crops and orchards coexist with industrial areas and an abandoned sand mine. Landscape structures considered in DFr (3) mainly consist of hedgerows, small forests, and grass patches in interstitial areas, only covering 13% of AI (AFrBw = 0). The bigger water bodies (Reno and Lavino rivers) are outside the AI buffer, which only includes smaller canals (DBw = 3). The situation dramatically changes in Ca' Battistini (7): over 75% of AI is constituted by forests and grasslands, with a

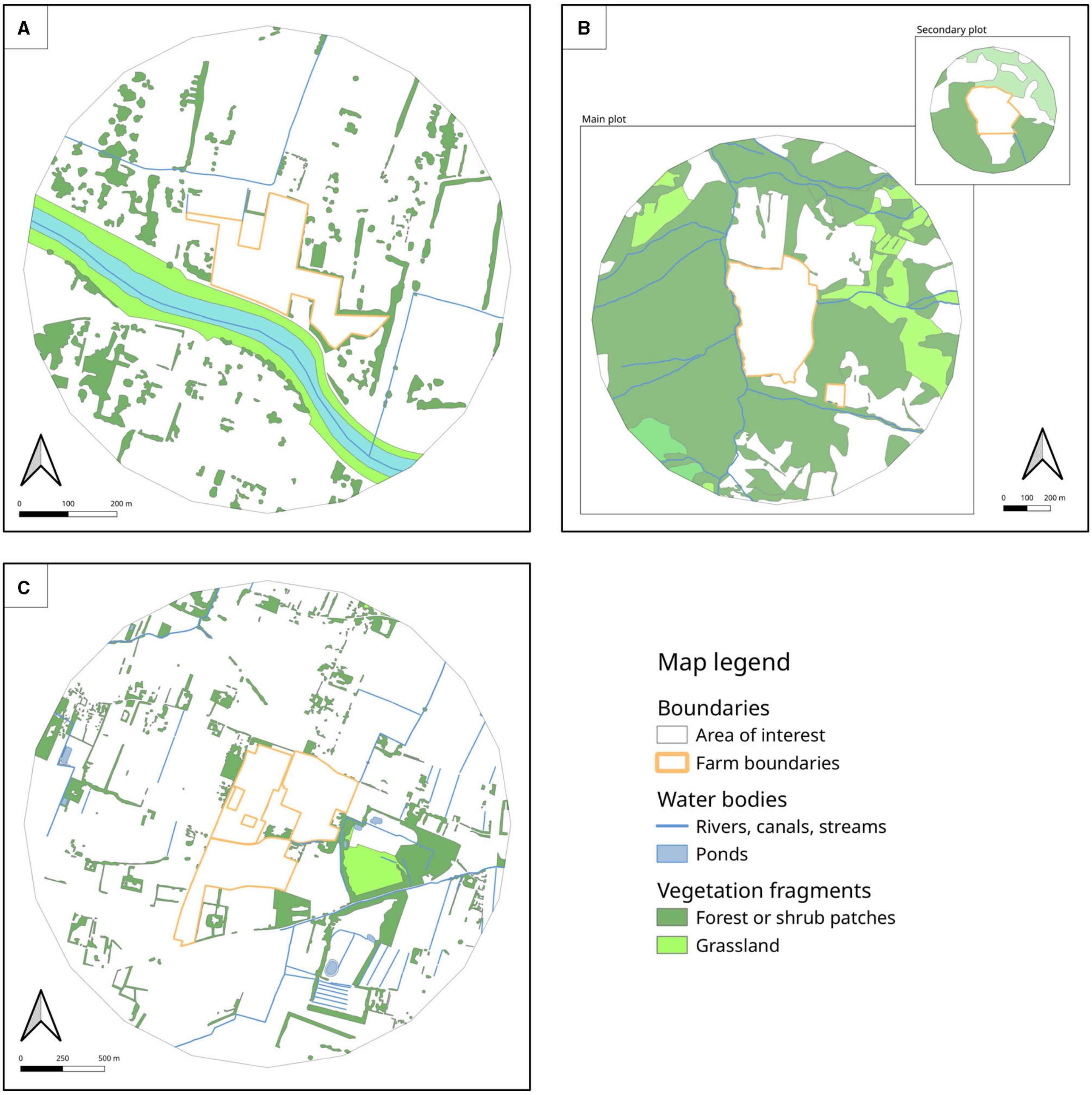


FIGURE 5
CMESL: vegetation fragments and water bodies inside the Area of Influence of the selected case studies. Le Terre del Fiume is represented in **(A)**, Ca' Battistini in **(B)**, and Arvaia in **(C)**.

positive influence on AFrBw (8) and DFr (6). The farm borders the Samoggia stream and is surrounded by several canals (DBw = 6).

If CMESL values are highly impacted by external territorial factors, criteria dealing with internal and external connectors (EEC, EIC, DEC, DIC) start to show the role of farmers' agency in co-creating the landscape structure (Figure 6). Artificial fences are rare on all the studied farms, and green connectors are generally used. In Le Terre del Fiume, the conservation of pre-existent hedgerows and tree rows is complemented by new plantations of such connectors (EEC = 10; EIC = 10). In addition, DEC (5) and DIC (6) benefit from the presence of forest areas and connectors composed of purposefully chosen plant species planted to increase in-farm connectivity. Similarly, Arvaia has also carried out intentional plantings of new hedgerows and tree rows. Almost 90% of the boundaries result to be constituted by such connectors, that have been placed also among most parcels (EEC = 10; EIC = 10). The preservation and management of *Vite maritata* plantings (a traditional association of vine and maple, with the latter acting as a living trellising structure for the former) interspersed with other tree species also impact the values of DEC (8) and DIC (7). In Le Terre del Fiume and Arvaia, a stark contrast is present between newly planted connectors, showing higher stratification

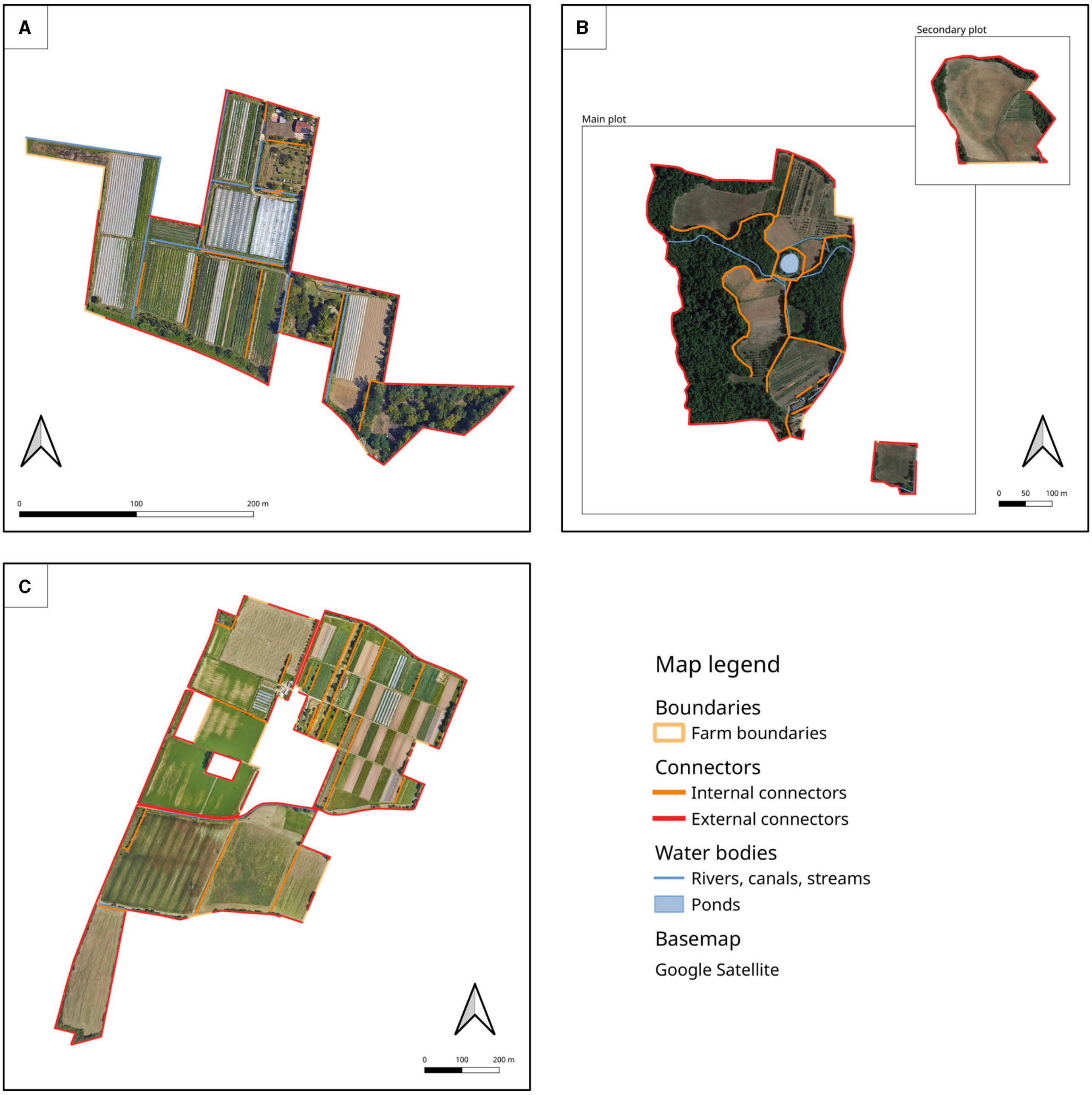


FIGURE 6
EIC and EEC: internal and external connectors in the selected case studies. Le Terre del Fiume is represented in **(A)**, Ca' Battistini in **(B)**, and Arvaia in **(C)**.

and richness values, and street-side tree rows managed by other actors. Forests and hedgerows cover almost 90% of Ca' Battistini boundaries, also connecting different parts of the farm (EEC = 10; EIC = 10); richness and stratification parameters benefit from the high diversity of species present in the local oak forests (DEC = 9; DIC = 9).

Different degrees of intentional planting and preservation of vegetation covers with a high ecological value were observed in all the considered farms, impacting LU values (Figure 7). Such covers are present in over 40% of the area of Le Terre del Fiume (LU = 4) and over 50% of Ca' Battistini (LU = 6), while in Arvaia, this percentage is estimated at 23% (LU = 2). A gradient is present inside this farm, the biggest among the considered case studies: while the northern part presents a complex matrix of different crops and connectors, the southern one is characterized by larger parcels dominated by extensive crops.

In the context of aMP, all the studied farms source plant materials from both seed self-production and external nurseries. Le Terre del Fiume (aMP = 8) tries to support actors focusing on varieties adapted to organic farming, while both Ca' Battistini (aMP = 8.5) and Arvaia (aMP = 7.5) also grow evolutionary populations (Ceccarelli et al., 2022) as part of a multi-year effort


FIGURE 7
LU: land use in the selected case studies. Le Terre del Fiume is represented in **(A)**, Ca' Battistini in **(B)**, and Arvaia in **(C)**.

aiming to select locally adapted populations. All the considered case studies widely use rotations and complementary practices. Weeds are controlled through mulching or mechanical intervention. As regards pest management, products allowed in organic farming are used in Le Terre del Fiume, while the other two farms tend to reduce their use in emergencies. Arvaia mainly focuses on preventive measures (repellents, physical barriers, removal of pests during the early stages of infestation), while Ca' Battistini benefits from a high degree of biological control due to the vast presence of ecological infrastructure in and around the farm. Experiments in the production of organic fertilizers and microbial preparations are carried out to a different degree in all the considered case studies, also in collaboration with university researchers. A high degree of interest in experimenting with novel practices was generally observed.

High CP values were observed in all the considered farms, characterized by the fundamental idea of "doing agriculture backed by an idea" (i.e., ecological restoration and small-scale food production) expressed by one of the interviewees. Erosion is kept under control by the maintenance of permanent grass covers, anticipating sowing, extensive mulching, and the creation of canals; water bodies are adequately protected. Different degrees of soil and water analysis frequencies were observed depending on the farm: water is not analyzed or rarely analyzed in Ca' Battistini (CP = 7.33), as most of the crops are not irrigated, and Arvaia (CP = 9), as it comes from the public supply network, while the presence of polluted canals leads to frequent analyses and measures to prevent contamination in Le Terre del Fiume (CP = 9.33). Both Le Terre del Fiume and Arvaia work toward the preservation of fallow land and the intentional creation of ecological infrastructures with the explicit goal of creating habitats for arthropods, reptiles, birds, and amphibians. On the other hand, the landscape surrounding Ca' Battistini strongly affects its conservation practices: being the zone mostly comprised of forests and wild areas, less time has to be devoted to the intentional creation of new habitats if compared to the two peri-urban farms, while effort is given to preserving existing ecological infrastructures. All the farms have some degree of access to germplasm banks. Le Terre del Fiume manages a small seed bank on site, stressing how food sovereignty starts locally through the interaction of communities and networks. Ca' Battistini farmers are actively involved in peasant networks working to create shared germplasm banks, which are considered necessary to reach food sovereignty. In Arvaia, access to germplasm banks is mainly related to using evolutionary populations and collaborations with the university.

In all the considered case studies, the evaluation of PAK was linked with the cultural background of farmers and their relationship with the ecosystem, stemming from their awareness regarding conservation, their reoccurring academic training in agricultural or natural sciences, their reflection and further investigation on ways to make their production processes more ecologically and socially sound. In Le Terre del Fiume (PAK = 10), the farmer once again highlighted how agriculture should be considered a way of practicing conservation ecology without idealizing traditional agriculture. The academic education in agricultural sciences (whose mindset and framework are partially criticized) is complemented by an ongoing collaboration with other farmers, university professors, and technicians in the context of horizontal experiential schooling. In Ca' Battistini (PAK = 10), farmers stressed how the preservation of biodiversity is fundamental on an ecological, social, and political level and has represented a key factor in their choice of doing agriculture. High value is conferred to their academic background (MSc and PhD levels in Agricultural Sciences and Forest Ecology) and experience in research institutes. It is noted how the first years after the farm's foundation have been devoted to making it economically viable and how further work on ecological aspects has only started once such bases were established. Arvaia (PAK = 10) interviewees also highlighted how the recovery of traditional rural landscape structures had represented a key point since the beginning: creating and maintaining ecological infrastructures are conceived as collective care for a common. Keeping the farm open to citizens willing to visit it for leisure or communal activities is also linked to this mindset. Academic backgrounds vary among members: some have university degrees in agricultural sciences, while others attended shorter educational classes. Regular visits to other farms are carried out to exchange knowledge. Additionally, a few members of the CSA hold teaching positions in the context of a Master of Philosophy at the University of Bologna.

Analyzing AC, different outlooks on the availability of funding are observed. Le Terre del Fiume (AC = 7) and Ca' Battistini (AC = 7.25) deem institutional support programs as almost non-existent, as the requisites for accessing the few available public programs are usually targeted to bigger farms, while Arvaia (AC = 8.25) manages to get further financing by participating in regional and university programs. Unlike the other two family-run farms in the study, Arvaia determines its budget according to the amount of funds collected during the yearly "auction," in which each member finances a share of the cooperative through an open donation. In Ca' Battistini, it is emphasized how the earnings that support on-site research on agroecological practices come from the sale of transformed products on one side and voluntary work on the other. Limited financial resources also affect the ability to hire an adequate number of co-workers. A similar set of problems is also expressed by Arvaia interviewees. The availability of means of transportation, tools, and plant material is generally deemed sufficient; the possibility of creating a collectively managed plant nursery has been investigated by Ca' Battistini in the past but has been abandoned due to stringent regulatory requisites. A common trait among the studied farms is a negative evaluation of the relationship with institutions. Ca' Battistini emphasizes that there is almost no interlocution or access to programs for farms located outside protected areas, and the few existing initiatives are more focused on defining and protecting typical products than preserving biodiversity. Arvaia views such relationship as deeply ambiguous. On the one hand, the municipality benefits from the existence of the CSA in creating its public image. On the other hand, it does not offer any real support. The situation changes if the capacity to form alliances with local actors is considered. Le Terre del Fiume considers local communities to be necessary to put together diverse abilities and aptitudes, working in the direction of fostering small-scale agriculture as a tool to reconcile ecological conservation and the creation of local economies. Ca' Battistini farmers are among the founders of Campi Aperti (an association mainly dealing with food sovereignty) and are involved in provincial and regional networks working on such topics. Arvaia has also participated in such networks since its foundation. A huge impact of the social context is seen in the availability of agroecological technical assistance, seen as lacking in Le Terre del Fiume and sufficient in the other two case studies. A few decades devoted to community building in the area surrounding Bologna are hypothesized to impact such a difference.

Averaging the values of 10 considered indicators, the values of MAS were calculated to be 8.4 for Ca' Battistini and 7.4 for Le Terre del Fiume and Arvaia.

## 4. Conclusions

A few possible changes and integrations to the original index may be considered in view of further applications to European agroecosystems. A bottleneck was identified in the degree of data availability and quality describing the distribution and nature of green infrastructures in the area of influence. This was especially clear in peri-urban areas, where such elements often cover areas too small to be represented at the scale commonly used in LULC maps. At the same time, manual digitization, as carried out in this study, may be considered too burdensome in other contexts. Alternative mapping paths may be considered depending on future research goals.

On the one hand, a participatory approach could involve a broader engagement of local actors. On the other hand, a technical approach may map green infrastructures by means of remote sensing, following protocols already present in the literature (Tansey et al., 2009; Hellesen and Matikainen, 2013; Betbeder et al., 2014; O'Connell et al., 2015; Scholefield et al., 2016). The extreme fragmentation of forest patches (as considered in DFr) in peri-urban areas may suggest weighting their distances from the farm centroid on their area. Further modifications should also consider the latest developments in the structure of the index (Quintero et al., 2022a).

As MAS was originally conceived to be applied to Colombian farms, restructuring the index to make it more suitable for the European agricultural context represents another potential avenue of development that was only partially tackled in this study. This adaptation would also allow us to mitigate excessive influence of different contexts on farm comparison, preventing the farmer's agency from becoming obscured. It may be considered how the index could be of greater use in diachronically comparing the same farm to focus on its developments through time or in comparing farms located in similar contexts. The relevance of both the surrounding landscape and social factors is already evident in the present study, which explores both the geographical dimension (with farms located in peri-urban and rural areas) and the social dimension (with case studies in areas with different degrees of associative, grassroots, or institutional support). Further modifications may involve different scaling of species richness weighting factors (considering local floristic assemblages). Artificial divisors are used less in Europe than in Colombia, so their importance in criteria such as EEC and EIC may also be reconsidered. At the same time, considering its correlation with species richness, hedgerows area may be considered a further factor of interest in DEC and DIC (Sitzia et al., 2013).

As León-Sicard (2021) suggested, the area of influence may be better identified in pre-existing geographical features. Considering the analyzed case studies, these features may have been identified in the surrounding rural park (Le Terre del Fiume), in the area among the rivers Reno and Lavino and road infrastructures (already used in previous studies on Arvaia), and in the hydrographic basin (Ca' Battistini).

Water bodies reported to be highly polluted by farmers were filtered out of the analysis. An indicator dealing with the presence of elements of ecological risk may be useful in future studies to further emphasize their presence. At the same time, the presence of water bodies inside farms may be further valorized by a dedicated indicator: in all the case studies, canals, streams, ponds, and wetlands were also preserved for habitat creation.

All these potential changes could be easily integrated into the GIS workflow proposed in the present article.

Applying the index to three Italian farms allowed us to consider factors that are often neglected when analyzing rural areas. We were able to place these factors side by side—in their respective integration and interaction—with elements already taken into consideration by landscape ecology. Among those, the creation and conservation of ecological infrastructures, the choice of sustainable farming techniques and the symbolic, cultural and political milieus backing farmers' daily actions and influences on the territory. By focusing on the interaction of human factors with the ecosystem, the authors justify their decision to aggregate the selected metrics around the agricultural management unit (in our case, the farm or *Community-Supported Agriculture* project). This approach bridges landscape ecology with approaches and standpoints emerging from the debate on agroecology, which encompasses practice, a scientific framework, and a movement. The primary objective of this approach is to highlight the decision-making and mindset of farmers in their interaction with the landscape (Cleves-Leguízamo et al., 2017; León-Sicard et al., 2018; León-Sicard, 2021).

Focusing on the participative dimension, this index could be used as a tool for the activation of bottom-up territorial processes. The recognition of the existence and action of farming communities may thus finally make its entrance into territorial planning, also through the creation of cartographic outputs taking into consideration agricultural management units as active parts of the landscape. This may lead to the creation of agroecosystem maps on a regional or national level, as suggested by the authors and, to some extent, already tested in Colombia (León-Sicard et al., 2015). In such cases, being the scale smaller, aggregates of farms with similar characteristics may be identified and described collectively, with a possibility of sampling representative ones.

Previous studies carried out in South America (Vargas and León-Sicard, 2013; Cepeda-Valencia et al., 2014; Cleves-Leguízamo and Jarma-Orozco, 2014; Daza-Cruz, 2020) had the goal of investigating the correlation between MAS and a number of variables (pollination services, human appropriation of net primary production, climate change resilience, and biological pest control). The validation of the index for further variables may represent a possible line of research.

On a farm level, the index can provide an analytical framework, possibly allowing farmers to understand how to improve ecological infrastructure (León-Sicard, 2021). Diachronic analyses of the evolution of territories after agroecological farm settlements are also enabled (Pinzón Cortés, 2014).

The structure of the index itself requires strong interdisciplinary integration (agricultural and forest sciences, landscape ecology, and sociology are, at the very least, involved), and an active debate among these disciplines will be desirable and necessary in view of future studies.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

VR: Conceptualization, Data curation, Investigation, Methodology, Software, Writing—original draft. DC:

Conceptualization, Supervision, Writing—original draft. MD: Conceptualization, Supervision, Writing—review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1259419/full#supplementary-material

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# Open farmland is a hotspot of soil fauna community around facility farmland during a cold wave event

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In the future, the frequency, duration, and intensity of extreme weather may increase, thus posing a threat to soil biodiversity in farmlands, particularly in agricultural production bases. However, little is known about the effect of cold wave events on the soil fauna community compared with other extreme weathers. Laboratory experiments fail to capture the complicated field environment of cold wave events. We investigated soil fauna communities in facility farmland (strawberry) and open farmland (green cabbage) during a cold wave event in Ningbo City, southeastern China. The results showed that the taxonomic richness of the total soil fauna community in facility farmland was significantly lower than that in open farmland, but the difference in abundance was not significant. The taxonomic richness and body size of soil mites and collembolan communities in facility farmland were significantly lower than those in the open farmland. Obvious differences in abundance, mean body length, mean body width, and ratio of body width to body length of Scheloribatidae, Galumnidae, Onychiuridae, Entomobryidae, and Enchytraeidae were detected between facility farmland and open farmland. The results of this study showed that the taxonomic richness, abundance, and body size of the soil fauna community in open farmland were significantly higher than those in facility farmland during a cold wave event. We suggested that the open farmland could be a "refuge" and "hot spot" of soil fauna community during the cold wave events.

KEYWORDS
**soil mite, soil Collembola, body length, body width, facility farmland, open farmland**

## 1. Introduction

Current and future global change is one of the most serious challenges that ecosystems and biodiversities face. Global warming is causing drastic increase in the frequency, intensity, and duration of various abiotic stresses, such as extremely high temperatures, drought, and cold waves (Organization WWM, 2020). These stresses negatively affect agricultural ecosystems and soil biodiversity (Rivero et al., 2021).

Most studies performing controlled experiments have focused on the effects of high temperature and drought on tolerance (Xie et al., 2023), reproduction

(Organization WWM, 2020), biomass (Thakur et al., 2023), and vertical distribution (Dooremalen et al., 2012) of soil fauna populations and communities. However, few studies have focused on the effects of cold waves on soil fauna diversity, particularly through field experiments.

Owing to global warming, the increased frequency of soil freeze-thaw cycles featuring low temperatures have reduced the reproductive success of the soil nematode population (*Scottnema lindsayae*) in Taylor Valley, Antarctica (Knox et al., 2016). In fact, some soil invertebrates exhibit strong cold hardiness in the field. In the continental areas of Northeast Asia, some insects overwinter in a supercooled state and survive at temperatures ranging from −12 to −35°C, and earthworms can withstand temperatures ranging from −5 to −45°C in a frozen state (Berman and Leirikh, 2018). However, some soil invertebrates, such as termites (*Reticulitermes flavipes*), are not cold-tolerant. Termites likely rely on burrowing into the deep soil layers to avoid extremely low temperatures (Clarke et al., 2013).

Body size is a central functional trait in the community ecology of soil fauna (Andriuzzi and Wall, 2018). The temperature–size rule states that the adult body size of most ectotherms decreases with warming (Atkinson, 1994; Pequeno et al., 2018). Climatic changes may contribute to extreme body size diversity in terrestrial invertebrates (Karagkouni et al., 2016). Climate warming directly and indirectly results in body size changes in soil fauna (Frelich et al., 2012). For example, a warmer climate leads to higher litter quality, which indirectly promotes the replacement of small-bodied detritivores with large-bodied exotic earthworms (Frelich et al., 2012). Fluctuation around a mean temperature of 12°C affected nematode body size to a greater extent than when the average temperature was constant (Cedergreen et al., 2016). Although a few studies have focused on the relationship between temperature and the body size of soil fauna, the effects of cold waves featuring low temperatures on the body size of soil fauna communities is poorly understood.

China has experienced an unprecedented frequency of cold events (Chang and Xiao, 2023). Cold air influences high and low latitudinal areas (Abdillah et al., 2021). An extreme high–temperature event in the summer of 2022 had a negative effect on soil fauna diversity in agricultural ecosystems in Ningbo City, southeast China (Gao et al., 2023). Subsequently, a cold wave event affected the same area in January 2023. Cold wave events are often accompanied by extremely low temperatures and rapid temperature drops (Chang and Xiao, 2023), resulting in more frequent exposure to extremely low temperatures and sudden temperature fluctuations for the soil fauna community.

China is the largest producer of greenhouse vegetables (facility farmlands) worldwide (Yuan et al., 2022). Sunlight, temperature, and humidity inside the facility farmland are controlled for the production of high-quality vegetables, fruits, and crops throughout the year; thus, the microclimate inside the facility is significantly different from that of an open farmland (Liu et al., 2021). Therefore, we hypothesized that (1) the richness and abundance of the soil fauna community in the facility farmland was higher than that in the open farmland during the cold wave event, as it was protected from cold air and strong temperature fluctuations, and (2) the body size of the soil fauna community in the facility farmland was smaller than that in the open farmland during cold wave events based on the temperature–size rule.

To identify the composition and body size of the soil fauna community during the cold wave event of January 2023, we investigated the soil fauna community in facility farmland and open farmland in Ningbo, southeastern China. We expected that the facility farmland would be a refuge and shelter for the soil fauna community during the cold wave event. Therefore, we assumed that a “hot spot” of the soil fauna community would be observed in the facility farmland.

## 2. Materials and methods

### 2.1. Study area

The study area is located in the Ningbo city (28°51′-30°33′ N, 120°55′-122°16′ E) in Zhejiang Province, southeastern China. Ningbo is an important port city on the southeast coast of China and an economic center in the southern wing of the Yangtze River Delta. At the end of 2022, the permanent resident population of Ningbo was 9.618 million, and the proportion of the urban population to the total population (i.e., urbanization rate) was 78.9%. Ningbo has a dominant subtropical monsoon climate. The mean annual temperature is 16.4°C. The highest temperature in July is 28.0°C, and the lowest in January is 5.4°C. The mean annual precipitation is approximately 1,480 mm, and rainfall in May–September accounts for 60% of the annual precipitation. The plain area of Ningbo accounts for 40.3% of its land area (http://www.ningbo.gov.cn/col/col1229099787/index.html).

During the summer of 2022 (June–August), Ningbo reported an extremely high temperature event (Ningbo Climate Center, 2022; Gao et al., 2023). Subsequently, Ningbo was affected by a strong cold wave in January 2023 (winter). The temperature in Ningbo dropped from 17.5°C (January 13) to 1.7°C (January 15) and −5.3°C (January 23) (Ningbo Climate Center, 2023) (Figure 1). During the cold wave period, some crops, vegetables, and fruits in open farmlands exhibited cold-related damage (Ningbo Climate Center, 2023). However, plants grown in facility farmlands were not affected by the strong cold wave event because of the relatively warm and stable temperatures inside the facility (field survey data).

### 2.2. Experimental design and sample collection

The study was conducted at the Feihong Farm (29.99 N, 121.56 E) located in Zhenhai District, Ningbo. Feihong Farm was established in 2006 and covers an area of 46.66 $hm^2$. There were 33.33 $hm^2$ facility farmland structures in steel sheds. In 2007, the vegetable output of Feihong Farm was more than 1500 tons, making it an important “vegetable basket” for Ningbo. In recent years, the main planting mode in facility farmlands has been tomato/strawberry rotation. Simultaneously, farmers also grow various vegetables in small areas of open farmlands adjacent to facility farmlands. The main planting mode in open farmland was a green cabbage/lettuce/carrot/onion rotation, which depends on the preferences of workers and farmers. These vegetables were

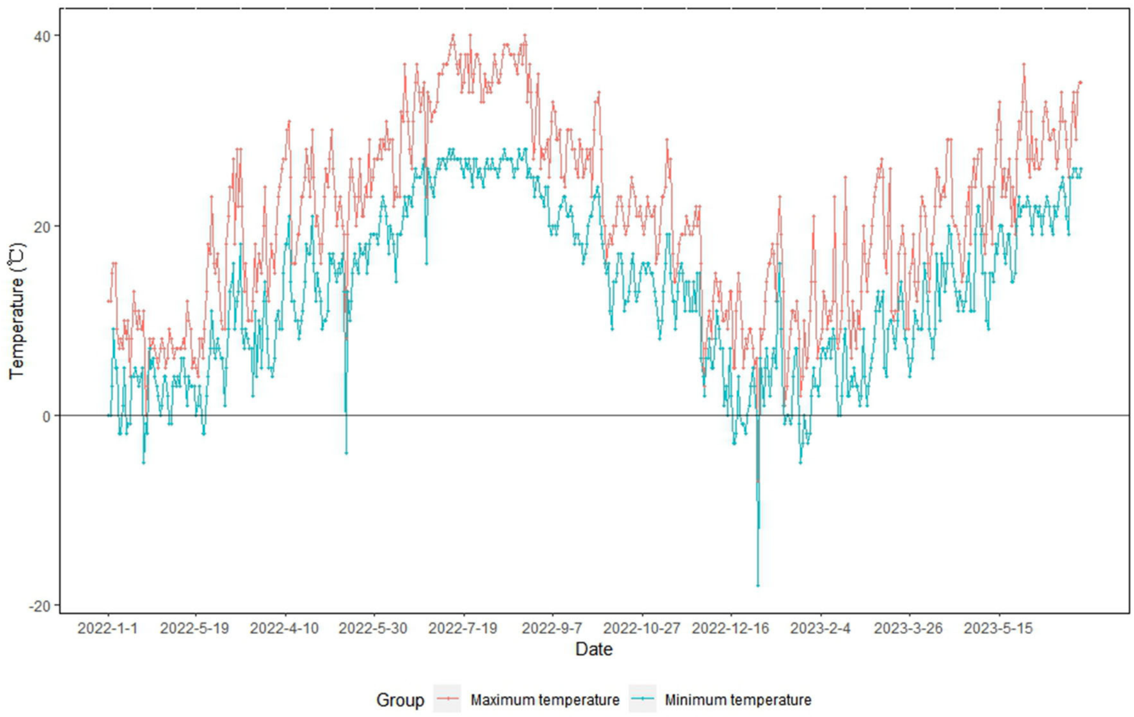


FIGURE 1
Maximum and minimum temperatures in Ningbo from 1 January 2022 to 30 June 2023.

mainly used as food resources for workers in Feihong Farm and were not sold. When this experiment was conducted, strawberry and green cabbage were planted in the facility and open farmlands, respectively (Figure 2). The soil types of both farmlands were red soil (Argi-Udic Ferrosols under the Chinese Soil Taxonomy and Adults under the USDA soil classification system) (Gong et al., 2007). The facility farmland was irrigated using drip irrigation tubes. There was no irrigation system in the open farmland, and soil water mainly originated from rainfall and casual manual watering from canals.

Three plots (covering areas of 3×3 $m^2$ and set 50 m apart) were set up as three replicates in both the facility and open farmlands. The facility farmland covered an area of 4,320 $m^2$ with a width of 60 m and length of 72 m. For open farmland, at least one canal with a width of 2 m and a height of 1.5 m separated each plot. Three cylindrical soil cores (7-cm diameter, 15-cm depth) were randomly collected from each of the six plots. The samples were collected on January 21, 2023 (winter). In total, 18 samples (three replicates in each plot × three plots for each type of farmland × two types of farmlands) were collected.

## 2.3. Soil fauna extraction and taxon identification

A Berlese–Tullgren funnel was used to extract the soil fauna (Straalen and Rijninks, 1982). The soil samples were placed on a sieve (2 mm-meshed diameter) above a funnel and exposed to ambient temperature for 10 days. Soil fauna were collected in plastic bottles with 95% alcohol and preserved in a refrigerator at −20°C.

All extracted soil fauna were picked out for further study. The soil fauna were calculated and identified under a stereo-microscope (Olympus Lympus SZX16 and Nikon Eclipse 80i) according to past studies (Bellinger et al., 1996–2012; Yin et al., 1998; Krantz and Walter, 2009). Collembola, oribatids, and Enchytraeidae were identified at the family level, whereas other soil fauna were identified at the order level and labeled as different taxa. Body length (μm) and body width (μm) were measured using a stereo-microscope (Olympus SZX16) and Image View software (Moretti et al., 2017). The body width to body length (body ratio) was calculated. Soil water content was measured gravimetrically by drying the soil samples at 105°C for 48 h. Soil water content was described as a percentage of dry weight (Lu, 2000).

## 2.4. Data analysis

Taxonomic richness (taxonomic number) and abundance (individual number) were used to describe the diversity of the soil fauna community. Mean body length (mm), mean body width (mm), and body ratio were used to describe the body size features of the soil fauna community.

Community dominance degree was calculated to reveal the dominance of soil fauna taxon in abundance:> = 10% of the total abundance of individuals represented the dominant taxon (+++); 1–10% the common taxon (++); and < 1% was rare taxon (+) (Wei et al., 2022).

Differences in richness, abundance, mean body length, mean body width, body ratio, and soil water content between the facility and open farmlands were examined using a nonparametric

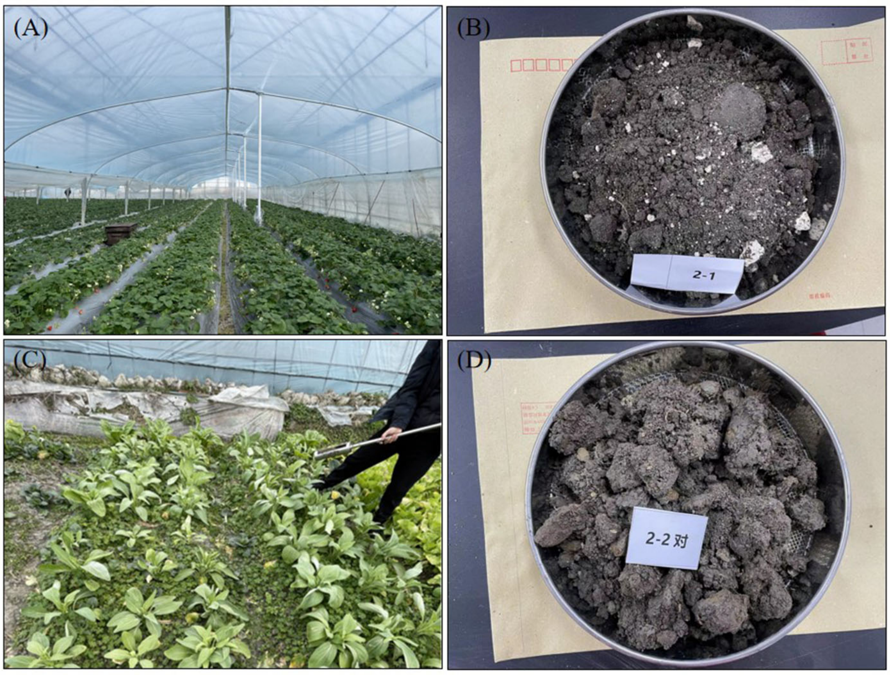


FIGURE 2
Experimental plots and soil core samples from facility **(A, B)** and open farmlands **(C, D)**.

Mann-Whitney *U* test. A linear mixed effect model was used to evaluate the effects of soil water content on richness, abundance, mean body length, mean body width, and body ratio of soil fauna and abundance of each taxon using the function "lmer" in the "lme4" package (Bates et al., 2015). The fixed effect was soil water content and the random effect was the two types of farmlands. Principal component analysis (PCA) was performed to evaluate the associations among richness, abundance, mean body length, mean body width, and body ratio of soil fauna using the functions "prcomp" and "fviz_pca_biplot" in the "tidyverse" (Wickham et al., 2019) and "factoextra" (Kassambara and Mundt, 2020) packages. All calculations were performed in the R 4.2.2 (R Core Team, 2022).

# 3. Results

## 3.1. Community composition and abundance

In total, eight taxa were recorded in the facility farmland, whereas 19 taxa were collected from the open farmland. Isotomidae and Mesostigmata sp.1 were the dominant abundant taxa in the facility farmland. Mesostigmata sp.1 was the dominant taxon in the open farmland (Table 1). The density of the total soil fauna community was 3,637.83 ± 2,268.58 individuals/m$^2$ in the facility farmland, and 4,850.44 ± 2,083.56 individuals/m$^2$ in the open farmland (Table 1).

The taxonomic richness of the total soil fauna community in the facility farmland was significantly lower than that in the open farmland ($p < 0.01$) (Figure 3A). Soil fauna abundance did not differ significantly between the facility and open farmlands (Figure 3B).

The taxonomic richness of the soil mites ($p < 0.01$; Figure 4A) and collembolan ($p < 0.01$; Figure 4C) communities in the facility farmland was significantly lower than that in the open farmland. However, no significant difference was detected in the abundance of soil mites and collembolan communities between the two farmlands (Figures 4B, D).

The abundances of Scheloribatidae ($p < 0.01$; Figure 5A), Galumnidae ($p < 0.05$; Figure 5B), Onychiuridae ($p < 0.01$; Figure 5C), Entomobryidae ($p < 0.05$; Figure 5D), and Enchytraeidae ($p < 0.05$; Figure 5E) in the facility farmland were significantly lower than those in the open farmland.

## 3.2. Mean body length, mean body width, and body ratio

Mean body length, mean body width, and body ratio of the total soil fauna community in the facility and open farmlands was 918.83 ± 989.72 mm and 1,107.07 ± 296.91 mm, 213.34 ± 145.26 mm and 296.77 ± 74.61 mm, 0.23 ± 0.09 and 0.27 ± 0.1, respectively. There was no significant difference in mean body length, mean body width, or body ratio of the total soil fauna communities between the facility and open farmlands (Figures 6A–C).

Except the mites community (Figure 7A), mean body lengths of the collembolan community ($p < 0.01$; Figure 7B), Scheloribatidae ($p < 0.01$; Figure 7C), Galumnidae ($p < 0.05$; Figure 7D), Onychiuridae ($p < 0.01$; Figure 7E), Entomobryidae ($p < 0.05$; Figure 7F), and Enchytraeidae ($p < 0.05$; Figure 7G) were significantly difference between facility and open farmlands.

Mean body width of the soil mite community ($p < 0.05$; Figure 8A), collembolan community ($p < 0.05$; Figure 8B), Scheloribatidae ($p < 0.01$; Figure 8C), Galumnidae ($p < 0.05$;

TABLE 1 Composition and abundance of soil fauna communities in facility and open farmlands during the cold wave event.

| Taxon | Facility farmland | | | Open farmland | | |
|---|---|---|---|---|---|---|
| | Abundance | Percentage (%) | | Abundance | Percentage (%) | |
| Oppiidae | 1 | 0.79 (+) | | 3 | 1.79 (++) | |
| Scheloribatidae | | | | 15 | 8.93 (++) | |
| Galumnidae | | | | 13 | 7.74 (++) | |
| Eremobelbidae | | | | 2 | 1.19 (++) | |
| Mesostigmata sp.2 | 1 | 0.79 (+) | | 1 | 0.6 (+) | |
| Mesostigmata sp.1 | 39 | 30.95 (+ + +) | | 50 | 29.76 (+ + +) | |
| Mesostigmata sp.3 | | | | 7 | 4.17 (++) | |
| Mesostigmata sp.4 | | | | 2 | 1.19 (++) | |
| Isotomidae | 69 | 54.76 (+ + +) | | 5 | 2.98 (++) | |
| Hypogastruridae | | | | 4 | 2.38 (++) | |
| Onychiuridae | | | | 15 | 8.93 (++) | |
| Entomobryidae | | | | 13 | 7.74 (++) | |
| Neanuridae | | | | 5 | 2.98 (++) | |
| Staphylinidae | 3 | 2.38 (++) | | | | |
| Diptera (larva) | 9 | 7.14 (++) | | 2 | 1.19 (++) | |
| Spider | 3 | 2.38 (++) | | 2 | 1.19 (++) | |
| Enchytraeidae | 1 | 0.79 (+) | | 21 | 12.5 (+ + +) | |
| Microcoryphia | | | | 3 | 1.79 (++) | |
| Aphid | | | | 1 | 0.6 (+) | |
| Taxa | 8 | | | 19 | | |
| Abundance | 126 | | | 168 | | |
| Density (mean ± SD; ind/m$^2$) | 3,637.83 ± 2,268.58 | | | 4,850.44 ± 2,083.56 | | |

+ + +, ++, and + represent dominant, common, and rare taxa, respectively.

Figure 8D), Onychiuridae ($p < 0.01$; Figure 8E), Entomobryidae ($p < 0.05$; Figure 8F), and Enchytraeidae ($p < 0.05$; Figure 8G) were significantly different between the facility and open farmlands.

The body ratio of soil mite community ($p < 0.01$; Figure 9A), collembolan community ($p < 0.05$; Figure 9B), Scheloribatidae ($p < 0.01$; Figure 9C), Galumnidae ($p < 0.05$; Figure 9D), Onychiuridae ($p < 0.01$; Figure 9E), Entomobryidae ($p < 0.05$; Figure 9F), and Enchytraeidae ($p < 0.05$; Figure 9G) was significantly different between the two farmlands.

## 3.3. Effects of soil water content on taxonomic richness, abundance, body size, and taxon abundance

Mean soil water content was 28.49% and 27.90% in the facility farmland and open farmland, respectively, exhibiting no significant variation. The mean soil water content had no significant effect on taxonomic richness, abundance, mean body length, mean body width, and body ratio of the total soil fauna. Mean soil water content significantly affected abundance ($F = 9.94$, $p < 0.01$), mean body length ($F = 8.68$, $p < 0.01$), mean body width ($F = 9.65$, $p < 0.01$), and body ratio ($F = 10.22$, $p < 0.01$) of Mesostigmata sp.3, and body ratio of Staphylinidae ($F = 4.95$, $p < 0.05$) (Table 2).

The first two components, accounted for 72.7% of the cumulative variation. Significant correlations were identified between mean body length and mean body width, richness, and body ratio (Figure 10).

# 4. Discussion

## 4.1. Taxonomic richness and abundance of soil fauna community during the cold wave event

Contrary to the first hypothesis of this study, the richness and abundance of the soil fauna community in the facility farmland was lower than that in the open farmland after the cold wave event.

The taxonomic richness of the total soil fauna community was more than two-fold higher in the open farmland than in the facility farmland, which was a significant difference. The abundance of the total soil fauna community in the open farmland was one-third higher than that in the facility farmland, although the difference was not statistically significant. Previous studies in temperate regions

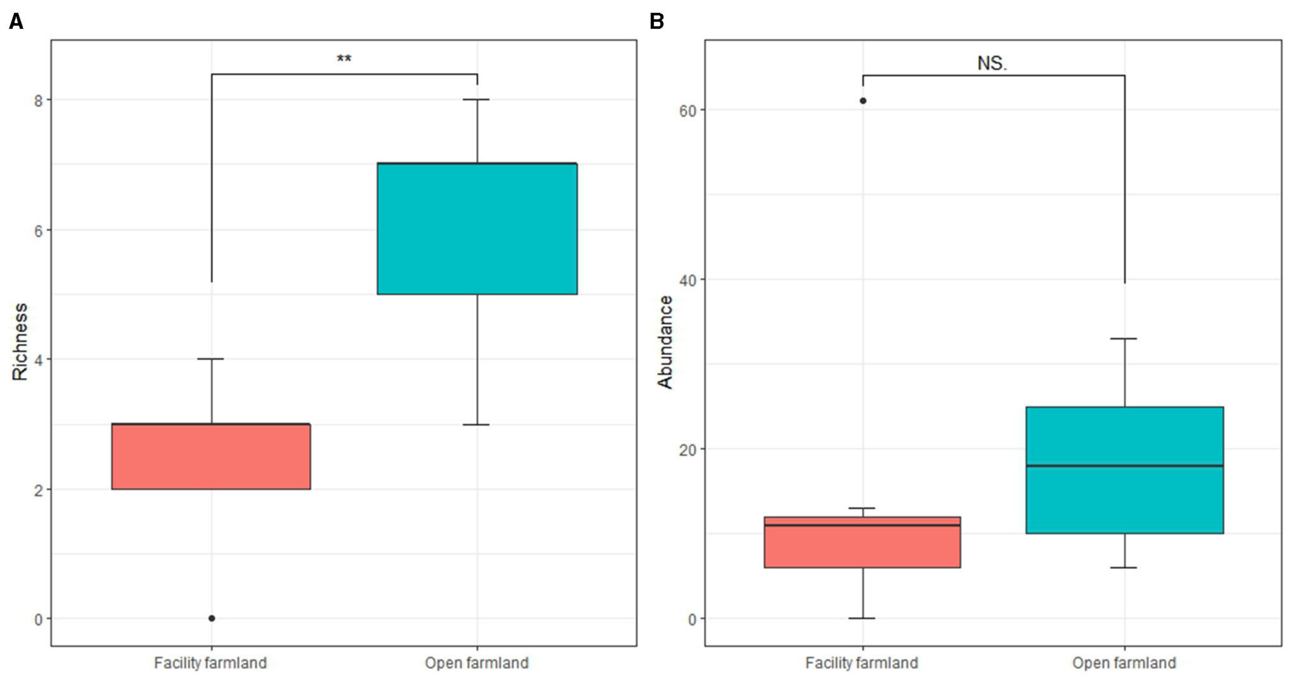


FIGURE 3
Taxonomic richness **(A)** and abundances **(B)** of total soil fauna communities in facility and open farmlands during the cold wave event. NS, not significant; $^{**}p < 0.01$.

have demonstrated that the richness, abundance, and biodiversity indices of soil fauna communities in facility farmlands were lower than those in open farmlands (Dong et al., 2008; Wang, 2008; Chen et al., 2019). This study exhibited a similar finding for richness in the subtropical region during the cold wave event but not for abundance. After continuous investigation of more than a year in the study areas, researchers reported that the daily maximum and daily minimum temperatures in facility farmlands that planted strawberry were higher by 5–10°C and 3–6°C, respectively, than that in open farmlands (Fu et al., 2011). In fact, the temperature was warmer by approximately 11°C in the facility farmland (20°C at 10 a.m., field measurement using a thermometer) than that in open farmland (8.5°C on average, https://m.tianqibag.com/ningbo2yuetianqi/). Furthermore, soil water content had no significant effect on the richness or abundance of the total soil fauna community in either farmland types during the experimental period (Figure 10). Therefore, we were unable to determine the impact of the cold wave event and sudden temperature drops on the differences in richness and abundance of the total soil fauna community between the facility and open farmlands. We speculate that overfertilization, over irrigation, pesticide application, and continuous monocropping in facility farmland might have contributed to this observed phenomenon, as these factors cause considerable soil degradation and soil-borne disease spread (Wan et al., 2023), and they may have contributed to the decreased soil fauna diversity (Jiang et al., 2019).

Soil mites and collembolan communities were dominant in both the facility and open farmlands during the cold wave event, which is consistent with the results of other studies (Dong et al., 2008; Wang, 2008). For example, the abundance of both soil mites and Collembola accounted for 56.9% (Dong et al., 2008) and 91.9% (Wang, 2008), respectively, of the total abundance of soil fauna communities in facility farmlands in temperate regions. Additionally, soil collembolan communities were dominant in the facility farmland (54.80%) in the present study, whereas the soil mite community was dominant in the open farmland (55.40%). A study in temperate regions also reported that the abundance of Collembola rather than soil mites prevailed in facility farmlands during different years of cultivation (Wang, 2008). Winter air temperature regulates soil mite and Collembola populations at the local scale in Arctic ecosystems (Coulson et al., 2023). A higher abundance was observed for Oribatid in the environment at −2°C compared with that at +2°C in a sub-arctic soil (Sjursen et al., 2005). In a study on black soil farmlands, the richness and abundance of soil mites were significantly higher than those of Collembola, indicating that soil mites are more tolerant to cold winter temperatures in temperate regions (Zhang et al., 2020). Additionally, Scheloribatidae, Galumnidae, Onychiuridae, and Entomobryidae were significantly abundant in the open farmland in the present study but absent in the facility farmland. Similarly, a different study observed the abundance of Onychiuridae and Entomobryidae in open corn farmlands adjacent to facility farmlands (Chen et al., 2019). Therefore, we speculated that the low temperature constrained the abundance of the Collembolan community rather than that of soil mites in the open field, indicating that soil mites were better able to withstand the low temperature in open farmland during cold wave events.

Enchytraeidae are important biological indicators that are sensitive to chemical stress in farmlands (Didden and RoKmbke, 2001). Therefore, the obvious preference of Enchytradae worms for

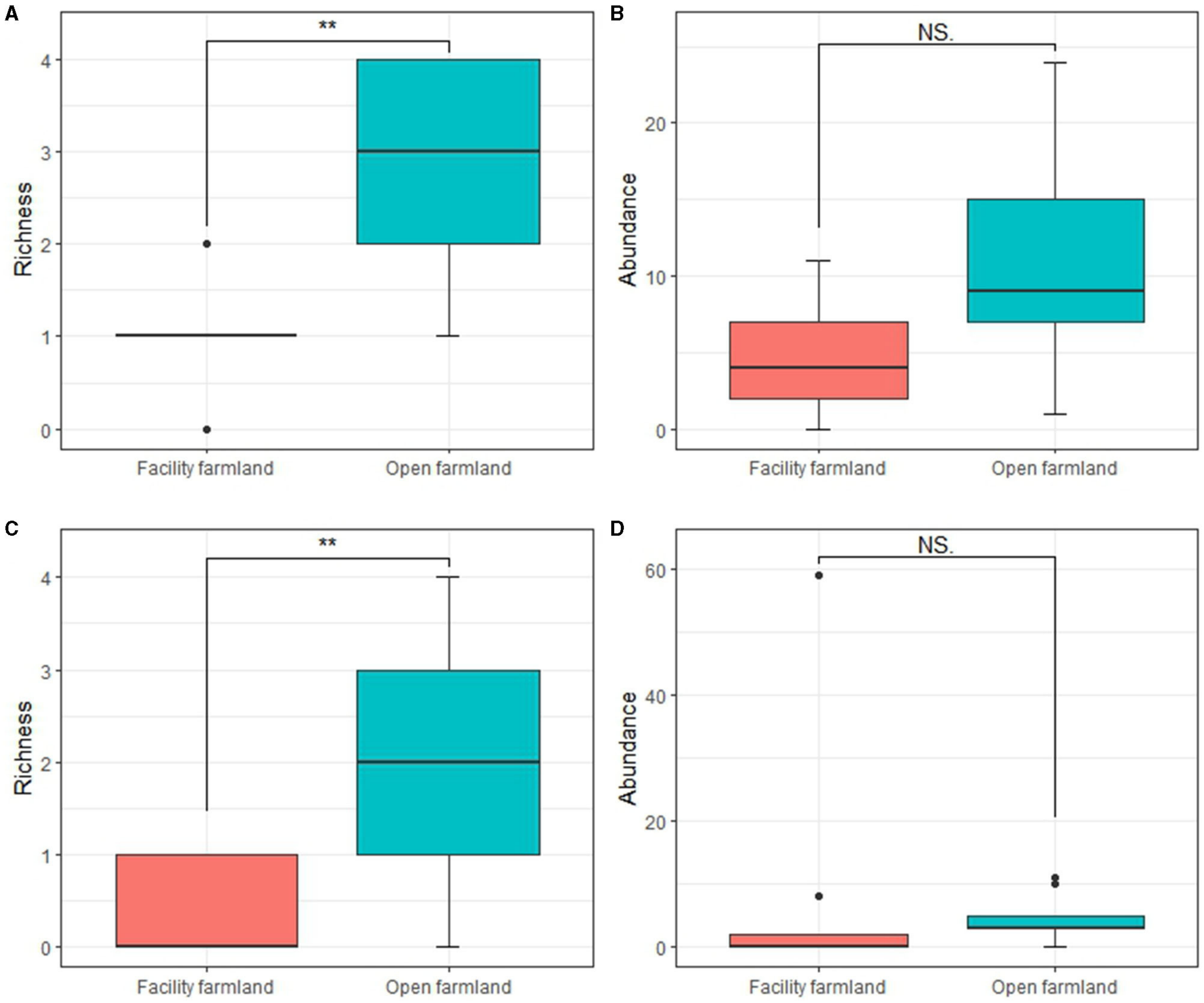


FIGURE 4
Taxonomic richness and abundances of soil mite **(A, B)** and collembolan **(C, D)** communities in facility and open farmlands during the cold-wave event. NS, not significant; $^{**}p < 0.01$.

open farmland rather than facility farmland can be attributed to the chemical stress from intensive management such as fertilization and pesticide application in the facility farmland. Precipitation, temperature, and pH influence species composition rather than mean abundance in Enchytraeid communities (Didden, 1993). Enchytraeids prefer habitats with sufficient moisture, organic matter, and oxygen (Niva et al., 2015). However, the facility farmland with relatively warmer air temperatures and moist soil failed to maintain a relative abundance of worms, indicating that the cold temperature during the cold wave event was not a significant regulator of Enchytraeidae worms.

Isotomidae thrived on facility farmland with 13 times more abundance in the facility farmland than in the open farmland. A previous study reported that Isotomidae showed dominant abundance in facility farmlands in temperate regions (Chen et al., 2019). However, in this study, only one family of Collembola existed on the facility farmland. Some Collembola have been proposed as potential regulators that suppress pathogens and diseases in facility farmlands by promoting the activities of soil microbes and feeding on pathogens (Zhang et al., 2023). For example, *Folsomia hidakana* (Isotomidae) suppresses damping-off disease in cabbage by feeding on *Rhizoctonia solani* (Shiraishi et al., 2003) and *Proisotoma minuta* (Isotomidae) suppresses pathogens and diseases in cotton (Lartey et al., 1994) in facility farmlands. Common diseases that have been reported in strawberry facility farmlands in Ningbo include powdery mildew, Verticillium wilt, downy mildew, anthracnose, gray mold, sharp eyespot, and spot blotch (Lian et al., 2018). Pathogens of these diseases may serve as food resources for Isotomidae in the facility farmland. However, direct evidence for Isotomidae feeding on pathogens is limited to the study area, and further studies are needed to validate this claim.

In this study, Staphylinidae were detected in the facility farmland and not in the open farmland during the cold wave event. This could be attributed to their sensitivity to the temperature

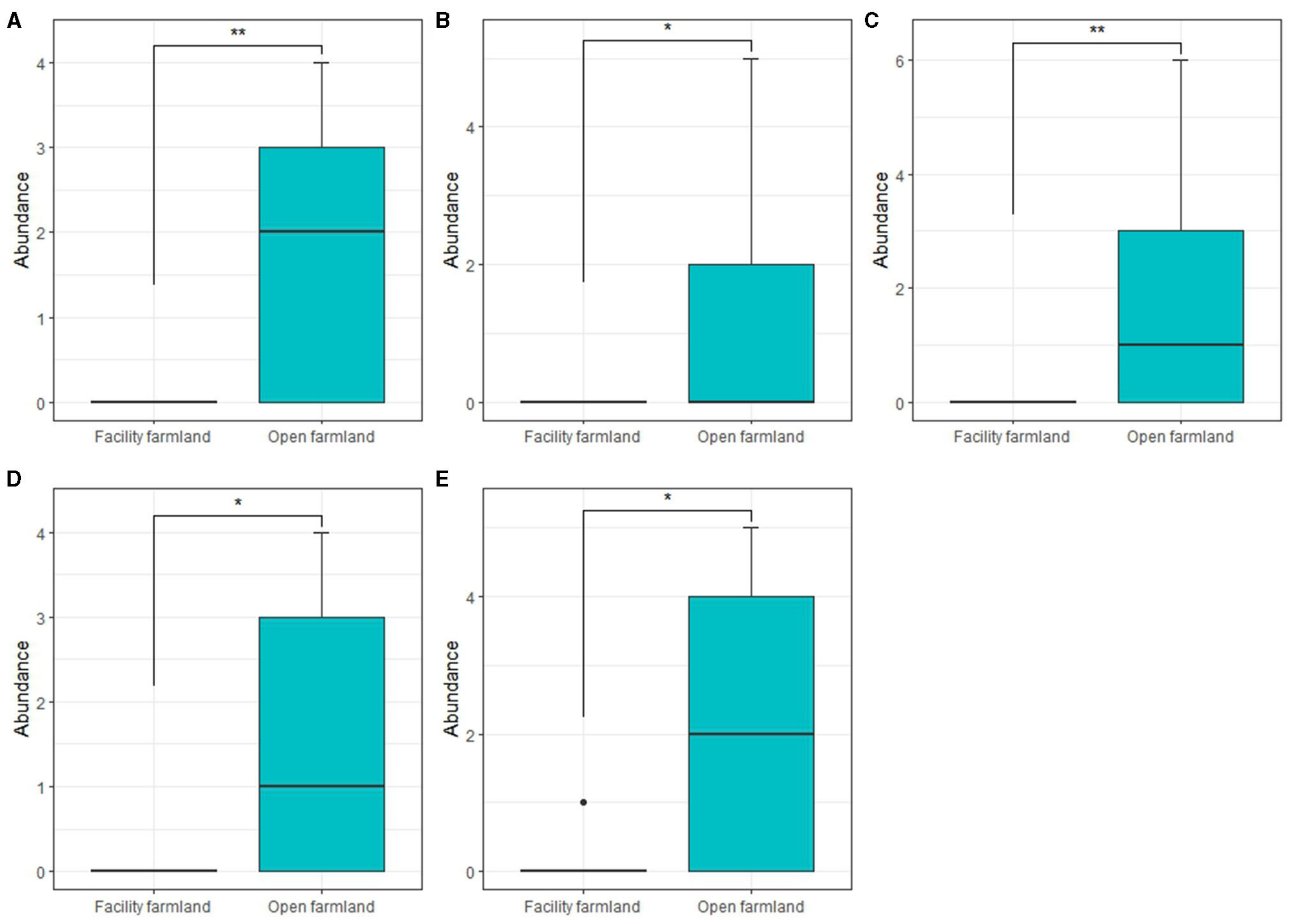


FIGURE 5
Taxonomic abundances of Scheloribatidae **(A)**, Galumnidae **(B)**, Onychiuridae **(C)**, Entomobryidae **(D)**, and Enchytraeidae **(E)** in facility and open farmlands during the cold wave event. $^{*}p < 0.05$; $^{**}p < 0.01$.

in farmlands (Porhajašová et al., 2018). Staphylinidae (*Quedius pellax*) is a winter-active taxon with a preferred distribution among habitats with relatively high winter temperatures and humid environments (Topp and Smetana, 1998). This suggests that the low temperature and sudden temperature drop (particularly at night) (Lima et al., 2015) in the open farmland constrained the activity of Staphylinidae. Another possible reason is the relatively sufficient food resources available for Staphylinidae at the facility farmland. Staphylinidae is an important pest predator that suppresses the soil-dwelling life stages of western flower thrips (Li et al., 2019) and controls fungus gnats (Jandricic et al., 2006) and maggot (Read, 1962) in facility farmlands. Natural predators that control pests in open farmland are usually absent in the facility farmland, resulting in a more rapid and severe development of pests in the facility farmland than in the open farmland (Thao et al., 2022). Therefore, Diptera larva, mites (Perumalsamy et al., 2009), Collembola (Jaloszynsk, 2012), and other possible pests in the facility farmland might provide more food resources for Staphylinidae.

Soil parameters (Minor et al., 2016) and cover crops (Madzaric et al., 2017) affected the composition and diversity of soil fauna community in facility farmland and in cold field environment. Soil water content did not significantly affect taxonomic richness and abundance of total soil fauna community, and abundance of each taxon, except for Mesostigmata sp.3 in this study. Numerous studies have found that soil fauna, such as Collembola (Dombos, 2001), oribatid mites (Jakšová et al., 2020), and spider mites (Gill et al., 2023) respond to changes in soil water content. However, certain studies reported that soil water content did not affect soil fauna communities (Sinka et al., 2007; Gergocs and Hufnagel, 2009). The low soil moisture difference between the facility and open farmlands might not result from their own textural characteristics but from irrigation management. Soil water content in the facility farmland in the present study primarily originated from irrigation; however, that in the open farmland primarily originated from rainfall and casual manual irrigation. In fact, irrigation also affected the richness and abundance of Collembola (Cutz-Pool et al., 2007) and oribatid mites (Iglesias et al., 2019) except for rainfall in farmlands. Therefore, sources of soil water, that is irrigation and rainfall, might affect soil fauna in both farmlands. Additionally, crop rotation affected the richness and abundance of Collembola (Twardowski et al., 2016), oribatid mites (Bosch-Serra et al., 2023), and other soil fauna (O'Rourke et al., 2008). A tomato/strawberry rotation with intensive management was performed in the facility farmland,

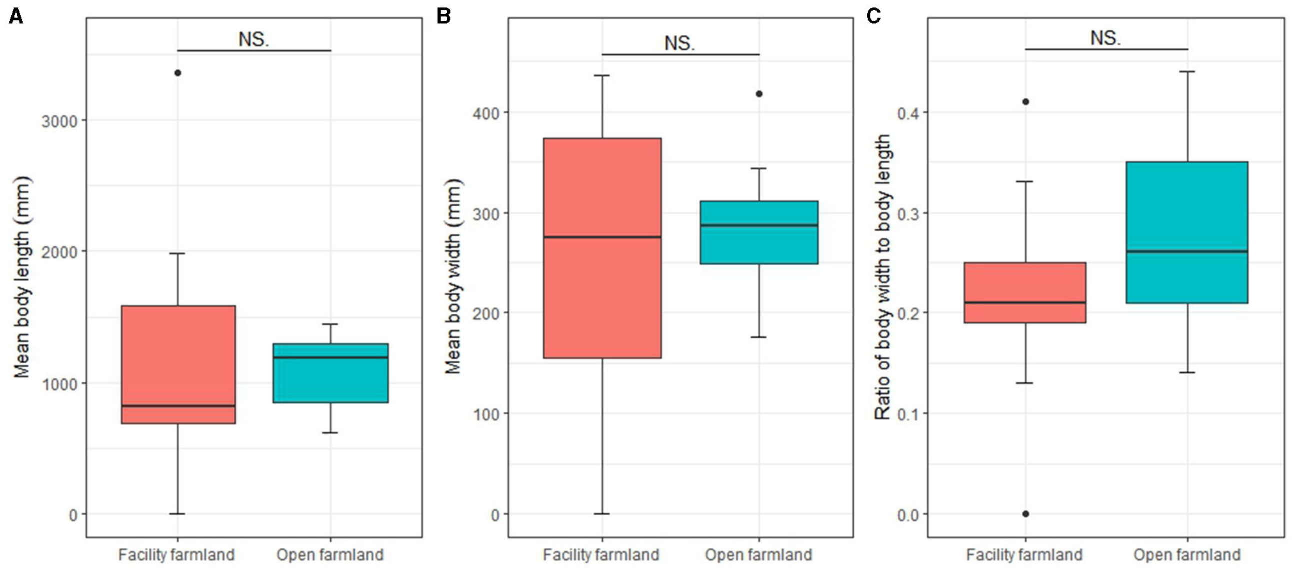


FIGURE 6
Mean body lengths **(A)**, mean body widths **(B)**, and body ratios **(C)** of total soil fauna communities in facility and open farmlands during the cold wave event. NS, not significant.

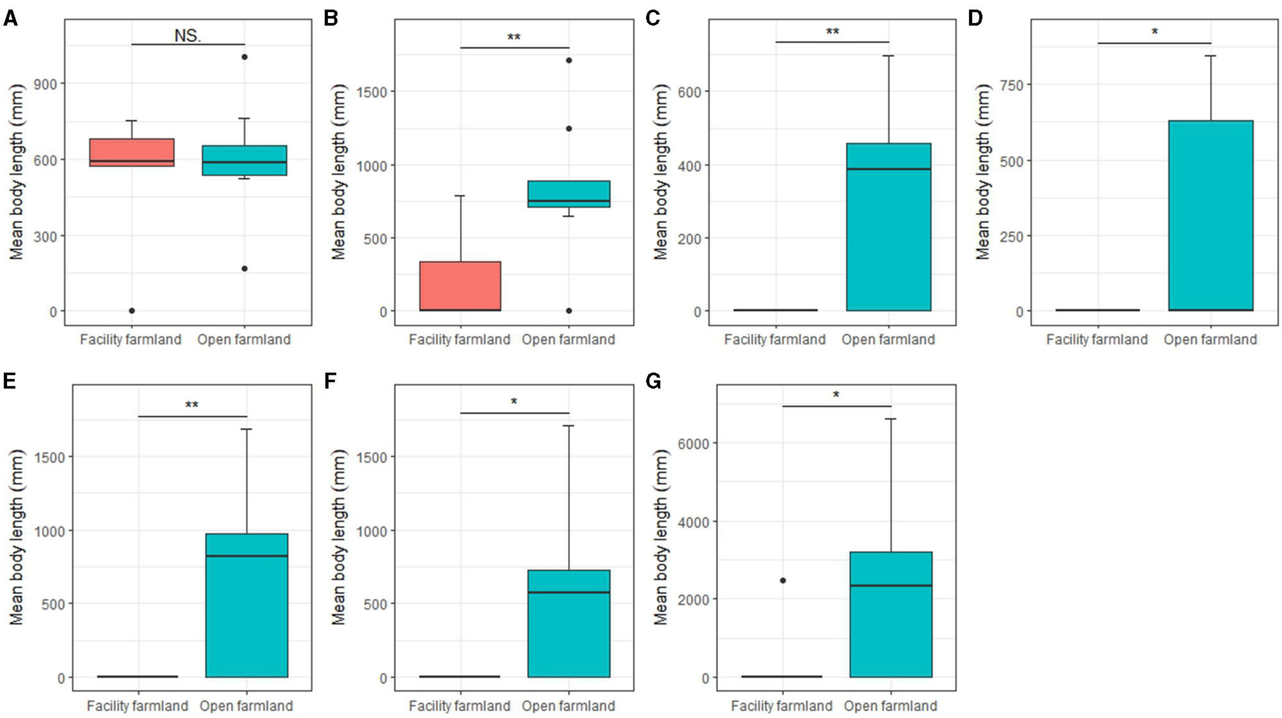


FIGURE 7
Mean body lengths of mite community **(A)**, collembolan community **(B)**, Scheloribatidae **(C)**, Galumnidae **(D)**, Onychiuridae **(E)**, Entomobryidae **(F)**, and Enchytraeidae **(G)** in facility and open farmlands during the cold wave event. NS, not significant; $^{*}p < 0.05$; $^{**}p < 0.01$.

whereas a green cabbage/lettuce/carrot/onion rotation system with less intensive management was conducted in the open farmland. The soil management, fertilization, and pest and disease control were less intensive and casual in the open farmland, and depended on the preferences of the farmers and workers. Therefore, soil parameters and different management strategies, including the irrigation and rotation system, should be studied further.

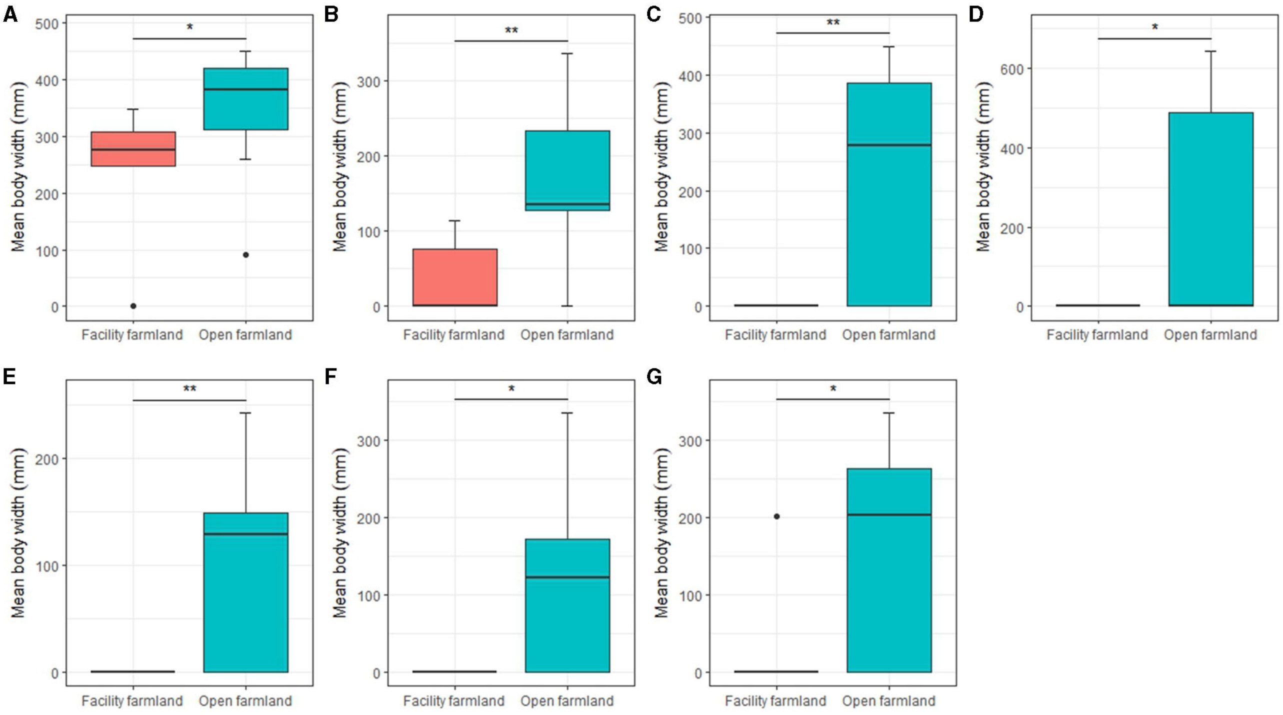


FIGURE 8
Mean body widths of soil mite community **(A)**, collembolan community **(B)**, Scheloribatidae **(C)**, Galumnidae **(D)**, Onychiuridae **(E)**, Entomobryidae **(F)**, and Enchytraeidae **(G)** in facility and open farmlands during the cold wave event. $^{*}p < 0.05$; $^{**}p < 0.01$.

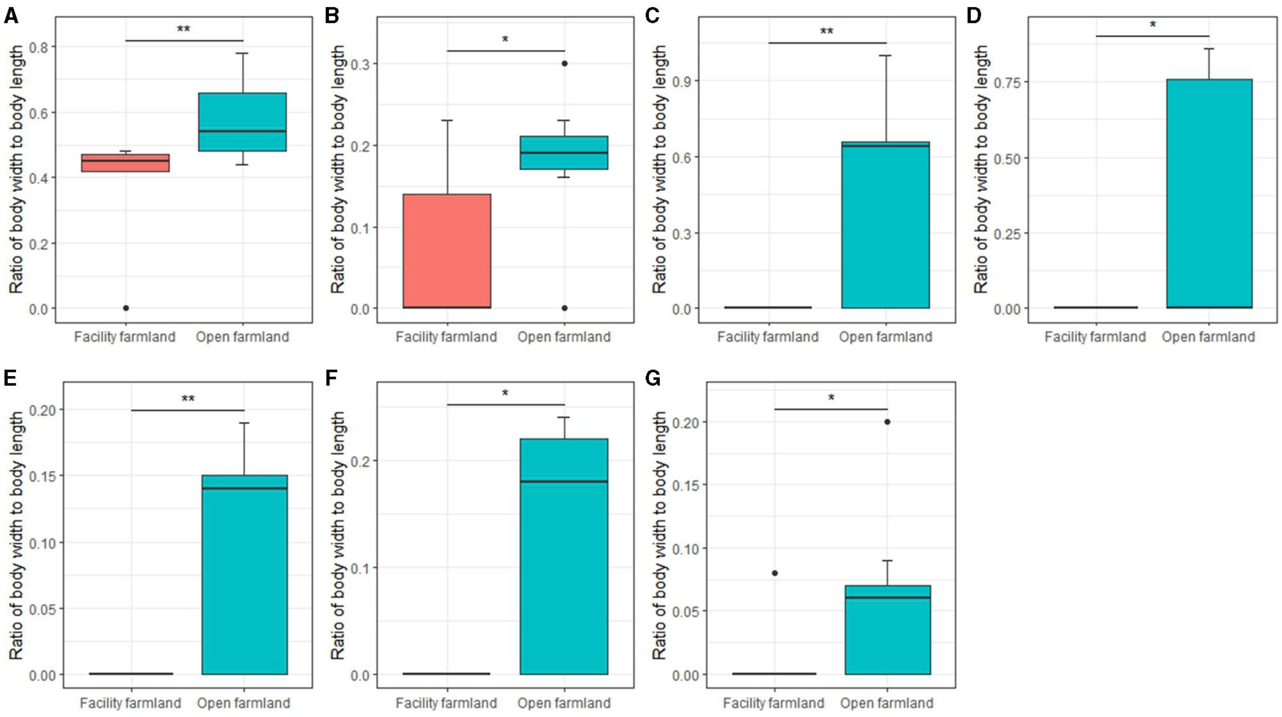


FIGURE 9
Body ratios of soil mite community **(A)**, collembolan community **(B)**, Scheloribatidae **(C)**, Galumnidae **(D)**, Onychiuridae **(E)**, Entomobryidae **(F)**, and Enchytraeidae **(G)** in facility and open farmlands during cold wave event. $^{*}p < 0.05$; $^{**}p < 0.01$.

TABLE 2 Effects of mean soil water content on richness, abundance, mean body length, mean body width, and body ratio of soil fauna community, and on abundance of each taxon.

| | Diversity | | Body length | | Body width | | Body ratio | |
|---|---|---|---|---|---|---|---|---|
| | *F* | *p* | *F* | *p* | *F* | *p* | *F* | *p* |
| Abundance of total soil fauna | 0.00 | 0.99 | | | | | | |
| Richness of total soil fauna | 0.01 | 0.94 | | | | | | |
| Body size of total soil fauna | | | 0.61 | 0.45 | 0.03 | 0.86 | 0.74 | 0.40 |
| Collembolan abundance | 0.09 | 0.77 | 0.10 | 0.75 | 0.43 | 0.52 | 0.15 | 0.70 |
| Collembolan richness | 0.28 | 0.60 | | | | | | |
| Mite abundance | 0.22 | 0.65 | 0.77 | 0.39 | 2.15 | 0.16 | 1.56 | 0.23 |
| Mite richness | 0.01 | 0.92 | | | | | | |
| Oppiidae abundance | 0.65 | 0.43 | 0.83 | 0.38 | 0.86 | 0.37 | 0.59 | 0.45 |
| Scheloribatidae abundance | 2.10 | 0.17 | 1.00 | 0.33 | 1.52 | 0.24 | 1.84 | 0.20 |
| Galumnidae abundance | 2.83 | 0.11 | 4.49 | 0.05 | 4.39 | 0.05 | 4.35 | 0.05 |
| Eremobelbidae abundance | 0.09 | 0.77 | 0.10 | 0.76 | 0.09 | 0.77 | 0.08 | 0.78 |
| Mesostigmata sp.2 abundance | 0.07 | 0.79 | 0.03 | 0.87 | 0.01 | 0.94 | 0.04 | 0.85 |
| Mesostigmata sp.1 abundance | 0.41 | 0.53 | 0.01 | 0.92 | 0.03 | 0.87 | 0.28 | 0.60 |
| Mesostigmata sp.3 abundance | 9.94 | 0.01 | 8.68 | 0.01 | 9.65 | 0.01 | 10.22 | 0.01 |
| Mesostigmata sp.4 abundance | 1.27 | 0.28 | 1.27 | 0.28 | 1.27 | 0.28 | 1.27 | 0.28 |
| Isotomidae abundance | 0.01 | 0.91 | 0.03 | 0.86 | 0.13 | 0.72 | 0.08 | 0.78 |
| Hypogastruridae abundance | 0.08 | 0.79 | 0.02 | 0.88 | 0.16 | 0.69 | 0.01 | 0.94 |
| Onychiuridae abundance | 0.02 | 0.88 | 0.88 | 0.36 | 1.01 | 0.33 | 0.33 | 0.57 |
| Entomobryidae abundance | 1.15 | 0.30 | 0.02 | 0.88 | 0.02 | 0.90 | 0.00 | 0.98 |
| Neanuridae abundance | 1.01 | 0.33 | 1.03 | 0.33 | 0.97 | 0.34 | 1.12 | 0.31 |
| Staphylinidae abundance | 5.55 | 0.03 | 2.93 | 0.11 | 4.02 | 0.06 | 4.95 | 0.04 |
| Diptera abundance | 0.06 | 0.81 | 0.02 | 0.89 | 0.16 | 0.70 | 1.70 | 0.21 |
| Spider abundance | 2.24 | 0.15 | 0.80 | 0.38 | 1.34 | 0.26 | 5.01 | 0.05 |
| Enchytraeidae abundance | 0.03 | 0.87 | 0.10 | 0.75 | 0.18 | 0.68 | 0.05 | 0.82 |
| Microcoryphia abundance | 1.36 | 0.26 | 0.57 | 0.46 | 0.51 | 0.49 | 0.92 | 0.35 |
| Aphid abundance | 0.43 | 0.52 | 0.43 | 0.52 | 0.43 | 0.52 | 0.43 | 0.52 |

## 4.2. Body size of soil fauna community during the cold wave event

The body sizes, including the mean body length, mean body width, and body ratio, of soil mites and collembolan communities in the facility farmland were significantly smaller than those in the open farmland. The body sizes of Scheloribatidae, Galumnidae, Onychiuridae, Entomobryidae, and Enchytraeidae in the facility farmland were also significantly smaller than those in the open farmland. Soil water content significantly affected mean body length, mean body width, and body ratio of Mesostigmata sp.3 and body ratio of Staphylinidae, but not for any other soil fauna.

Temperature is an important factor that affects the body size of soil fauna (Cedergreen et al., 2016). Climate warming is often more detrimental to fauna with relatively large body sizes than to those with relatively small body sizes (Thakur et al., 2023). The total biomass of soil Collembola declined in warm soil primarily because the species density decreased as the body size increased (Thakur et al., 2023). The adult body size of spider mites (*Tetranychus ludeni* Zacher) (Ristyadi et al., 2021) and Enchytraeidae decreases with increasing temperature (Didden and RoKmbke, 2001; Holmstrup et al., 2022). Therefore, we inferred that the reduction in the body sizes of soil mites and collembolan communities possibly resulted from the relatively warmer and more stable temperature in the facility farmland compared with those in the open farmland.

Additionally, the distribution of soil fauna depends on aggregate pores (Quénéhervé and Chotte, 1996). For example, soil pore space influences the nematode body size (Briar et al., 2011). Intensive management of farmland results in increased soil compaction and bulk density and decreased total porosity and capillary porosity (Wang et al., 2010). Therefore, the small

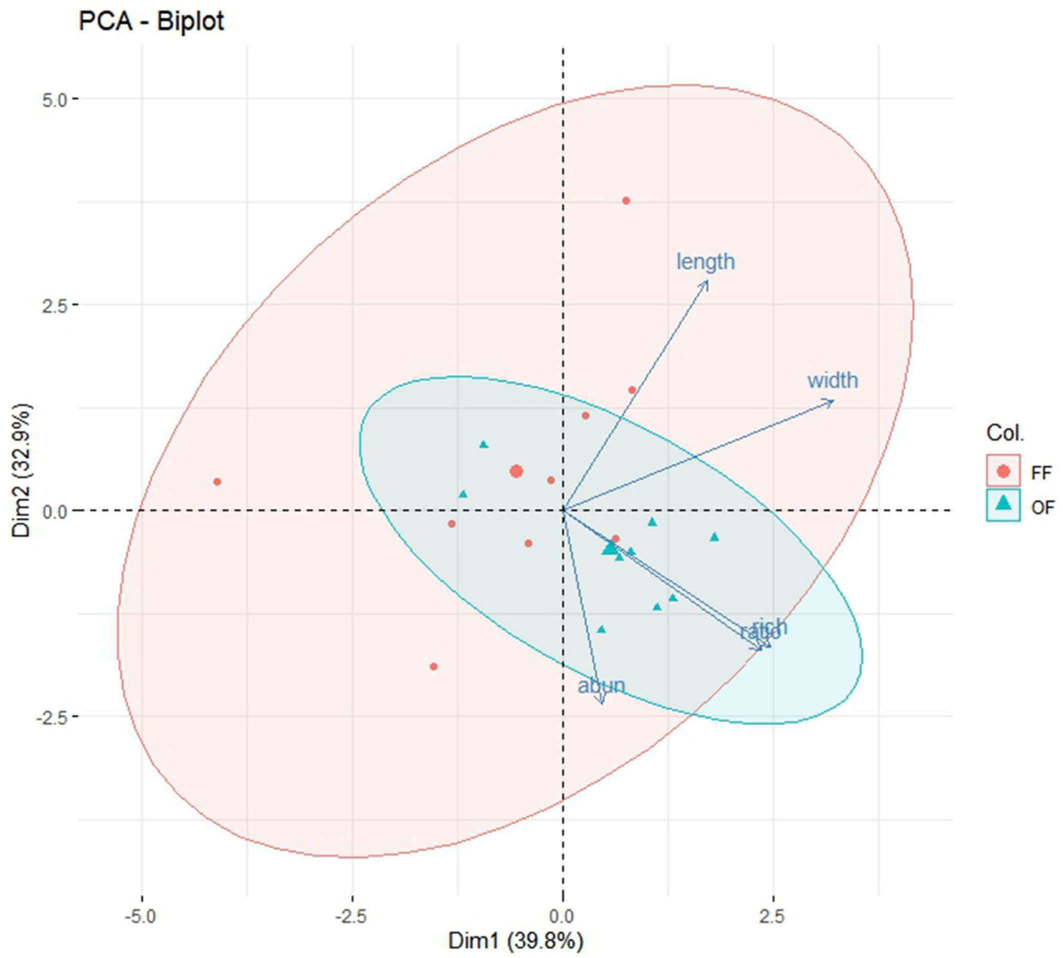


FIGURE 10
Biplot of principle component analysis (PCA). The x-axis and y-axis represent principal component 1 (Dim1) and principal component 2 (Dim2), respectively. The percentages on the x- and y-axes represent the variance explained by each principal component (% variances explained). The abun, rich, length, width, and ratio represent abundance, richness, mean body length, mean body width, and body ratio, respectively.

body sizes of soil mites and Collembola might allow for easy movement and increased activity within small soil pore spaces in facility farmlands.

However, no significant difference in the body size of the total soil fauna community was detected between the facility and open farmlands. Given that the body size of soil fauna varies remarkably (Andriuzzi and Wall, 2018), we were unable to account for the considerable heterogeneity in the body sizes of different taxa and identify any significant differences between the body sizes in the facility and open farmlands in the present study.

Bottom-up and top-down effects have been reported with respect to body size determination in soil fauna communities and soil parameters (Andriuzzi et al., 2020), resource availability (Andriuzzi and Wall, 2018), habitat type (Palmer, 1994), and disturbance (Tyler, 2008) have been proposed as significant underlying reasons. Compared to the open farmland, soil water content in vertical distribution might be more even due to thorough irrigation and plowing in the facility farmland. Considering the characteristics of the strong vertical stratification of soil fauna (Dooremalen et al., 2012), soil fauna with small body sizes might remain active in the top soil layer without being affected by drought. Although we did not detect significant effects of soil water content (top soil) on the body sizes of collembolan and soil mites communities and taxa abundances, soil water content in vertical layers should be studied further. Additionally, soil temperature has been identified as an important factor affecting body size of soil fauna (Xu et al., 2012; Lindo, 2015; Thakur et al., 2023). Moreover, other soil parameters, such as soil pH, soil texture, soil compaction, total carbon, soil organic matter, and aridity exhibited significant effects on the body size of soil fauna (Costa-Milanez et al., 2017; Schmidt F. A. et al., 2017; Andriuzzi et al., 2020; Wang et al., 2023). Agricultural fertilization (Liu et al., 2015; Niu et al., 2022), management intensification (Yin et al., 2020), herbivores and grazing (Andriuzzi and Wall, 2018), crop rotation (Postma-Blaauw et al., 2010), crop diversity (Postma-Blaauw et al., 2010), and plant presence (Gao et al., 2022) were found to affect the body sizes of soil fauna. Unfortunately, this study did not consider other factors except for soil water content; more environmental and human factors should be considered in future research studies. To reveal the objective of this study and avoid the influences of planting time, crop variety, and agricultural management among other factors, one farmland (Feihong Farm) was selected in the present study. This limitation would be resolved through selecting more farms in future studies. Additionally, comparing the facility farmland with adjacent soil with non-agricultural activity in the future would be beneficial to constructing "baseline data" of soil quality and biodiversity. This analysis would reveal the general effect of air and soil temperature changes in the study area.

Additionally, soil fauna have been used as biological control agents and indicators for facility farmland management (Campos-Herrera and Gutiérrez, 2009; Schmidt J. M. et al., 2017). The study results suggested that facility farmland failed in the provision of refuge or shelter for soil fauna community in cold wave events. By providing habitats, refuge, and food resources for pests and their natural enemies, open-field crops around facility farmlands could affect pest dynamics in facility farmlands (Doehler et al., 2023). Therefore, pest management methods in facility farmland should consider using the surrounding environment (Doehler et al., 2023). Installing hedgerows around facility farmlands to maintain natural enemies and encourage biological pest control is a useful practical management strategy (López-Felices et al., 2022). However, local farmers are reluctant to implement these measures despite the obvious economic and environmental advantages (López-Felices et al., 2022). According to the study results, open field farmlands could be a hotspot, refuge, shelter, and recruitment pool for soil fauna communities for facility farmlands. The study results also indicate the usefulness of more open farmlands with small areas adjacent to facility farmlands. We believe having open farmlands near the facility farmlands would not cause conflict in the demands of agricultural products; Moreover, their areas and shapes vary and they require non-intensive management. The soil biodiversity of facility farmlands can be recovered and rescued through such suitable management strategies. The study findings indicate that the management of open farmlands adjacent to facility farmlands is a relatively effective and economical restoration method and conservation strategy for agricultural management.

## 5. Conclusions

This study aimed to reveal the diversity and body size of the soil fauna community in facility and open farmlands during a cold wave event in Ningbo in the winter of 2023. The richness, abundance, and body size of the soil fauna community in the facility farmland were significantly lower than those in the open farmland, indicating that the facility farmland failed to be a refuge or shelter for soil fauna communities during the cold wave event. This study also suggests that the open farmland adjacent to the facility farmland is a "hot spot" for the soil fauna community during cold wave events in subtropical regions. However, more factors including soil parameters, food resources, and agricultural managements, which were important factors affecting soil fauna community, should be further studied. The results of this study emphasize that the maintenance mechanisms of soil fauna communities are affected by cold wave events and provide useful information for soil biodiversity restoration in intensively managed facility farmlands.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

## Author contributions

MG: Conceptualization, Data curation, Methodology, Writing—original draft, Writing—review and editing. YJ: Investigation, Methodology, Writing—original draft, Data curation. JS: Investigation, Methodology, Writing—original draft, Data curation. TL: Writing—original draft, Methodology, Investigation. YZ: Methodology, Investigation, Writing—original draft. JLa: Methodology, Writing—review and editing, Formal analysis. JLi: Conceptualization, Methodology, Supervision, Writing—original draft, Writing—review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Developing improvement strategies for management of the Sisrè berry plant [*Synsepalum dulcificum* (Schumach & Thonn.) Daniell] based on end-users' preferences in Southern Nigeria

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*Synsepalum dulcificum* is a valuable horticultural and lesser-known crop, famous for the uniqueness of its taste modifying properties, which is candidate for genetic improvement in West Africa. Semi-structured interviews were conducted with 100 respondents purposively selected to analyze the current production systems and constraints as well as to document the farmers' and consumers' preferences for breeding traits in Southern Nigeria. The results showed that none of the investigated farmers applied all required crop management practices to produce the species (land cleaning before establishment, pegging and lining, holing, base manure application, crop irrigation, weeding, pruning, fertilizers application, and pests and diseases control). Farmers were grouped into three clusters based on crop management practices. There was a strong and highly significant agreement among farmers (Kendall's $W = 0.8$, $p < 0.001$) that bush fire, poor plant growth, drought, pests, and parasitic weed were the five most important constraints in Southwest Nigeria. In Southeast Nigeria, damage by insects and birds, poor seed germinability and poor knowledge of cultivation technics were the most important constraints challenging production. Farmers' agreement around these constraints was moderate but highly significant (Kendall's $W = 0.6$, $p < 0.001$). Overall, the top three desired breeding traits by farmers included: high growth rate, extended fruit shelf-life, and high fruits yield while the top three consumer's preferences included: high miraculin potency (long lasting action of the miraculin), fruit glossiness, and high metabolites content. However, cultural specificities were detected in these preferences with a higher agreement in Yoruba farmers' preferences compared with their counterparts Igbo. The Igbo consumers showed a higher concordance in their traits' preferences than the Yoruba consumers. These findings pave the way for an informed cultivar development for the Sisrè berry plant in Nigeria and expand knowledge on end-users' preferences for the species in West Africa.

KEYWORDS

sweet berry, Southern Nigeria, management system, end-users' preferences, *Richardella dulcifica*

# 1. Introduction

The Sisrè berry (Syn: miracle fruit) plant [*Synsepalum dulcificum* (Schumach & Thonn.) Daniell] is a West African native shrub/tree species belonging to the Sapotaceae family with its centers of diversity shared between the Dahomey Gap and the Upper Guinea parts of the West African rainforest (Tchokponhoué et al., 2020; Huang et al., 2022). The species can reach 7.5 m height (Tchokponhoué et al., 2020) and produces green fruits called Sisrè berry (Syn: magic berry, sweet berry, and miracle fruit) that turn to red when they are ripe (Figure 1). *Synsepalum dulcificum* is famous for being a unique natural source of "miraculin" a sweetening glycoprotein contained in the miracle fruit pulp, which has the ability to change any sour taste in a sweet one (Kurihara and Beidler, 1968). Besides this sweetening property that has been valued in diabetes treatment throughout insulin resistance improvement (Chen et al., 2006) and cancer treatment throughout taste perception restoration during chemotherapy (Wilkie et al., 2012), the species has many other modern applications in cosmetics as well as in the food and the beverage industries. For instance, the seeds have been recently reported as a potential drug against Alzheimer's disease (Huang et al., 2022) whereas the derived oil is used to treat women hair breakage (Del Campo et al., 2017). The Sisrè berry red exocarp served as an excellent beverage colorant in addition to be an excellent source of flavonols and anthocyanins (Buckmire and Francis, 1976). Recent developments also revealed the potential of the miracle fruit to reliably replace synthetic sugar in lemonade (Rodrigues et al., 2016). In Florida (United States) for instance, the Sisrè berry was reported to help some patients suffering from COVID-19 to beat taste loss.[1] In addition to be a rich source of Vitamins A, C, and E (Njoku et al., 2015), the species also exhibits a number of healing properties and constitutes a rich reservoir of a number of phytochemicals (Achigan-Dako et al., 2015). The species is also an excellent source of income since a kg of the dry powder of the Sisrè berry fetches an astounding price of USD 2,500.[2]

Given all its above-mentioned importance, the species constitutes a strong asset for an improved livelihood and lifestyle, with the potential to contribute to West Africa economic growth. Consequently, a sub-region-wide breeding initiative bringing together the countries where the species naturally occurs including Benin, Togo, Ghana, and Nigeria is ongoing with the objective to develop elite cultivars for an increased production and utilization of the species. One of the very first steps in any plant improvement endeavor is the development of product profiles. Such an exercise is important in that it helps focus on traits that guarantee a high adoption rate for the released varieties. This can be highly successful when it is conducted using a participatory approach (e.g., participatory rural appraisal) as this latter emphasizes local knowledge and assists local people to make their own appraisal, analysis, and plans (Almekinders et al., 2007). In Nigeria, the nutritional importance, the phytochemical contents, and the health-promoting benefits of the species had been extensively documented (Nkwocha et al., 2014; Jeremiah et al., 2015; Njoku et al., 2015; Obafemi et al., 2019). However, no evidence suggested the existence of an active breeding initiative for the species while the development of pre-breeding tools in the species is still at its infancy (Iloh et al., 2017).

FIGURE 1
Branches of Sisrè berry plant bearing ripe (red) fruits.

Many studies on traits preference highlighted instances of preference variation following sociolinguistic groups, gender, and region. In Nigeria for instance, traits preference in Cassava (*Manihot esculenta* Crantz) differed between farmers in Southeast and Southwest, with those in the Southeast prioritizing traits such as "high yielding" and "early maturity," whereas farmers in the Southeast placed more value on traits like "Fast cooking" (Teeken et al., 2018). In Uganda, while women mainly indicated traits such as "taste," "color," and "biotic and abiotic stress resistance/tolerance" as the most preferred breeding traits in Banana (*Musa sp*), men rather prioritized yield-related traits such "high yielding" and "big bunch size" (Marimo et al., 2019). Similarly, in Burkina-Faso, while kersting's groundnut [*Macrotyloma geocarpum* (Harms) Maréchal & Baudet] farmers in Bobo indicated tolerance to high soil moisture as preferred breeding trait, their counterpart in Bwamu rather were looking for grains with a "short cooking time" (Coulibaly et al., 2020).

In this study, we investigated the current Sisrè berry plant farming systems, documented the production constraints, and analyzed farmers and consumers' preferences for breeding traits and preference variation across sociolinguistic groups, gender, and regions (Southwest and Southeast).

# 2. Materials and methods

## 2.1. Study area

The study was carried out from November 2019 to March 2020 in four States of Southern Nigeria including Anambra, Enugu,

1 https://www.youtube.com/watch?v=AfkOp2o47Wg
2 https://www.miraclefruitfarm.com/supplements

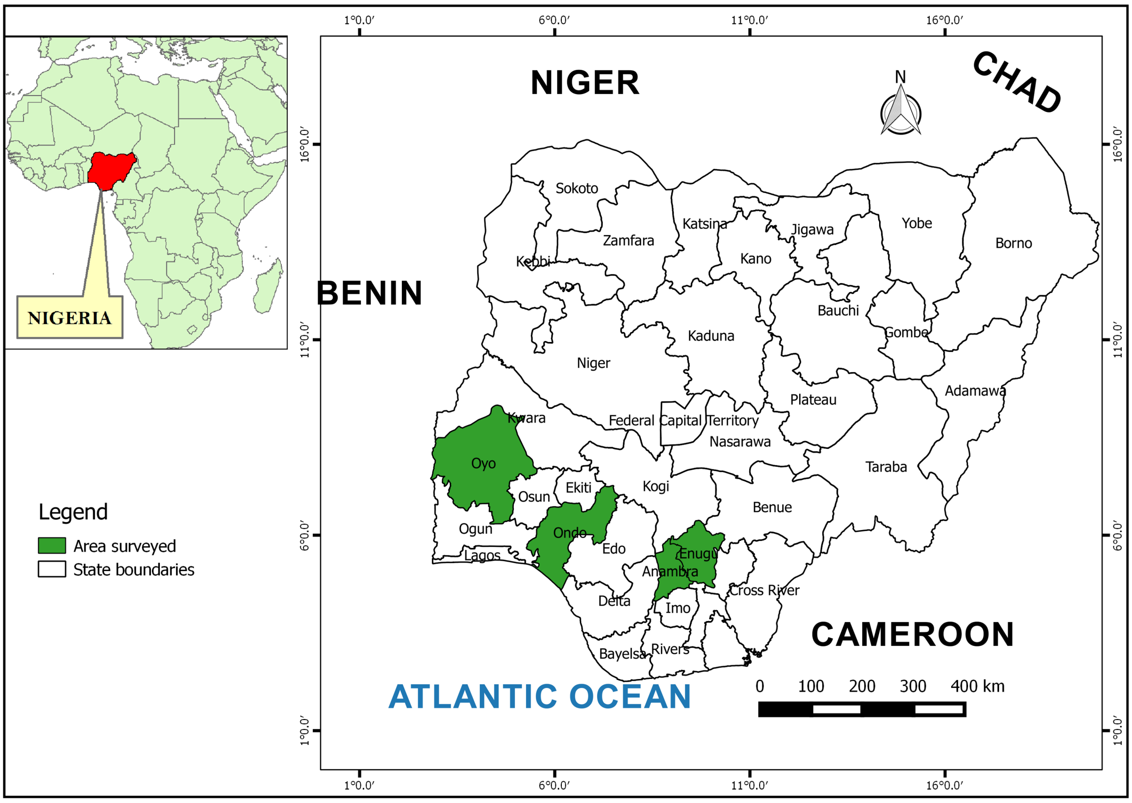


FIGURE 2
Map showing the study area.

Ondo, and Oyo (Figure 2), situated between longitudes 2°0′ and 10°5′ E and latitudes 2°5′and 11°0′ N (Iloeje et al., 1981). These sites were selected based on information retrieved from literature which indicated them as home of the species in Southern Nigeria (Ogunsola and Ilori, 2008; Nkwocha et al., 2014; Njoku et al., 2015). Anambra and Enugu, forming the Southeast region, are inhabited by Igbo, while Ondo and Oyo, forming the Southwest, are Yoruba populated. The climate of south Nigeria is dominated by the presence of three major wind currents, namely the maritime tropical (mT) air mass, the continental tropical (cT) air mass, and the equatorial easterlies (Ojo, 1977; Iloeje et al., 1981). The regions enjoy a tropical climate with two distinct seasons including the rainy season (April–October) and the dry season (November–March). The mean annual rainfall falls between 1,250 and 1,500 mm, whereas the mean monthly temperature ranges between 25.7°C (in July) and 30.2°C (in February). The soils are of sandy, loamy sandy or clay loamy, sandy clay, sandy loam, silty clay, and silty loam. Generally, the soil is deep and well drained (Adejuwon and Ekanade, 1988; Nkwunonwo et al., 2020).

## 2.2. Respondents sampling approach

The respondents were selected by combining convenience and referral-chain sampling approaches, two commonly used non-probabilistic sampling methods (Pechansky et al., 2004; Bolfarine and de Oliveira Bussab, 2005; Mendenhall et al., 2006). Convenience sampling is a sampling method in which units are selected based on easiness of access or availability. This method of sampling is generally less time-consuming and of lower cost. Referral-chain sampling is a technique that is often used for intentional selection of expert informants. In this study, we were only interested in respondents who have produced the species for at least 5 years, and/or who consumed/exploit its fruits. In this method, the first contact with the community may be through a well-known expert who then indicates another expert, and so on, until the sample size is reached (Albuquerque et al., 2010). The entry points in our case were the community chiefs or leaders. Combining these two sampling strategies was relevant to our study since we did not have any prior information on the species owners, and interestingly the sampling threshold imposed by the saturation point (defined as the point at which there are no new names of key informants being mentioned by the last interviewee; N'Danikou et al., 2015) was observed to represent enough the population studied.

## 2.3. Data collection

Data were collected through formal semi-structured interviews with respondents using a questionnaire. During the exercise, information describing the respondents' socio-demographic and cultural characteristics (sex, age, and sociolinguistic group affiliation), farm characteristics, cultivation practices of Sisrè berry plant, awareness of existence of varieties or morphotypes of the species, farmers and consumers' preferences for breeding traits as well as their production constraints.

## 2.4. Statistical analyses

Analysis of data involved the use of descriptive statistics such as frequency, percentages, standard deviation, and mean, to describe the socio-economic characteristics of respondents. The mean values and the standard deviation were calculated on farmers and consumers preferences scores. The $\chi^2$ Fisher exact test was performed to assess the dependence relationships between (i) the awareness of a specific morphotype and the sociolinguistic group affiliation and (ii) the respondent's involvement in Sisrè berry cultivation and their gender / education level /main activities. The ANOVA with least significant different (LSD) *post hoc* test was performed using "agricolae" package (de Mendiburu and de Mendiburu, 2019) to assess the statistical grouping in informants' age, household size, total farm size (acre), and farmers experience in Sisrè berry plant management (years). The factorial analysis of mixed data was performed to describe Sisrè berry plant farming systems and establish the typology of the farmers while the Factorial Analysis of Correspondence (FAC) was performed using "FactoMineR" package (Lê et al., 2008) to test the relationship between the listed preferences and sociolinguistic groups, regions, and gender. The mean value and the standard deviation were calculated for scored constraints across regions and sociolinguistic groups. The Kendall's Coefficient of Concordance (KCC) was computed using "irr" package (Gamer et al., 2012) to test the level of agreement among the listed constraints. The value of KCC is positive and ranges from 0 to 1. All the analyses were carried in the R environment (version 4.1.2; R Core Team, 2021).

# 3. Results

## 3.1. Socio-demographic characteristics of respondents

A total of 100 respondents from four States including Ondo, Oyo, Anambra, and Enugu were interviewed in this study. Across these four States, a greater proportion of male farmers was involved in the Sisrè berry plant cultivation compared with women (Table 1). The greatest proportion of women involvement (36% of respondents) was observed in Enugu state. Respondents from Anambra and Enugu belong to the "Igbo" sociolinguistic group, while those from Ondo and Oyo are "Yoruba." Informants from Oyo and Enugu were the most literate (68 and 16% for tertiary and secondary levels, respectively, in Oyo region; and 36 and 32% for tertiary and secondary levels, respectively in Enugu). The highest proportion of respondents with no formal education was observed in Ondo. Agriculture ($p < 0.0001$, $\chi^2 = 28.04$, df = 3) and trade ($p < 0.0001$, $\chi^2 = 42.41$, df = 3) were the main activities of the respondents with high significant difference across the states.

TABLE 1 Characteristics of the informants.

| Variables | Igbo ($n1 = 50$) | | Yoruba ($n2 = 50$) | |
|---|---|---|---|---|
| | Anambra ($n1.1 = 25$) | Enugu ($n1.2 = 25$) | Ondo ($n2.1 = 25$) | Oyo ($n2.2 = 25$) |
| Gender of respondents (%) | | | | |
| Male | 84 | 64 | 76 | 80 |
| Female | 16 | 36 | 24 | 20 |
| Significance | $p < 0.0001$, $\chi^2 = 46.2$, df = 1 | $p < 0.005$, $\chi^2 = 7.8$, df = 1 | $p < 0.0001$, $\chi^2 = 27.0$, df = 1 | $p < 0.0001$, $\chi^2 = 36$, df = 1 |
| Level of formal education (%) | | | | |
| Tertiary | 28 | 36 | 12 | 68 |
| Secondary | 32 | 32 | 16 | 16 |
| Primary | 24 | 28 | 36 | 4 |
| No formal education | 16 | 4 | 36 | 12 |
| Significance | $p < 0.05$, $\chi^2 = 7.5$, df = 3 | $p < 0.0001$, $\chi^2 = 33.1$, df = 3 | $p < 0.0001$, $\chi^2 = 26.2$, df = 3 | $p < 0.0001$, $\chi^2 = 135.5$, df = 3 |
| Main occupation (%) | | | | |
| Farmers | 36 | 24 | 52 | 20 |
| Business | 12 | 36 | 12 | 44 |
| Drivers | 28 | 16 | 12 | 24 |
| Teachers | 16 | 16 | 20 | 8 |
| Others (nurse, tailor, etc.) | 8 | 8 | 4 | 4 |
| Significance | $p < 0.0001$, $\chi^2 = 34$, df = 4 | $p < 0.0001$, $\chi^2 = 35.9$, df = 4 | $p < 0.0001$, $\chi^2 = 88$, df = 4 | $p < 0.0001$, $\chi^2 = 62$, df = 4 |
| Means ± standard deviation (statistical group) | | | | |
| Informant age (years; $p = 0.08091$, df = 3) | 47.4 ± 7.5 (a) | 50.2 ± 9.9 (a) | 49.3 ± 7.4 (a) | 44.5 ± 8.1 (a) |
| Household size ($p = 0.01123$, df = 3) | 9.3 ± 3.2 (a) | 7.8 ± 2.7 (ab) | 8.8 ± 3.1 (ab) | 6.8 ± 2.5 (b) |
| Total farm size (acre; $p = 0.129$, df = 3) | 14.6 ± 8.5(a) | 7.7 ± 6.7 (a) | 13.5 ± 9.0(a) | 9.8 ± 18.20 (a) |
| Experience in Sisrè berry plant management (years; $p = 0.00518$, df = 3) | 26.1 ± 6. (a) | 12.9 ± 7.1 (ab) | 18.6 ± 4.9 (ab) | 18.1 ± 7.9 (b) |

Means with different letters in the same row are statistically different at $p = 0.05$ (LSD test).

The respondents were on average 47.8 ± 8.5 years old, with respondents in Oyo being the youngest (44.5 ± 8.1 years old), while those from Enugu were the oldest (50.2 ± 9.9 years old). Informants from Anambra and Enugu states had a greater experience (26.1 ± 6.5) in the Sisrè berry plant management (Table 1).

## 3.2. Management practices-based farmers typology

The Sisrè berry plant was mainly found in home gardens although also existing in cultivated farms, fallows or naturally growing in forests. Most of Sisrè berry plant owners also possessed plantations of other perennial species including for instance cashew (*Anacardium occidentale* L.), cocoa (*Theobroma cacao* L.), coconut (*Cocos nuciferae* L.), palm trees (*Elaeis guineensis* L.), among others. None of the farmers applied all required management practices in the production of the species (land clearing before crop establishment, pegging and lining, holing, base manure application, crop irrigation, weeding, pruning, fertilizers application, and pest and diseases control).

The factorial analysis of mixed data grouped the farmers into three (03) categories based on the various farming practices they applied (Figure 3). The distribution of variables characterizing these various categories is presented in Figure 4. The cluster 1 contained 93.6% of the interviewed farmers. Famers in this cluster owned on average two stands of Sisrè berry plant and had 18.50 ± 8.8 years of experience in the species management. None of them attended a training in biodiversity conservation and 97.7% of them possessed individual trees of Sisrè. Trees were mainly inherited (59.1%) and dispersed in home gardens or cultivated farms. Seeds were obtained from the ripe fruits and the regeneration mode they applied included: seeds sowing (97.9%), seedlings transplanting (82.9%), and cuttings (23.4%). A small proportion of these farmers (21.3%) applied base manure before transplanting the seedlings and irrigated the transplanted seedlings (44.7%). Farmers mostly applied the weeding (65.9%) while the chemical pesticides spray was only applied by 2.1% of them. This cluster included 22.7% of farmers from Ondo, 31.8% of farmers from Oyo (54.5% of Yoruba), 18.2% of farmers from Anambra, and 38% of farmers from Enugu (45.5% of Igbo).

The cluster 2 contained 2.1% of farmers (one respondent) belonging to the Yoruba sociolinguistic group (Oyo). This farmer was the only one to possess a plantation of Sisrè berry plant with up to 2,700 stands. This farmer established the Sisrè berry plant orchard by transplanting the seedlings produced by sowing matured fruits. Required management practices such as basal dose of manure, irrigation, weeding, and phytosanitary spraying were done.

The cluster 3 encompassed 4.2% of farmers from Oyo (Yoruba) with a moderate number of Sisrè berry trees (up to 115 stands). They have attended some training in biodiversity conservation and established the plantations themselves. The land clearing, pegging, lining, holing, and base manure application were systematically carried out before transplanting the seedlings. Crop management included weeding and irrigation. There were no phytosanitary products spraying by farmers in this cluster (Figure 4).

## 3.3. Knowledge of varieties and morphotypes in the Sisrè berry plant

None of the surveyed farmers in Southern Nigeria differentiated any variety of *S. dulcificum*. However, they recognized two morphotypes based on the color of the fruit exocarp: a red-skinned

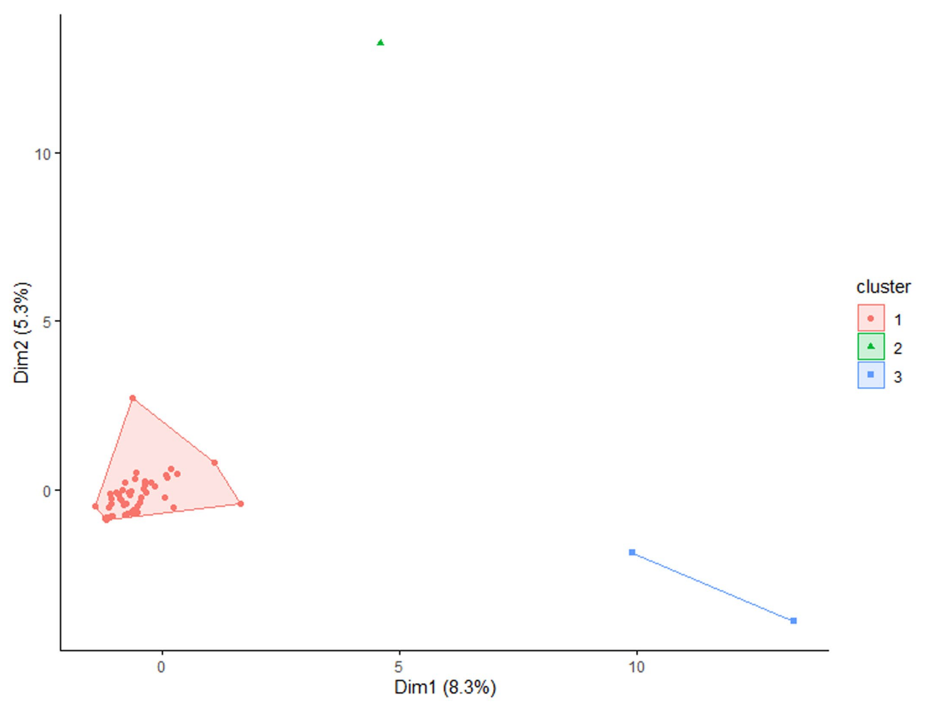


FIGURE 3
Typology of Sisrè berry plant farmers in Southern Nigeria.

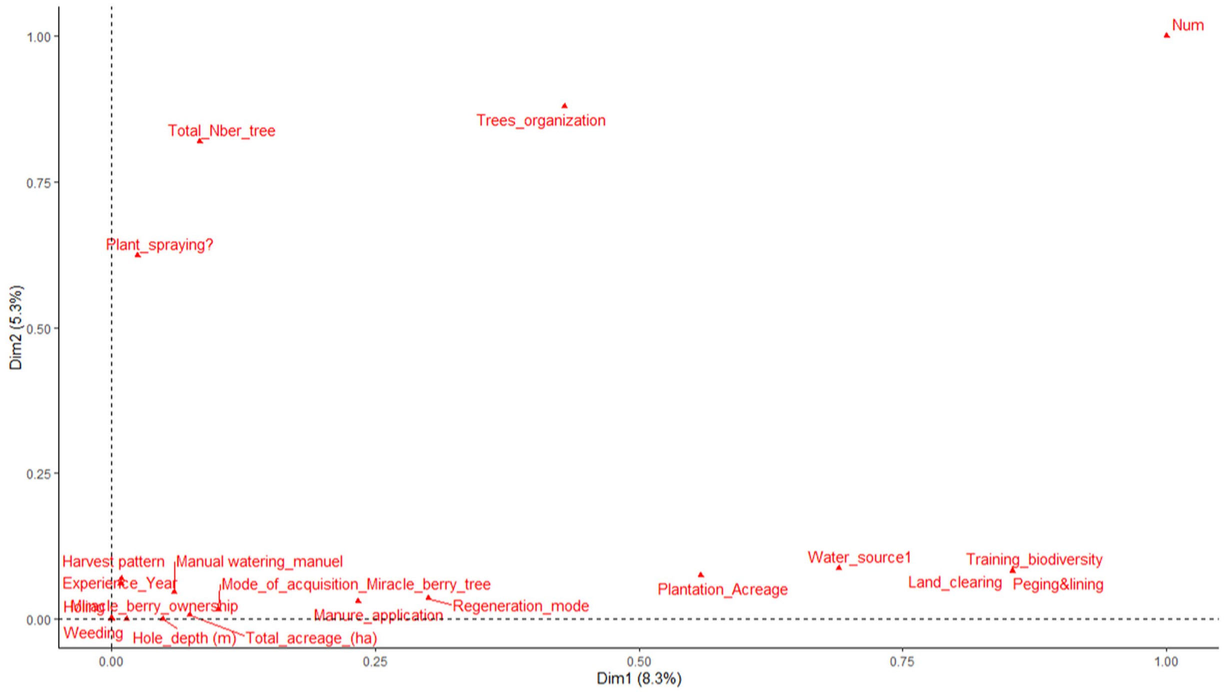


FIGURE 4
Factor map displaying the variables associated with farmers' clusters detected.

morphotype (Figure 5A) and a yellow-skinned morphotype (Figure 5B). There was a strong association between awareness of different morphotypes and sociolinguistic group affiliation ($p < 0.0001$, $\chi^2 = 96.0$, df = 1) and the agroecological region ($p < 0.0001$, $\chi^2 = 96.0$, df = 3) with the yellow morphotype exclusively reported by the Igbo in the Southeast region and the red-skinned morphotype only known by the Yoruba, in the Southwest. In both regions, the species is becoming less and less available despite having two fruiting seasons yearly. Seventy-four percent (74%) of the respondents confirmed the scarcity of the species in Southeast as compared to 62% in Southwest ($p = 0.30$, $\chi^2 = 1.0$, df = 1). Several reasons justified this state of availability including bush fire during the dry season, destruction of the habitat of the species for settlement, road construction or agriculture expansion, the poor rate of the plant growth, and the fact that the species is not yet entirely domesticated and that cultivation in agricultural production systems remained low (Figure 6).


FIGURE 5
Morphotypes of Sisrè berry plant recorded in the study: red-skinned morphotype **(A)** and yellow-skinned morphotype **(B)**.

## 3.4. Production constraints

In Southeast Nigeria, inhabited by Igbo, the top five constraints identified by the Sisrè berry plant growers included insect and birds' damages, poor knowledge of cultivation technics, drought, and low seed germination (Table 2). While farmers in Anambra and Enugu had three (03) out five of these constraints in common, there was only a moderate agreement in their ranking of the constraints (Kendall's W = 0.6, $p < 0.001$). In the Southwest region inhabited by the Yoruba, the five most important constraints included insect and birds' damages, drought, bushfire, and low seed germination. There was a higher concordance in the ranking of the constraints between farmers in Ondo and Oyo (Kendall's W = 0.8, $p < 0.001$) compared with their peers in Anambra and Enugu (Kendall's W = 0.6, $p < 0.001$). Overall, there was a good agreement for the constraints list and ranking between the surveyed Igbo and the Yoruba farmers (Kendall's W = 0.6, $p < 0.001$; Table 3).

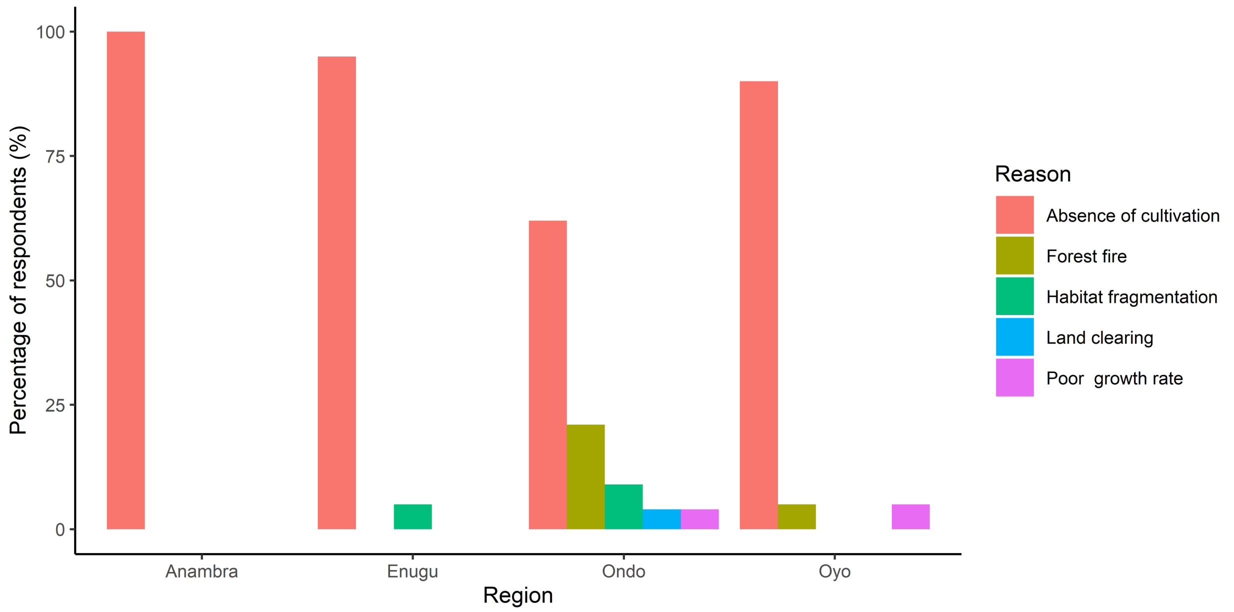


FIGURE 6
Reasons of the scarcity of Sisrè berry plant across the studied regions in Southern Nigeria.

## 3.5. Market chain analysis

The harvested products were mainly for household use (63.2%), followed by sales (21.3%) and gifts (15.5%). The fruits sales mainly occurred on local market (94.3% of respondent selling the fruits), while only a low proportion of harvested fruits was processed into powder or juice and sold in capital city Lagos or exported to the United States (Table 4). There was not specific selling unit for sales in the local market while the kilogram is used for the international market.

## 3.6. Farmers' and consumers' preferences for breeding traits

Producers and consumers desired a range of traits for an improved variety of *S. dulcificum*. A total of 11 and six traits were mentioned by farmers and consumers, respectively. For farmers, the top five most preferred breeding traits for *S. dulcificum* included by descending importance, a high plant growth rate, an expanded fruit shelf -life, a high fruit yield, a high pest and drought resistance or tolerance, and a high fruiting frequency. The most important traits for consumers in descending importance included a longer sweetening action of the fruit, a higher fruit glossiness, higher metabolites content, a thicker pulp size, and a larger fruit size (Table 5). All these desired attribute were in comparison with their local landraces' performance.

The factorial analysis of correspondence revealed a variation of farmers' preferred traits across sociolinguistic groups and gender. For Igbo, the priority breeding traits included fruits size, early fruiting, seed viability, and germinability, while Yoruba rather mainly targeted fruits yield, fruits shelf life, fruits glossiness, plant growth rate, tree life span, and the fruiting frequency. The gender exerted a lesser influence on farmers' preferences compared with sociolinguistic groups, with men prioritizing fruits glossiness, fruits shelf life, early fruiting, and seed viability while women did not show any specific preference (Figure 7). There was also a larger variation of trait preferences within Igbo compared with Yoruba farmers (Figure 8). Noticeably, the Anambra respondents had a higher interest for traits such as early fruiting, fruit glossiness, and seed viability, while their counterpart from the Enugu were more interested in fruits shelf life and seed germination (Figure 8). Consequently, a higher congruity was found in farmers' preferences in Southwest also known as Yoruba land (Kendall's $W = 0.9$) compared with a moderate congruity in the identified preferences in the Southeast known as Igbo land (Kendall's $W = 0.5$; Table 6).

Consumer's preferences varied across ecological zones (Figure 9A) on one hand, and across sociolinguistic groups and gender (Figure 9B) on the other hand. Consumers from Southeast region, the Igbo, valued the glossiness of fruits (fruits aspect) and its metabolites content while those in the Southwest, the Yoruba, preferred a long sweetening action of the fruit, the taste, the fruits size, and the fruits shelf life. There was no variation in consumer's preferences within the Southeast region (Anambra and Enugu states). Conversely, in the Southwest region, while the informants from Ondo state preferred the fruit shelf life and the fruits size, their peers in Oyo state preferred the fruit taste and its potency (long lasting of the sweetening activity). There was also a significant concordance in consumers preferences in Southeastern Nigeria (Kendall's $W = 0.7$), while a weak congruity was found in the identified preferences in Southwestern Nigeria (Kendall's $W = 0.4$; Table 6). Consumers' preferences were also gendered with women prioritizing fruit taste, fruit shelf life, and metabolites content whereas men were rather interested in traits including the fruit glossiness, potency, and the fruit size (Figure 9B).

TABLE 2 Farmers-faced constraints in *Synsepalum dulcificum* production in Southern Nigeria.

| Constraints | Southeast Nigeria | | | | Igbo | |
|---|---|---|---|---|---|---|
| | Anambra | | Enugu | | | |
| | *Mean score ± SD* | *Rank* | *Mean score ± SD* | *Rank* | *Mean score ± SD* | *Rank* |
| Insect damages | 5.3 ± 0.6 | 1 | 3 ± 1.1 | 4 | 4.4 ± 1.5 | 1 |
| Bird damages | 3.8 ± 1.0 | 3 | 3.7 ± 1.7 | 3 | 3.7 ± 1.4 | 3 |
| Low germinability | 3.8 ± 2.2 | 4 | 2.3 ± 1.2 | 7 | 3 ± 1.9 | 5 |
| Poor knowledge of cultivation technics | 4.1 ± 1.2 | 2 | 4.4 ± 1.9 | 1 | 4.3 ± 1.7 | 2 |
| Quick seed viability loss | 2.2 ± 0.4 | 6 | 2.3 ± 0.5 | 5 | 2.3 ± 0.5 | 7 |
| Drought | – | – | 4.3 ± 1.5 | 2 | 3 ± 1.4 | 4 |
| Lack of selling market | 3.3 ± 2.0 | 5 | 2.3 ± 0.7 | 6 | 2.8 ± 1. | 6 |
| | Southwest Nigeria | | | | Yoruba | |
| Constraints | Ondo | | Oyo | | | |
| | *Mean score ± SD* | *Rank* | *Mean score ± SD* | *Rank* | *Mean score ± SD* | *Rank* |
| Poor plant growth rate | 3.7 ± 0.6 | 7 | 2.7 ± 1.2 | 8 | 3.2 ± 1.0 | 9 |
| Drought | 6.5 ± 0.7 | 1 | 4 ± 1.4 | 3 | 4.8 ± 1.7 | 2 |
| Insects' damages | 5.3 ± 01.5 | 2 | 6.3 ± 1.5 | 1 | 5.8 ± 1.5 | 1 |
| Parasitic weed | 2.7 ± 1.2 | 10 | 4.7 ± 2.1 | 2 | 3.7 ± 1.9 | 6 |
| Birds' damages | 3.7 ± 0.9 | 6 | 3.8 ± 2.2 | 4 | 3.8 ± 1.8 | 5 |
| Quick loss of seed viability | 3.2 ± 2.4 | 9 | 2.6 ± 0.7 | 9 | 2.9 ± 1.7 | 10 |
| Poor knowledge of cultivation technics | 4.1 ± 1.9 | 4 | 3.3 ± 2.3 | 6 | 3.7 ± 2.2 | 7 |
| Low germinability | 4.3 ± 3.3 | 3 | 3.5 ± 2.4 | 5 | 3.9 ± 2.7 | 4 |
| Bush fires | 4 ± 1.4 | 5 | – | - | 4 ± 1.4 | 3 |
| Lack of labor | 3.5 ± 2.1 | 8 | – | - | 3.5 ± 2.1 | 8 |
| Lack of selling market | 2.2 ± 0.4 | 11 | 2.8 ± 1.5 | 7 | 2.4 ± 1.0 | 11 |

TABLE 3 Kendall's concordance coefficient for the listed constraints in Southwestern Nigeria (Ondo and Oyo), in Southeastern Nigeria (Anambra and Enugu), and between Igbo and Yoruba sociolinguistic groups.

| Regions | Kendall's coefficient of concordance (W) | Chi square ($\chi^2$) | *p* value (*p*) |
|---|---|---|---|
| Southwest Nigeria | 0.8 | 182 | < 0.0001 |
| Southeast Nigeria | 0.6 | 46.1 | < 0.0001 |
| Southern Nigeria | 0.6 | 172 | < 0.0001 |

TABLE 4 Management of harvested products.

| | Proportion of fruits (%) | | | |
|---|---|---|---|---|
| | Anambra | Enugu | Ondo | Oyo |
| Fruits sales | 11.3 | 12.5 | 30.0 | 31.3 |
| Household use of fruits | 60.0 | 63 | 66.9 | 63.1 |
| Fruits gift | 28.7 | 24.5 | 3.1 | 5.6 |

# 4. Discussion

## 4.1. Management practices-based farmers typology

This study, conducted in Nigeria, expanded our knowledge of the current habitats of the Sisrè berry plant in West Africa. Previous studies reported the species to be predominantly present in-home gardens, cultivated farms, fallows, and gallery forests (Fandohan et al., 2017; Tchokponhoué et al., 2021). In this study, the species was also found in rainforests, which reflected that the suspected habitat fragmentation in the species may not be evolving at a similar rate across the distribution range in West Africa. Home gardens are overall becoming a back-up habitat for the species and serve as a reservoir for biodiversity conservation (Catalán et al., 2007; Galluzzi et al., 2010; Fandohan et al., 2017). The farmers typology pointed out to three groups with most of farmers (cluster 1 members) applying only limited practices, a result that corroborated observations in the republic of Benin where management intensity index was low (Management intensity Index < 15 vs. >30 in the evergreen region of Ghana; Tchokponhoué et al., 2021). The overall poor management of the species (from cluster 1 members) could be explained by the low economic value ascribed to the species by respondents in this cluster. Such a perception is not likely to trigger any active production initiative, and this was illustrated by the high tendency to inherit the species, a result that is also congruent with several previous studies on the dominant mode of acquisition of the Sisrè berry plant (Fandohan et al., 2017; Tchokponhoué et al., 2021). Only, a low proportion of

TABLE 5 Overall farmers' and consumers' preferences for breeding traits.

| Preferences | Variable definition | Mean score ± *SD* | *Rank* |
|---|---|---|---|
| Farmers-desired traits for ideal variety development | | | |
| Plants growth rate | Developed variety is required to grow faster than the existing landraces. | 1.8 ± 0.9 | 1 |
| Fruit shelf life | Fruits from developed variety is required to have a longer shelf life than the landraces. | 1.7 ± 6 | 2 |
| Fruit yield | New variety is expected to produce stable and consistent yield across production environments. | 1.6 ± 1.1 | 3 |
| Pest and drought tolerance | New variety is expected to tolerate the drought, pests, and diseases, and produce even in the bad season. | 1.4 ± 0.5 | 4 |
| Fruiting frequency | The improved Sisrè berry plant is expected to fruit at least twice times per year. | 1.3 ± 0.7 | 5 |
| Seed longevity | New variety is required to have a high seed longevity and a good capacity to germinate. | 1.2 ± 1.1 | 6 |
| Early fruiting | Developed variety must be capable to bear fruit earlier than their current landraces. | 1.2 ± 0.8 | 7 |
| Tree span | New variety of Sisrè berry plant is expected to have an upright growth habit with several branches. | 1.1 ± 1.1 | 8 |
| Fruit glossiness | Fruits from the new variety must be glabrous, uniform, attractive, and good looking. | 1.1 ± 0.9 | 9 |
| Seed germination | New variety is required to have a high seed viability and a good capacity to germinate. | 0.5 ± 0.7 | 10 |
| Fruit size | The new variety is expected to have bigger fruits than the existing landraces. | 0.3 ± 0.5 | 11 |
| End-consumers expectation for an improved sweet berry's variety | | | |
| High miraculin potency | The sweetening effect of the improved miracle fruits is expected to last longer. | 2 ± 1.6 | 1 |
| Fruit glossiness | Fruits from the new variety must be glabrous, uniform, attractive, and good looking. | 1.6 ± 0.8 | 2 |
| Metabolites content | Improved Sisrè berry plant is expected to have high miraculin content and other nutrients. | 1.5 ± 0.7 | 3 |
| Pulp size | Improved variety is expected to provide much more pulp to facilitate the processing. | 0.9 ± 0.7 | 4 |
| Fruits size | The new variety is expected to have bigger fruits than the existing landraces. | 0.4 ± 0.6 | 5 |
| Taste | Improved variety is expected to have a good taste. | - | 6 |

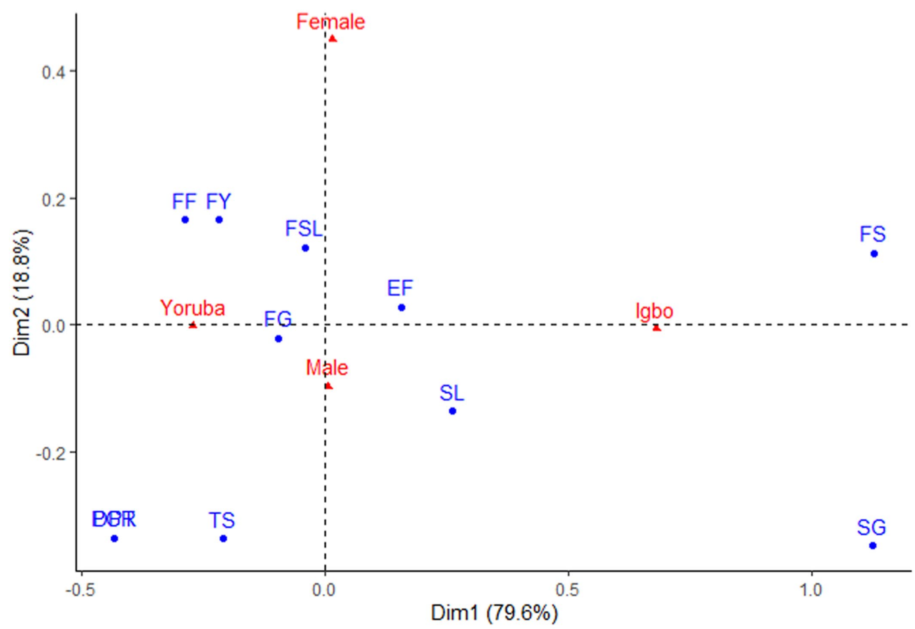


FIGURE 7
Association between farmers' preferences for breeding trait and sociolinguistic group and gender. DPT, Drought and pest tolerance/resistance; EF, Early fruiting; FF, Fruiting frequency; FY, Fruits yield; FS, Fruits size; PGR, Plant grow rate; TS, Tree span; FSL, Fruits shelf life; SL, Seeds longevity; SG: Seeds germination; and FG, Fruit glossiness.

respondents (cluster 2 and cluster 3) considered the species as economically important. Noticeably, those respondents mostly had a high level of education, which explained their motivation for large-scale cultivation of the species (up to 2,700 stands). These farmers have a better access to the information about the crop, in particular the trading opportunities in the crop. Indeed, these farmers

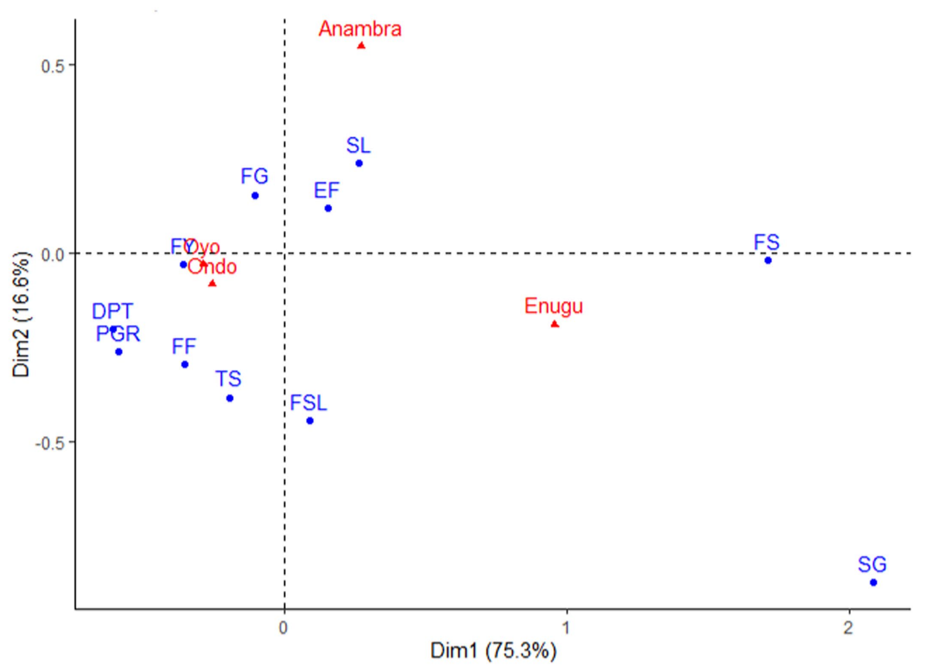


FIGURE 8
Association between farmers' preferences for breeding traits and ecological zone. DPT, Drought and pest tolerance/resistance; EF, Early fruiting; FF, Fruiting frequency; FY, Fruits yield; FS, Fruits size; PGR, Plant grow rate; TS, Tree span; FSL, Fruits shelf life; SL, Seeds longevity; SG, Seeds germination; and FG, Fruit glossiness.

**TABLE 6 Kendall's concordance coefficient for the identified preferences in Southwest Nigeria (Ondo and Oyo), in Southeast Nigeria (Anambra and Enugu), and between Igbo and Yoruba sociolinguistic groups.**

| Regions | Kendall's coefficient of concordance (W) | Chi square ($\chi^2$) | *p* value (*p*) |
|---|---|---|---|
| Consumers' preferences | | | |
| Southwest Nigeria (Yoruba) | 0.4 | 4.1 | 0.5 |
| Southeast Nigeria (Igbo) | 0.7 | 7 | 0.2 |
| Farmers' preferences | | | |
| Southwest Nigeria (Yoruba) | 0.9 | 18.4 | 0.0 |
| Southeast Nigeria (Igbo) | 0.5 | 10.5 | 0.4 |

are anticipating on the potential value of the species and are targeting either the international niche market (cluster 3) or have local market to satisfy (Cluster 1). In Ghana already, it was noticed that any single farmer holding a plantation of the Sisrè berry plants has a contract with a processing company that not only guarantees the market, but also provides funding for the plantation maintenance (Tchokponhoué et al., 2020). This calls for the necessity for implementing a subsidy system for the production of the Sisrè berry plantations, should West African governments promote this tremendous resource.

## 4.2. Awareness of varieties or morphotypes in Sisrè berry plant

The two cultivars of Sisrè berry reported in this study were previously signaled by various authors (Njoku et al., 2015; Tchokponhoué et al., 2020). While the red-skinned morphotype is widely distributed across Africa (Inglett and May, 1968; Bartoshuk et al., 1974; Huang et al., 2012; Njoku et al., 2015; Iloh et al., 2017) and well known worldwide (Inglett and May, 1968; Bartoshuk et al., 1974; Huang et al., 2012; Njoku et al., 2015; Iloh et al., 2017), the yellow-skinned morphotype seemed to be confined to Southeast Nigeria in West Africa (Inglett and May, 1968; Bartoshuk et al., 1974; Huang et al., 2012; Njoku et al., 2015; Iloh et al., 2017). Indeed only the red morphotype was reported by famers investigated in Benin, Ghana, and Togo in the framework of the ongoing breeding initiative on the species (Tchokponhoué et al., 2020). The fact that the two morphotypes reported by farmers are each specific to a region could be explained either by a low or absence of exchange of planting material of the species between Igbo and Yoruba or the hypothesis of habitat preference by each morphotype. Angeles et al. (2017) already reported an emergence of the yellow-fruited morphotype in a lot of 23,000 Sisrè berry plants cultivated in Calauan, Laguna, Philippines though where these plants batches were obtained from was unclear. Nevertheless, since the Sisrè berry plant is known to originate from West Africa, we can speculate that Southeast Nigeria would the center of origin of the yellow morphotype. In the context of the breeding strategies in the species, this yellow morphotype represents a potential source of favorable alleles that can be tapped to improve some key traits of interest for the farmers. Indeed, the fruit of the yellow morphotype is nearly two times bigger (data not shown) than the red morphotype and can for instance be relevant in the development of big fruit-sized cultivars. In addition, the yellow morphotype exhibited some primitive characters such as prominence of pubescence in several plant parts (fruits, leaves), seed coat thickness (data not shown). Consequently, further in-depth comparative phenotypic analysis and molecular phylogenetic analysis

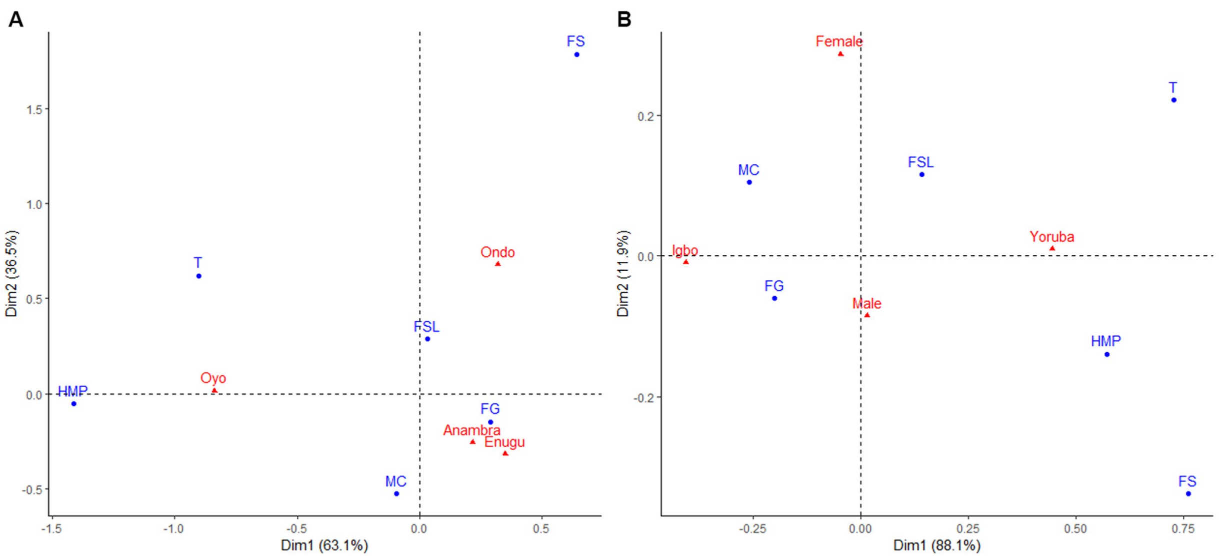


FIGURE 9
Association between consumers' preferences for breeding traits and ecological zone **(A)**, and sociolinguistic group and gender **(B)**. HMP, High miraculin potency; MC, Metabolites content; FG, Fruits glossiness; FS, Fruits size; T, Taste; FSL, and Fruits shelf life.

are then needed to clarify the relationship between these supposed morphotypes.

## 4.3. Production constraints and other challenges

Insect and bird damages and difficulties in the crop management were the major constraints faced by the surveyed farmers in Southern Nigeria. In fact, the ripe miracle fruit is a small berry finely pubescent with bright red/yellow skin. The brightness combined with the fruit's sweetness attracts herbivorous insects and birds which feed on the fruits (Stevens and De Bont, 1980). These insects and birds-induced damages were previously reported in cherries (Lindell et al., 2012), peach, apple, pear, grape, and loquat cultivation (Hao et al., 2011; Lindell et al., 2012) and are likely to induce important economic impact on producers (Anderson et al., 2013; Angeles et al., 2017). As a physical protection technique, pre-harvest bagging of fruits was developed and have been chiefly used in several species including *Vitis vinifera* L. (grapevines; Karajeh, 2018), *Psidium guajava* L. (guava; Srivastava et al., 2023), and *Mangifera indica* L. (mango; Nadeem et al., 2022). The pre-harvest bagging optimizes fruit quality by reducing physical damages and damages by pathogens, and increases market value of the fruits (Sharma et al., 2013).

Quick loss of seed viability and poor germination seemed to be more common in Southeast, while slow plant growth, drought, and bushfires were prominent in the Southwest region. It has been established that *S. dulcificum* produces recalcitrant seeds with seeds losing viability in few days after harvesting (Tchokponhoué et al., 2019). This explains farmers' observation of quick loss of viability and poor germination. A slow growth of plants was reported by over 70 % of respondents. This observation was experimentally established by Tchokponhoué et al. (2018). These observations suggested farmers' good knowledge of the species' biology. Other studies also reported Sisrè berry plant as a slow-growing species with two growth phases. The first growth phase corresponding to the first 4 years where the plant grows very slowly reaching about 50 cm tall, and a second phase, starting from 4-year-old onwards where the plant grows faster. *Synsepalum dulcificum*'s growth is slow compared to other economically important species. For instance, at the same age, *Vitellaria paradoxa* (a sister species to *S. dulcificum* in the Sapotaceae family) can be four times taller (Allaye Kelly et al., 2004). The higher frequency of seed-biology related challenges reported in the Southeast indirectly suggested that the yellow-skinned morphotype could have a more sensitive seed physiology compared with the red-skinned, since producers of the later morphotype did not face too much such a challenge. This poor seed physiology marked by a short seed lifespan of the yellow-skinned morphotype might explain its low popularity. Drought and bushfires are important constraints in the Southwest of Nigeria. Indeed, in this region, the species is mainly found in farms, fallows, or forests, which are open-habitats, hence low protection and management by farmers as compared with plants found in home gardens in the Southeast. Bushfires were commonly reported to threat for several economically important trees such as *Vitellaria paradoxa* C. F. Gaertn., *Tamarindus indica* L., and *Sclerocarya birrea* (A. Rich.) Hochst (Gaisberger et al., 2017). The dry season in southern Nigeria lasts for 6 months (November to March) yearly (Ojo, 1977), a period over which local communities used to burn the bush and some parts of forests which are also habitats of Sisrè berry plant.

## 4.4. Market chain analysis

The harvested products were mainly for household use or sold on local markets by about 94% of respondents. However, the other 6% of the farmers have access to the international market, with an important export of fresh fruits to United States. This more advanced farmers also explore the potential for processing fruits into powder or juice locally. This indicates that there is a potential to up-scale production as market opportunities exist. An illustration is the European Union market that has recently admitted the dry powder of the Sisrè [EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA) et al., 2021]. Besides fruit uses, the dry seeds have high commercial value as the dry seeds attract approximately two times higher price compared with the fresh fruits. The dry seeds are used in the production of a cosmetic oil used in women hair breakage treatment (Del Campo et al., 2017).

### 4.5. Farmers' and consumers' preferences for breeding traits

An analysis of end-users' preferences helps breeders detect hidden traits of interest, and both famers and consumers formulated their trait preferences (Bolfarine and de Oliveira Bussab, 2005). For instance, the slow growth was on the highlighted challenges, indicating the desire of farmers to have a fast-growing cultivar that can bear fruits earlier. Although farmers in Nigeria listed a lower number of preferred-traits (11) compared with their counterparts in Benin and Ghana (who highlighted 19 traits), it is worth pointing out that seven out of the 11 traits were already reported by farmers in Benin and Ghana (Tchokponhoué et al., 2021). This suggest that Sisrè berry plant farmers in West Africa share preferences for an improved variety of Sisrè berry plant. More importantly, four out of the top five desired traits in this study were previously highlighted by the species producers from Ghana and Republic of Benin (Tchokponhoué et al., 2021), thus strengthening the necessity to promote region-wide cultivars development initiatives.

Most of the farmer's preferences converged to high fruit yielding while consumers preferred visual and nutritional traits. Farmers in miracle fruits production are seeking to maximize the profit through increased fruits yield while consumers would like to enjoy quality fruits with high glycoproteins and metabolites contents. End-users' preferences are most important to increase adoption of new varieties. To illustrate, most farmers in Africa and Latin America keep growing some specific Andean type of rice varieties with lower yield to satisfy particular traits required by consumers, even though some high-yield improved varieties (Mesoamerican types) exist (Beebe, 2012). Our findings revealed a variation of farmer's preferences across regions, sociolinguistic groups, and gender. However, from a West Africa regional perspective, combining previous findings (Tchokponhoué et al., 2020) with the current ones will lead to the definition of key breeding traits for both farmers and consumers, and the establishment of product profiles by breeders.

## 5. Conclusion

The study investigated the management practices, farmers and consumers' preferences for Sisrè berry plant. Several constraints limited Sisrè berry plant cultivation with the insect and bird attacks and seed germinability related constraints being dominant. Additionally, parasitic weeds infestation was exclusively mentioned in Southwest Nigeria. A total of nine preferred traits were mentioned by farmers while six traits were reported by consumers. For farmers, the desired variety should be a fast growing and high yielding one that withstands pests and birds' attacks while producing fruit with an extended shelf life. As for the consumers, the desired variety should be big size fruits with a high edible mass, metabolite content and a high potency of miraculin. These findings pave the way for a west Africa-wide elite cultivar development to meet the increasing demand in the Sisrè berry plant and its by-products.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

DT and EA-D: conceptualization, visualization, and project administration. DT and EL: methodology, formal analysis, and writing—original draft preparation. EA-D and HO: validation and supervision. EL: investigation, data curation, and funding acquisition. SN'D, DN, HO, and EA-D: writing—review and editing. All authors contributed to the article and approved the submitted version.

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## In memoriam

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Sustainability of dairy farming in Colombia's High Andean region

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Bovine livestock covers more than a third of the earth's surface and has transformed various natural ecosystems in different parts of the world, including those in fragile, biodiverse regions. Such livestock is found in several of these ecosystems throughout Colombia, and face productivity limitations and environmental impacts. One of them, the High Andean region represents a strategic ecosystem for the conservation of biodiversity globally. Dairy farming in this area has undeniable socioeconomic relevance that is currently threatened by climate variability and market globalization. In this article we explore key elements for the sustainability of dairy livestock in the High Andean region, considering environmental conditions, technical and economic viability, as well as its relationship with society's values and objectives. Through applied research, field trials, participant observation, consultation with experts, and bibliographic review, we analyze the factors that hinder dairy farming in the High Andean region. We conclude that the traditional models-extensive and conventional intensification-present economic problems, generate environmental impacts and are vulnerable to current changes in the social and environmental plains. We propose to venture into different approaches and technologies, such as agroecological production with silvopastoral systems.

KEYWORDS

**high altitude tropics dairy system, silvopastoral systems, ecosystem services, agroecological transition, sustainability**

## 1. Introduction

Cattle ranching stands as a prevailing agricultural activity in Colombia, featuring economic and social importance. In 2022, the country accounted for a domestic livestock population of 29.6 million (ranking 11th globally) representing 21.8% of the agricultural GDP and 48.7% of the national livestock GDP (FEDEGAN–Fondo Nacional del Ganado, 2022). Livestock is carried out in 620,509 farms, with 80.24% of them operating with less than 50 animals. This economic activity generates livelihoods for many small farmers and provides direct employment for about 1,100,000 people (19% of agricultural employment) (FEDEGAN–Fondo Nacional del Ganado, 2022). However, productivity levels per unit area and per animal at the national level are very low, with an average carrying capacity of 0.7 cattle per hectare (ICA-Fedegán, 2020), with a predominance of extensive livestock systems (Vergara, 2010) that generate environmental impacts common to livestock at a global scale (Herrero et al., 2009; Gerber et al., 2013). Livestock activities are widespread across the country, especially in the Andean, Caribbean, and Orinoquia regions, encompassing over 85% of the national herd (Parodi et al., 2022). A portion of Colombia's livestock production takes place within biodiverse and fragile ecosystems, including lowland tropical forests, dry forests, wetlands, and the High Andean region. These areas are characterized by low productivity and a high impact of livestock on its natural resources (Zuluaga and Etter, 2018).

Studies on biodiversity conservation and sustainable land use propose excluding or conditioning livestock in different regions of the country. This recommendation is based on different criteria such as the presence of endemic species, topography, and the occupation of protected regions or high-interest ecosystems (Zuluaga et al., 2021). Considering this aspect, the national livestock policy aims to release production zones unsuitable for livestock, to allocate them to the conservation of natural ecosystems or other agricultural production (MADR and MADS, 2021). In this scenario, intensification of livestock systems is promoted to free up areas for other uses and achieve production that meets the growing demand, while improving producers' economic conditions (FEDEGAN, 2006).

## 1.1. Livestock intensification

In the last 50 years, agricultural intensification has been based on the Green Revolution model characterized by the adoption of industrial synthetic inputs (agrochemicals), seed selection, single-crop systems, specialized livestock breeds, and technology reliant on non-renewable energy sources (Funes-Monzote, 2008; Altieri et al., 2012; Serrano-Tovar, 2014; Preston et al., 2021). The specialized dairy sector in Colombia mainly concentrated in the High Andean region has followed this trend, and stands out as one of the most productive livestock systems in the country (Holmann et al., 2003; Carulla and Ortega, 2016; UPRA, 2020). Besides, this type of intensification in livestock systems implies high costs, inefficiencies, reliance on non-renewable energy, and limited profitability (Holmann et al., 2003; Llanos et al., 2018). This is especially evident in regions characterized by special biophysical conditions, such as the high Andean hillsides. This production model also gives rise to both the direct and indirect environmental consequences observed in conventional intensive systems (Funes-Monzote, 2008), including the loss of biodiversity in a globally significant region (Orme et al., 2005). In contrast, dairy farming in Colombia faces threats from climate change and the demands of globalized markets, which demand increased competitiveness (Carulla and Ortega, 2016; Cadena et al., 2019). This situation leads to a reflection on the sustainability and resilience of dairy farming in the high tropics, within the global discussion derived from the growing demand for animal protein and, at the same time, for environmental services (FAO, 2018; Preston et al., 2021).

## 1.2. Livestock in High Andean region ecosystems

The Northern Tropical Andes are considered one of the richest and more biologically diverse regions globally, accounting for more than 100 different ecosystems, 45,000 vascular plant species (20,000 endemic), and 3,400 vertebrate species (1,567 endemic), all within just 1% of the earth's continental area (Josse et al., 2009). The mountain forests of the Northern Andes hold great significance for conservation efforts, being recognized as one of the world's six biodiversity hotspots. This region has been a focal point for the diversification of numerous species (Scatena et al., 2010). Additionally, it is also recognized as an area with a high level of endemisms (Tejedor et al., 2012) and threatened species, being the only region on the planet in which these three categories coincide (Orme et al., 2005). The heterogeneity of ecosystems in the Andean region stems from the emergence of the longest mountain range on Earth (Orme, 2007). This diversity is further shaped by factors such as volcanic activity, tectonic shifts, soil formation, and the equatorial climate with year-round rainfall distribution (Guhl, 1959; IGAC, 2015).

In Colombia, the Andes Mountain range divides into three branches, resulting in distinct environments on both the western and eastern flanks. These disparities encompass a wide range of factors, including differences in precipitation levels (varying from 500 to 4,000 mm), average temperatures (ranging from 12° to 18° C), evapotranspiration rates, altitude, and topographic features (Rodríguez et al., 2006). Despite the differences, some characteristics can be generalized in the Andean region, such as the maintenance of a stable temperature throughout the year, albeit with fluctuations in daily maximum and minimum temperatures of up to 20°C (Buytaert et al., 2006), relatively low temperatures comparative to those at lower altitudes in the tropics, steep, sloping topography (>12%), smooth highlands, and fog in higher elevations (Hall et al., 2015). The Andean region experiences the dual influence of the Pacific Ocean to the west and the Orinoco and Amazon River basins to the east. The interplay of oceanic and continental air masses in the region's intertropical confluence zone results in a bimodal pattern of rainfall (Buytaert et al., 2006). This distinguishes it from other regions in Colombia and provides specific benefits for agricultural endeavors, especially in the production of coffee, tropical fruits, and livestock.

## 1.3. Transformation of the High Andean region's ecosystem

The earliest human settlements in the eastern Andes region of Colombia can be traced to approximately 10,000 to 12,000 B.C., as evidenced by the Tequendama rock shelters (Correal Urrego and Van der Hammen, 1977). Evidence suggests that the Andes ecoregion has been transformed by humans for nearly 9,000 years (Young, 2009). Currently, 70% of the Colombian Andean region is used for agricultural activities, especially livestock, which began to increase its coverage and intensity from the beginning of the 20th century (Etter and Van Wyngaarden, 2000; Murgueitio, 2003). The grasslands expanded in newly converted areas from 65.8% in 1750, to 97.2% after 1970 (Etter and Van Wyngaarden, 2000). These alterations in land use have resulted in the modification of landscapes, leading to significant fragmentation of both altitudinal and longitudinal corridors within the Andean forests, thus affecting biodiversity (Etter and Van Wyngaarden, 2000; Young, 2009).

Despite the extent of alteration, the paramo ecosystems cover approximately 1,925,410 hectares in the Colombian Andes, of which 746,644 are in National Natural Parks. They host natural habitats characterized by high level of endemism at nearly 90% (Rivera and Rodríguez, 2011). In addition, relicts of Andean forests are still

TABLE 1 Conditions of mountain ecosystems that potentiate the mechanisms of biodiversity loss and impact on ecosystem services generated by livestock.

| | Intrinsic conditions of mountain ecosystems that make them vulnerable | | | |
|---|---|---|---|---|
| Livestock impacts | Varied topography, steep mountainous areas | Low temperatures | Presence of fog | High altitude forest, paramo ecosystems, and hydraulic network |
| Deforestation and loss of native plant cover | Laminar or mantle erosion, reticular, in gullies and landslides, displacing mass | Limits recovery of native vegetation | Affects water regulation due to lack of trees and shrubs to retain moisture | Biodiversity, fragmentation, and endemism loss. Drag of sediments by micro-basins and rivers. GHG emission |
| Fodder monoculture, use of fire and herbicides, application of synthetic fertilizers and pesticides | Loss of soils in tillage, different grades of erosion. Herbaceous species in livestock systems are more susceptible to erosion processes than forest ecosystems. Agrochemical contamination of soils and waters. | Slow growth of native species does not compete with foreign species. E.g., *Cenchrus clandestinus* grass dominant in the region. Slow soil recovery rate. Accumulation of contaminants. | Pasture cover does not retain, regulate, or take advantage of moisture like the rest of the natural ecosystem. Reduction of "horizontal rain." | Biodiversity loss due to invasion of fast-growing species. Forest fragmentation, agrochemical contamination of water bodies, micro-basins, and basins. Eutrophication of wetlands and lentic bodies of water. Loss of hydrobiological resources. |
| Direct effects of livestock, grazing, and trampling | Loss of soil, compaction, damage to the physical structure. High erosion in cattle transit areas. | Slow recovery of vegetation after grazing. Delayed soil biophysical recovery processes. | | Grazing hinders the maintenance of forest cover and natural regeneration. Water pollution by leaching and excreta runoff. Loss of aquatic species in bodies of water. Reduction of functional biodiversity for nutrient recycling (dung beetles, earthworms, fungi, and bacteria). |

Source: Author's elaboration based on: Morales and Armenteras (2013), UPRA (2020), and Zuluaga and Etter (2018).

preserved on the highest mountainsides, as well as on the eastern and western flanks, while on the slopes toward the inter-Andean valleys the ecosystems are highly deteriorated, with some areas retaining only 10% of the original ecosystem (Tejedor et al., 2012). Part of this remaining biodiversity is found within cattle farms in which relicts of native forests are preserved (Chaves et al., 2007). These areas represent a crucial focus for restoration and conservation efforts due to the ecoregion's significance.

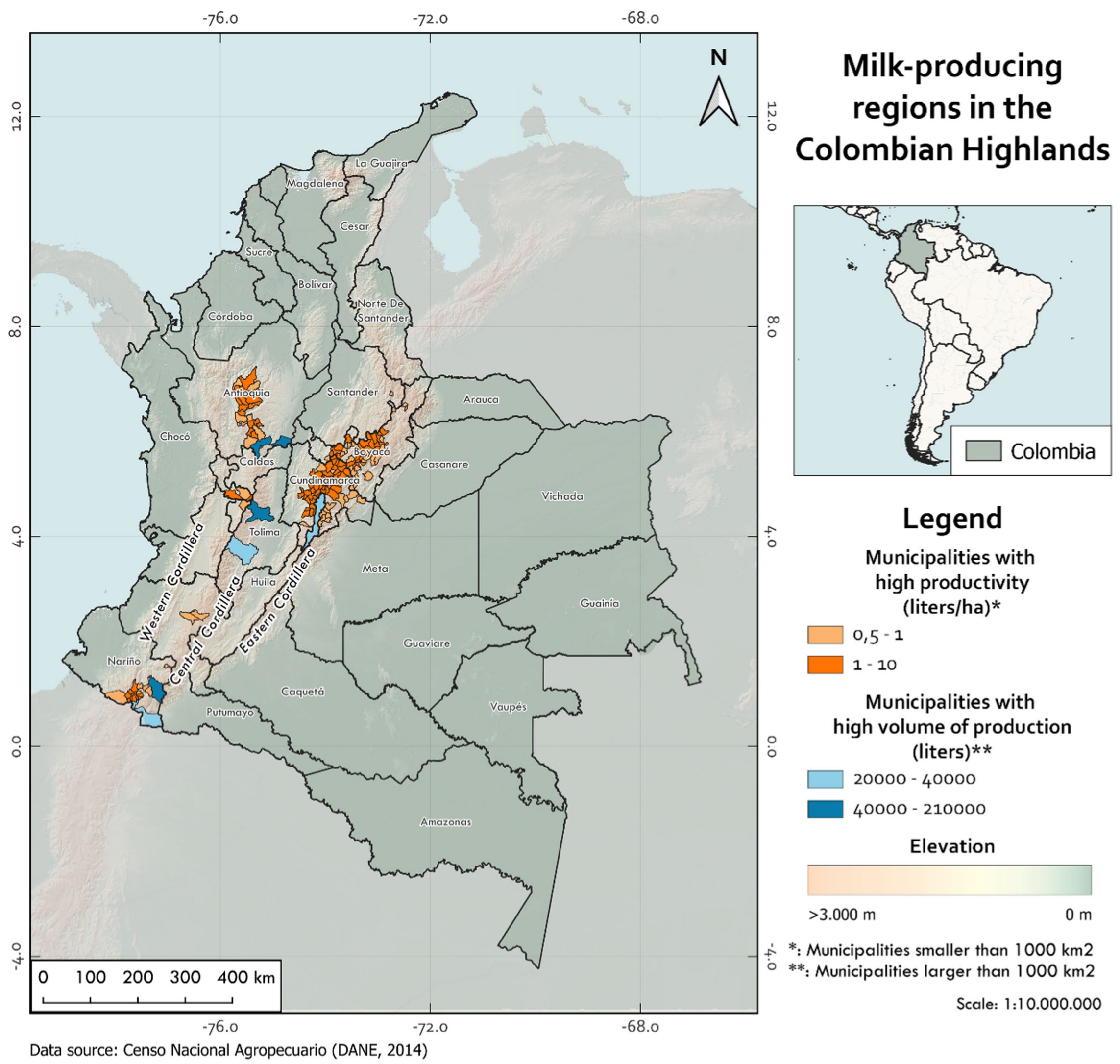
The definition of the High Andean region ecosystem varies according to the mountain range and authors' classification, with altitudes between 2,000 and 3,700 meters above sea level (Rodríguez et al., 2006). Here, references made to the High Andean region correspond to the mountainous areas of the Andes located higher than 2,000 m.a.s.l. and lower than the paramo ecosystem, generally up to 3,200 m.a.s.l., although important local variations are recognized that can expand or reduce the upper limit (Rivera and Rodríguez, 2011; UPRA, 2020).

### 1.3.1. Impact of livestock on biodiversity

The conditions of the high Andean zone make it especially fragile to current livestock models, mainly due to the transformation of forest ecosystems that causes loss of biodiversity. Amongst other related problems there is the emission of greenhouse gases (GHG) and the reduction of ecosystem services such as water supply, soil protection, and pest control (Galindo and Murgueitio, 2007; Balvanera et al., 2015). These challenges also impact other aspects of biodiversity values, including the cultural, spiritual, and aesthetic ones (Milcu et al., 2013). The distinctive attributes of mountains, including their diverse topography, reduced solar radiation, and lower temperatures, are linked to habitat loss, delayed native vegetation recovery, the extinction of endemic species, and the invasion of fast-growing non-native species in areas where livestock farming is introduced (Rodríguez et al., 2006; Tejedor et al., 2012; Morales and Armenteras, 2013) (Table 1).

## 1.4. Dairy farming in the Colombian High Andean region

The mountain forests and part of the lowland paramos were transformed by extractive agricultural and mining human settlements in addition to other civil work uses. Currently, most Andean Mountain land outside protected areas and inhabited regions is dedicated primarily to cattle farming (Etter and Van Wyngaarden, 2000). These farms typically operate according to the predominant conventional model, focusing on specialized or dual-purpose milk production (FEDEGAN, 2021). These are in highlands and slopes over 2,000 meters above sea level with temperatures between 12 and 17°C (Murgueitio, 2008; Carulla and Ortega, 2016; UPRA, 2020). Collectively, they contribute to 32% of the country's total milk production, equivalent to 2,270 million liters per year (approximately 6.21 million liters per day) (FEDEGAN–Fondo Nacional del Ganado, 2022). This production is obtained in moderate to high-tech grazing systems on predominantly small and medium-sized farms with an average of 3,480 liters/ha/year and 3,689 liters/cow/year (Ministerio de Agricultura y Desarrollo Rural de Colombia, 2020). Livestock farms are grouped into dairy farm regions: the "Cundiboyacense" highland, with 44% of production, Antioquia, with 45%, and Nariño, with 5% (Ministerio de Agricultura y Desarrollo Rural de Colombia, 2020), presenting differences in productivity between regions and production types (FEDEGAN, 2019). Map 1 illustrates the dairy areas of the highland tropics in Colombia.




MAP 1
High Andean dairy areas in Colombia. Source, Author's elaboration based in: DANE (2014) and IGAC (2015).

The intensified specialized dairy farming follows the principles of the Temperate Grazing System (TGS), a model that has been established in southern Australia, New Zealand, select areas of the United States, China, Chile, Mongolia, and the highlands of South America (Seré et al., 1996). This system is characterized by the utilization of enhanced forage, extensive irrigation, high nitrogen fertilization, concentrated feed, and the application of specialized dairy genetics. It results in above-average production levels compared to the national average in Colombia (FEDEGAN, 2015; UPRA, 2020).

This livestock activity is threatened by climate variability which has been manifesting in increasingly extreme patterns (IDEAM et al., 2015), as well as market volatility (FEDEGAN–Fondo Nacional del Ganado, 2022). Considering this, the sustainability of milk production systems in high-tropical regions has become a frequently discussed concern (Durana, 2011; Ruiz et al., 2019; Escobar et al., 2020). In this article, we examine sustainability within the conceptual framework established by Giampietro and Mayumi (2000). Our analysis incorporates field trials, participant observation, interaction with farmers, expert consultations, and a comprehensive literature review. Therefore, we evaluate current production models alongside agroecological practices from silvopastoral systems, considering their ecosystemic context.

## 2. Factors influencing livestock sustainability in the High Andean region

This document addresses the sustainability of livestock farming considering external conditions imposed by the ecosystem (environmental feasibility), technical and economic factors that can be controlled by humans (viability), and the social values related to this activity (desirability) (Giampietro and Mayumi, 2000; Serrano-Tovar, 2014). We also consider their resilience, defined as the ability of social or ecological systems to absorb external disturbances, reorganize, and maintain their structure, functions, and identity (Walker et al., 2004; Nicholls, 2013).

## 2.1. Environmental feasibility

Environmental feasibility, as a component of sustainability, is associated to the external limitations that biophysical factors impose on the production system and are beyond human control (Serrano-Tovar, 2014). With regards to conditions in the biophysical environment, one of the current problems of livestock farming in the high tropics is that it is implemented without considering the particularities of mountain ecosystems such as: (i) steep mountainsides susceptible to water erosion and high soil diversity (originating in sedimentary rocks, sediments, pyroclasts, igneous and metamorphic rocks, as well as their combinations), most of which contain chemical, physical, or biological limitations (Malagón, 2003; IGAC, 2015); (ii) variable ranges of rainfall with increasingly noticeable variability (IDEAM et al., 2015); and (iii) low temperatures, limited daylight hours caused by persistent fog cover and diminished oxygen levels at high altitudes (IDEAM et al., 2007). In addition, their heterogeneity is not taken into account, particularly in relation to the differences between more fertile high plateaus, and hillside or slope areas with less productiveness.

### 2.1.1. Andean high plateaus and mountainsides

The formation of the Colombian Andean region can be attributed to the collision of the Nazca Plate beneath the South American Plate, resulting in the emergence of the Andean Orogenic Trifurcation, represented by the three Colombian mountain ranges (Central, Eastern, and Western). Upon formation and evolution of the soils, there was a notable influence of climate changes in the Quaternary period that determined heterogeneous conditions of precipitations, temperatures and potential evapotranspiration in the Andean region, associated with the relief and its influence on the vegetation. The Andean region includes practically all the soil conditions of the Colombian territory (Malagón, 2003).

This heterogeneity is often overlooked in livestock management. There has been limited research on the distinctions between the high plateaus and mountain slopes in livestock production, such as their agricultural potential, biophysical constraints, and the provision of ecosystem services. For decades, research findings from cattle farming systems in temperate zones or in the neotropical highlands, characterized by soils of fluvial-alluvial or volcanic origin, flat or gently sloping terrains (suitable for mechanization), ample solar exposure, and higher evapotranspiration rates, have been extrapolated for application to vastly different conditions on steep Andean slopes. This uniform treatment of two distinct land types in the Andes, without due consideration for substantial differences, has led to environmental and economic problems. Given the region's diversity, broad generalizations are not feasible. However, this article offers an initial assessment of the distinctions between highlands and slopes, considering the natural factors that influence agricultural production and ecosystem services. Table 2 provides a summary of significant differences concerning the viability of cattle ranching in the Andean region at elevations between 2,000 and 3,200 meters above sea level.

TABLE 2 Natural differences between highlands and equatorial Andean mountainsides.

| Natural differences between high plateaus and Andean mountainsides that condition agricultural production and water ecosystem services | | |
|---|---|---|
| **Variable** | **High plateaus** | **Andean mountainsides** |
| Geological formations and terrain slopes | Depressions of lacustrine or alluvial origin, raised peneplains, to a lesser extent old glaciers, or volcanic structures. Slopes, from flat to steeply sloping/undulating. (<25%) | Mountains, mountain ranges and hills emerged as part of the mountain ranges. Slopes from moderately steep to strongly steep (>75%). |
| Origin, formation, and evolution of soil | Sedimentary, igneous, alluvial, lacustrine rocks and volcanic sediments | Sedimentary, igneous, and metamorphic rocks, sometimes covered by volcanic deposits |
| Soil depth (A and B horizons) | Moderate to high (deep). Superficial in some sectors. | Shallow to superficial. Sometimes with buried horizons because of volcanic activity (Central Cordillera) |
| Edaphic water retention | Between high and very high; with saturated zones | Low to moderate |
| Infiltration speed | Slow to moderate | Slow to moderate |
| Runoff | Low to moderate | High to very high |
| Susceptibility to waterlogging (flooding) | Moderate to high | Very low to non-existent |
| Susceptibility to water erosion | Moderate to very low | High to very high |
| Vulnerability to landslides and gully creation | Minimal to non-existent; moderate in hilly areas of the "Antioqueño" plateau. | High to very high |
| Luminosity – Solar radiation | Moderate to high | Moderate to low; with shadow effect of neighboring slopes. |
| Presence of fog and cloud circulation | Moderate and seasonal | High to very high, almost every month |
| Radiation frost | Moderate to strong over 2,500 meters; seasonal | Few and moderate at most altitudes; seasonal |
| Gales and drying winds | In some regions; occasional | Frequent |
| Organic carbon in the soil | Moderate to high | Low to moderate |

Source: Author's elaboration from IGAC (2015), CAR (2009), Malagón (2003), and Guhl (1959).

The factors presented in Table 2 indicate several advantages for highland production when compared to mountainous slopes, particularly in terms of relief, soil characteristics, water retention, and solar radiation. In relation to ecosystem services and environmental impact, mountainsides are more prone to erosion and the role they play in water regulation and water quality is more sensitive to alterations in vegetation cover. These aspects take on increased significance due to the urbanization pressures in the high plateaus that are pushing livestock production toward hillside regions. This trend is further intensified by the prohibition of agricultural activities in adjacent paramo ecosystems.[1]

Furthermore, geological, edaphic, hydric, and climatic variations result in different conditions for the viability of agricultural production in these two regions, affecting factors such as productivity, costs, labor requirements, and mechanization opportunities, as shown in Table 3.

The conditions presented in Table 3 show disadvantages for production on the slopes compared to the highlands in terms of relief, soil, water retention and solar radiation. This implies that the conventional intensification model borrowed from temperate regions and proposed for dairy farming in highland tropics, yields disparate outcomes in production and different effects on livestock systems situated in highlands versus those on mountainsides.

## 2.2. Viability of dairy production systems

Within the sustainability framework used in this document, the viability component refers to the internal conditions of the system: technological, economic, and social factors necessary to maintain its structure, identity, and functions (Serrano-Tovar, 2014). In the context of dairy farming in High Andean region, two contrasting production models can be discerned: extensive and intensive grazing, encompassing a spectrum of production systems that vary in terms of productivity, profitability, and environmental impact (Holmann et al., 2003; Carulla and Ortega, 2016; Cadena et al., 2019; UPRA, 2020). Although attempts have been made, industrialized cattle confinement dairy models such as those in North America, Europe, Argentina, and Uruguay do not persist in Colombia due to economic infeasibility (De Haan et al., 1977; Frossasco et al., 2015).

### 2.2.1. Prevailing models

The historical approach to livestock management in the High Andean regions has predominantly been extensive or extractive. In this approach, forage is harvested with poor animal supervision, few paddock divisions and minimal pasture rotation avoiding the recovery of the grass. Over time, this has led to soil degradation, compaction processes, and varying degrees of erosion, which are further exacerbated by steep terrain and periods of heavy rainfall. This approach is not markedly distinct from what has been characterized as cattle ranching with detrimental impacts on the underlying natural resources that support it (Huss et al., 1996). In these systems, animals seek out drinking water in small basins, near spring sources, along riverbanks, and within wetlands, resulting in bank damage and water contamination (Chará and Murgueitio, 2005). In recent years, this model has been the subject of proposals for its transformation across all scales and several continents (Pinheiro, 2004; Global Agenda for Sustainable Livestock [GASL], 2014; Savory and Butterfield, 2016).

Milk production in the Colombian High Andean region tends to change the extensive model for intensive grazing livestock, influenced by the Green Revolution and production practices in countries with dairy development such as New Zealand. Specialized dairy breeds, primarily Holsteins, are utilized, along with improved pastures sourced from temperate regions (comprising cultivars and hybrids of *Lolium* sp.) fertilized with high nitrogen doses and other elements, including chemical nutrient application in African-origin Kikuyu grass (*Cenchrus clandestinus*). These systems implement rotational

1 Law 1753 of 2015 and Law 1930 of 2018 "By means of which provisions are issued for the integral management of the paramos in Colombia."

**TABLE 3** **Production conditions in the highlands and equatorial Andean mountainsides (2000–3200 masl).**

| Conditions related to farming systems | | |
|---|---|---|
| **Variable** | **High plateaus** | **Andean mountainsides (slopes)** |
| Ability to open and maintain access and internal roads | Highly feasible with reasonable maintenance costs | Difficult to very difficult; high opening and maintenance costs. Serious severe erosion impacts. |
| Requirement of alterations due to acidity of soil and limitation of key minerals (P, Ca, Mg, K, B, Cu, Zn) | Moderate to high | High to very high |
| Soil's organic matter | High to very high | Moderate to low |
| Ease of mechanization and tillage costs | Easy mechanization, reasonable costs | Difficult or impossible mechanization. Need for animal traction (oxen, horses, mules), monocultures, or labor. Higher costs. |
| Susceptibility to compaction by livestock | Moderate to high | High to very high |
| Ease of mechanical decompaction | Easy with mechanization. Reasonable costs. | Difficult, with animal traction or labor. High costs. |
| Forage biomass production potential | High to very high | Low to moderate |
| Conduction of milk to the refrigeration tanks (when milking is carried out in the field). | Machinery (tractors and vehicles). Fast and moderate cost. | Animal traction (load-pulling) or human labor. Slow and expensive. |

Source: Author's elaboration from: Céspedes et al. (2021), Dietl et al. (2009), Infante (2021), and Murgueitio (2008).

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grazing facilitated by electric fencing and wiring, supplementation with silage (primarily from corn), hay and haylage, and concentrated feed made from imported raw materials (Murgueitio, 2008; Carulla and Ortega, 2016; Ruiz et al., 2019). Invasive plants are eradicated with herbicides and mechanical controls, while harmful insects are controlled with chemically synthesized pesticides.

With the transition to the intensive grazing model, production per animal and per unit area increases. In specialized dairy production, the national average is 12 to 14 liters/cow/day, while in the most advanced production systems, average productions per cow of over 27 L/d with annual production ranging between 25,000 and 40,000 L/ha. These parameters are mainly achieved in high plateau areas with high use of fertilizers (1,500 kg or more/ha/year) and supplementation of up to 7 and 8 kg of concentrate/cow/day (Carulla and Ortega, 2016).

Both extensive and intensive management practices have environmental impacts, as shown in Table 4.

### 2.2.2. Challenges associated with conventional intensification

The frequent overapplication of chemical fertilizers rich in nitrogen and phosphorus in forage production leads to long-term soil contamination and subsequent declines in productivity (Gliessman, 2002; Pezo, 2019). They also affect water sources and produce greenhouse gases (Garzón and Cárdenas, 2013). On the other hand, Kikuyu monoculture with high doses of nitrogenous fertilizer is affected by a complex of chewing and sucking insects (*Collaria* sp.) that alter forage quality, and thus affect production (Lopera et al., 2015; Ochoa et al., 2017; Rodríguez et al., 2019; Lopera-Marín et al., 2020). These are controlled through the application of various chemical pesticides, which, owing to their concentration, persistence, and resistance factors, imply environmental and human risks that have not been sufficiently evaluated yet (Márquez et al., 2010). Furthermore, non-renewable energy sources are employed in the manufacturing and transportation of fertilizers and concentrated feed, as well as in mechanized farming and mechanical milking operations (Rivera et al., 2014; Benavides, 2016). In this intensification model, a vicious circle is generated, resulting in an increase of production costs, as shown in Figure 1.

The reliance on external inputs, many of them imported, makes the dairy farms vulnerable to fluctuations in international markets (Cadena et al., 2019), and susceptible to geopolitical and social changes. Some of these inputs, widely used, are balanced feeds known as "concentrates" composed of cereals (mainly corn and sorghum) and soybeans. According to Ruiz et al. (2019), these concentrates constitute a significant portion of production expenses, representing between 38 and 51% of total costs. These are products that compete with human food and are frequently sourced from genetically modified monoculture crops, contributing to the loss of genetic diversity (Altieri, 2005). The use of inputs that involve non-renewable energy and synthetic nitrogen, not only impacts the economic viability of the system due to an increase in costs, but also compromises its environmental feasibility, by using non-renewable resources and generating different types of pollution (Primavesi, 2002; Veltman et al., 2021).

### 2.2.3. Socioeconomic factors

The adoption of the conventional intensification model led to a resurgence in milk production in Colombia, accompanied by additional advancements, including enhanced collection for the dairy industry and improvements in the cooling chain (Carulla and Ortega, 2016; Cadena et al., 2019; UPRA, 2020). Progress was also made in promoting associativity, compositional quality, and hygienic and sanitation standards of milk (UPRA, 2020). However, the growth rate slowed down, shifting from a production increase of 76% from 1990 to 2003 to a 6.7% increase between 2003 and 2017 (Cadena et al., 2019).

Even though 69% (54% + 15%) of milk in Colombia is produced at costs below the world average, close to 80% of producers (66% + 14.2%) have low levels of productivity (Ruiz et al., 2019), as observed in Table 5. This means that most milk producers have low

TABLE 4 Livestock management practices in the high Andean regions region that generate impacts on ecosystems.

| Type | Management | Impacts on the ecosystem |
|---|---|---|
| Extensive | Grazing in larger extensions with minimal pasture rotation<br>Overgrazing<br>Permanent grazing in areas with moderate to high slopes<br>No tillage or rotation with monocultures<br>Use of fire to control shrubbery and plant life | Deforestation (when new areas are opened for production)<br>Soil erosion and compaction<br>Genetic uniformity due to gramineous monoculture<br>Pressure on forest ecosystems due to the demand for wood and the entry of livestock into micro-watersheds<br>Emission of enteric gases ($CH_4$) and derivatives of pasture burning ($CO_2$) |
| Intensive – Conventional Intensification with external inputs | Frequent pasture rotation with heavy stocking rates<br>Mechanized tillage with inadequate tools/machinery (disc plows and others)<br>Improved pastures<br>Use of silos and hay<br>Specialized animal genetics<br>Livestock supplementation with concentrates (imported raw materials)<br>Chemical fertilization in high doses<br>Use of pesticides (herbicides and pesticides)<br>Sprinkler or gravity irrigation. | Soil compaction<br>Emission of enteric gases ($CH_4$)<br>Higher GHG emissions due to fertilization and excess excreta in milking areas ($N_2O$)<br>Loss of biodiversity due to the use of pesticides and antiparasitic products<br>Contamination due to the use of antibiotics and hormones<br>Ecological footprint of grain supplementation<br>Water and soil contamination due to the use of synthetic fertilizers and pesticides<br>Elevated water footprint when irrigating meadows |

Source: Author's elaboration from Carulla and Ortega (2016), Herrero et al. (2009), Murgueitio et al. (2020), and Preston et al. (2021).

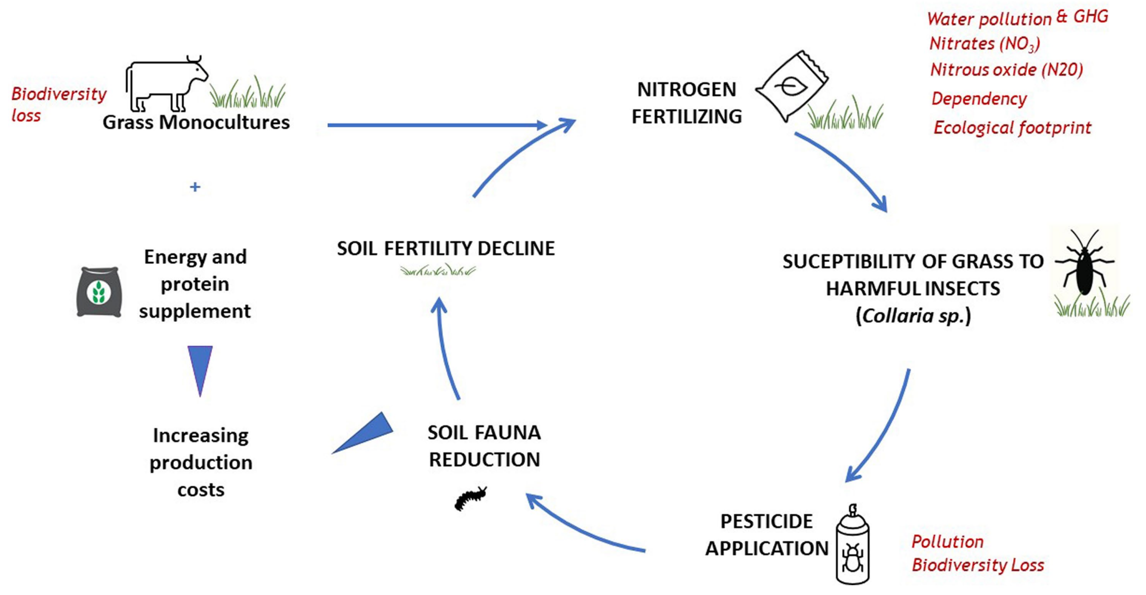


FIGURE 1
Vicious cost cycle of conventional intensification and environmental effects of milk production. Source: Author's elaboration from Lopera-Marín et al. (2020), Rodríguez et al. (2019), and Lopera et al. (2015).

TABLE 5 Distribution of dairy farms and milk production in Colombia based on productivity levels and production costs.

| | | Farm's milk output level | | | |
|---|---|---|---|---|---|
| | | Low | | High | |
| | | Share of total dairy farmers | Share of overall milk production | Share of total dairy farmers | Share of overall milk production |
| Production cost per liter of milk | Low (<0.27 US$) | 66% | 54 | 2.5% | 15% |
| | High (>0.27 US$) | 14.2% | N/A | 17.3% | N/A |

Author's elaboration from Carulla and Ortega (2016).

productivity; however, they also operate at lower costs. On the other hand, most of the farmers with high output level have higher costs per liter of milk. We infer that the intensification process, with the current model, should increase productivity but also implies higher costs.

An additional expense for the dairy sector is that of collecting milk, which is especially high in marginal areas due to the dispersion of small and medium-sized farmers who deliver a small amount daily to distant locations (Holmann et al., 2003; Carulla and Ortega, 2016; Cadena et al., 2019; UPRA, 2020). In addition to the inadequate state of the roads linking farms to consumption centers, there are occasional difficulties in traversing them due to adverse weather conditions or public disturbances. Rising costs are becoming increasingly significant due to competitiveness in the framework of the Free Trade Agreements (FTA) signed with the United States, Mexico, Chile, and the EU (Carulla and Ortega, 2016; UPRA, 2020). The recent global fertilizer crisis, triggered by Russia's invasion of Ukraine, coupled with inflation in numerous countries, including Colombia, has resulted in rising costs between 2022 and 2023 (Altieri and Nicholls, 2022). This illustrates the existing intensification model's reliance and susceptibility.

### 2.2.3.1. Differential markets

In addition to the high production expenses and their variability, milk prices are differential in the formal and informal markets, with the latter comprising more than 50% of the producers in Colombia (Cadena et al., 2019). The formal market, on the other hand, has its price regulated by the government (Carulla and Ortega, 2016; Cadena et al., 2019). As Colombia opens up to international markets, price regulation loses effectiveness and the sector requires to enhance its competitiveness (Cadena et al., 2019). Product characteristics, encouraged through price signals (Ruiz et al., 2019), have led to an improvement in milk quality, which indicates that they are an effective instrument to generate desirable changes in production systems (Durana, 2011).

During the last three decades of the 20th century, dairy farmers saw a substantial decline in their share of the final product price, as evidenced by the stagnant price per liter of milk paid to the farmers between 1996 and 2020, despite significant changes in input costs and labor (FEDEGAN–Fondo Nacional del Ganado, 2021). In 2022, a significant shift occurred as a result of the substantial global rise in input costs. This change led to a price increase of over 50% for milk in Colombia compared to its 2020 price (USP, 2022). However, this was partly offset by rising costs of fertilizers and animal feed. In short, the price of milk is increasingly subject to global market forces with uncertainty about future trends.

In addition to the barriers represented by certain characteristics of the High Andean regions' natural environment, the overarching technological advancements, climatic and market conditions, there exist factors in the land and labor markets that threaten the permanence of dairy farming in this region. Some authors have proposed relocating milk production to low-tropic regions, as high-tropic areas often entail a higher opportunity cost of land and face labor shortages due to urbanization processes (Valderrama, 2021). This poses a challenge that is not easy to handle for dairy farmers, society, and the government, because it is necessary to locate dairy farming areas on the legal border considering the soil's suitability (UPRA, 2020; Zuluaga et al., 2021). Climatic obstacles and parasitic diseases must also be fought against through practices such as crossbreeding and parasite control. Expenses and carbon footprint can increase due to extended transportation distances across inadequately maintained roads and the need to invest in the supply chain connecting farms to processing sites. Regarding social and cultural aspects, it will be essential to generate opportunities for rural workers in dairy production systems. This includes education and training, as well as improving living conditions to attract rural youth back to the countryside and promote generational succession of farmers.

## 2.3. Desirability

Desirability or convenience is one of the factors that influence the sustainability of a socioecological system and refers to its alignment with the social values that are expressed through culture, regulations, and institutions (Serrano-Tovar, 2014; Giampietro, 2015). This concept has a subjective component since it depends on the perspective of different actors involved; thus, it must be constructed from a consensus (Serrano-Tovar, 2014).

In the case of dairy farming in the Colombian high tropics, there is consensus that production is desirable. This is due to the significant amount of milk produced (32%) in a proportionally low area (9%), contributing to food security and economy while generating livelihoods and employment for the rural population. This, primarily comprises mainly small and medium-sized farmers (80%), along with the impact on various other participants of the dairy supply chain (Holmann et al., 2003; Carulla and Ortega, 2016; Cadena et al., 2019; UPRA, 2020). However, there is also consensus regarding the adverse effects of production systems, including pollution, the depletion of non-renewable resources, and the alteration of natural ecosystems (Murgueitio, 2008; Ruiz et al., 2019). It is also consensous that the biodiversity in these areas is important for environmental services (Calle, 2020).

## 2.4. Resilience of High Andean region livestock systems

The resilience of a socio-ecological system is defined as its ability to assimilate external disturbances, reorganize itself and preserve its structure, functions, and identity (Walker et al., 2004). It depends on the adaptability of individuals and social groups, that is, on the strategies derived from learning and innovation processes developed to assimilate changes in the environment (Salas-Zapata et al., 2012; Nicholls, 2013; León-Siccard, 2014). In agricultural systems, the environmental impacts at different scales can result in increased fragility in agroecosystems and a decrease of their resilience (Funes-Monzote, 2008; Altieri, 2013). In dairy farming in the High Andean region, the most significant challenges in recent years have been changes in climate patterns and the variable market conditions.

Climate change is evident in the form of fewer rainy days throughout the year in certain regions, an increase in atypical dry periods, more frequent frosts outside of typical seasons in the highlands, and longer and more intense rain periods than usual. In climate systems influenced by the Pacific Ocean, such as those in in the Andes, the frequency of the phenomena of El Niño and La Niña has increased significantly in the last two decades (Hurtado and Gonzalez, 2011; IDEAM et al., 2015). For example, in the milk production zone in the Ubaté and Chiquinquirá valley (Cundinamarca – Colombia) Gómez (2014) found that El Niño phenomenon increases the probability of frost by between 40 and 80% in the first dry months of the year. Furthermore, the outcomes of climate simulations show that kikuyu grass (*Cenchrus clandestinus*) is highly susceptible to frost, resulting in a decrease in milk production yields near 20%.

In seasons of prolonged or more intense rains, fodder production is also affected. This is compounded by poor water management, which exacerbates erosion, often leading to landslides that impact production areas, access roads, and livestock infrastructure. This, in turn, results in additional management and restoration costs. On the other hand, there is a loss in competitiveness with other countries that produce several times the volume of milk in Colombia and receive subsidies from their governments (Carulla and Ortega, 2016). This situation favors industries and large retail outlets, while significantly, and negatively, affecting dairy farmers, especially the smallest ones (Holmann et al., 2003; UPRA, 2020). All these factors combined simultaneously test the production system's resilience, as illustrated in Figure 2.

Figure 2 shows the trends in the establishment and intensification of livestock systems in highland Andean regions. In the first years, there is a process of deforestation and a decrease in the ecosystem services derived from the High Andean region forest, which drop abruptly in the areas that are transformed into pastures (a). The livestock system with the extensive model (blue lines) expands to new areas and a low level of productivity (blue line) and profitability (blue dotted line) is consolidated (b), which are gradually reduced when soils and pastures are degraded, and climate phenomenon occur (c and d). When an intensification process is carried out with the conventional model, productivity (red line) and profitability (red dotted line) increase (c), but new threats appear with climate change, input expenses, and additionally competitiviness in the globalized market. Under these conditions, productivity cannot be maintained unless external inputs are increased, which in turn affects profitability (d). Ecosystem services continue to deteriorate (b, c, and d).

Recent recommendations promote the transition toward models less dependent on inputs, with greater climate resilience that are concerned with environmental services, social responsibility, and animal welfare (Murgueitio et al., 2016; Gachetá et al., 2018; Mauricio

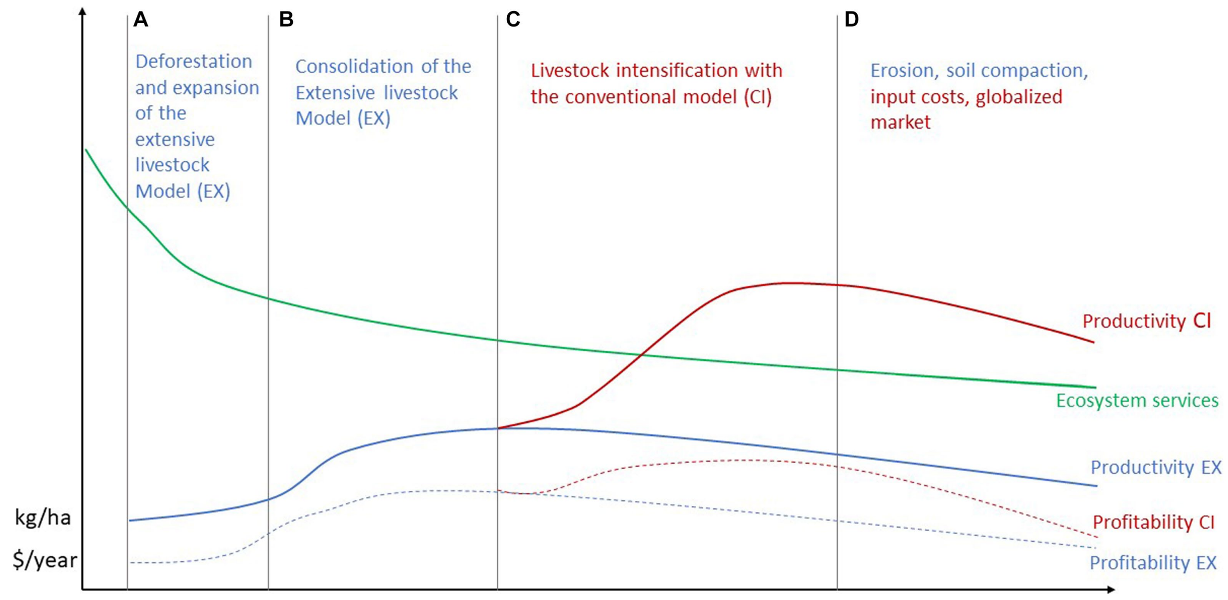


FIGURE 2
Diagram of temporal trends in productivity, profitability, and ecosystem services with extensive (EX) and conventional intensification (CI) models of cattle ranching in the High Andean regions. Author's elaboration from Cadena et al. (2019), Carulla and Ortega (2016), Holmann et al. (2003), and Pezo and Ibrahim (1998).

et al., 2019; Escobar et al., 2020; Lentijo et al., 2022; Montoya Uribe et al., 2023).

## 3. Silvopastoral systems for sustainable livestock in the High Andean regions

Considering the complexities of management and the environmental conditions in the high tropics, silvopastoral systems founded on agroecological principles offer a sustainable option for livestock production. They address issues of environmental feasibility, socioeconomic viability, and desirability, while ensuring the resilience of dairy farming in the High Andean regions. Additionally, they contribute to the preservation and restoration of rural landscapes (Murgueitio, 2008; Calle et al., 2012).

The establishment of silvopastoral systems is based on an allocation of land uses adjusted to the natural supply either for production or preservation, considering biophysical conditions such as slopes, wetlands, and poor, or infertile soil (Lopera et al., 2015; Infante, 2021). The pastures are managed as a diverse agroecosystem where the interactions between grass, legumes, *Asteraceae*, and other weeds are essential for the system (Cárdenas, 2003; Dietl et al., 2009; Galindo et al., 2019). The trees and shrubs integrated within the livestock system take nutrients from deeper layers with their roots, and generate biomass in their leaves and branches, producing fodder, enriching the soil with organic matter, and preventing erosion (Murgueitio et al., 2015; Zapata and Tapasco, 2016). Increased soil cover is achieved by different herbaceous species, including nitrogen-fixing species, as well as greater production of high-quality forage species, comprising those obtained from shrubbery (Cárdenas, 2011; Gallego et al., 2017; Guatusmal-Gelpud et al., 2020; Castro et al., 2021). Soil water retention and infiltration speed increase with this cover, reducing runoff, landslides, and gully formation (FAO, 2018; Giraldo and Chará, 2022). Different layers of vegetation, especially the trees, help maintain humidity, while the tree and shrub cover also protect the pastures against frost and wind (Snyder and de Melo-Abreu, 2010). A partial or total reduction of external inputs due to better management in forage production implies less use of non-renewable energy and synthetic nitrogen per liter of milk produced, and lower contamination rates (Silva et al., 2019; Rotz et al., 2020).

The technical and economic viability of dairy farming in silvopastoral systems in the high tropics relies on the application of agroecological principles to enhance high-quality forage production, reducing external inputs such as fertilizers, feed, and pesticides. This way, silvopastoral systems are more cost-efficient than those intensive in external inputs, and more productive than systems with the extensive model (Lopera et al., 2015; Chará et al., 2019). With the transition to silvopastoral systems in the High Andean regions, productivity and profitability can be maintained by allocating a greater proportion of the farm area for preservation. This approach also results in improved milk composition quality and less dependence on the market (Durana et al., 2022).

Figure 3 summarizes the actions implemented in a silvopastoral system, its effects over the agroecosystem, and the benefits for production it becomes more efficient, productive, and resilient. At the same time in contributes to the conservation of biodiversity and ecosystem services generation through agroecological production together with preservation and restauration of natural ecosystems in livestock landscapes (Calle, 2020).

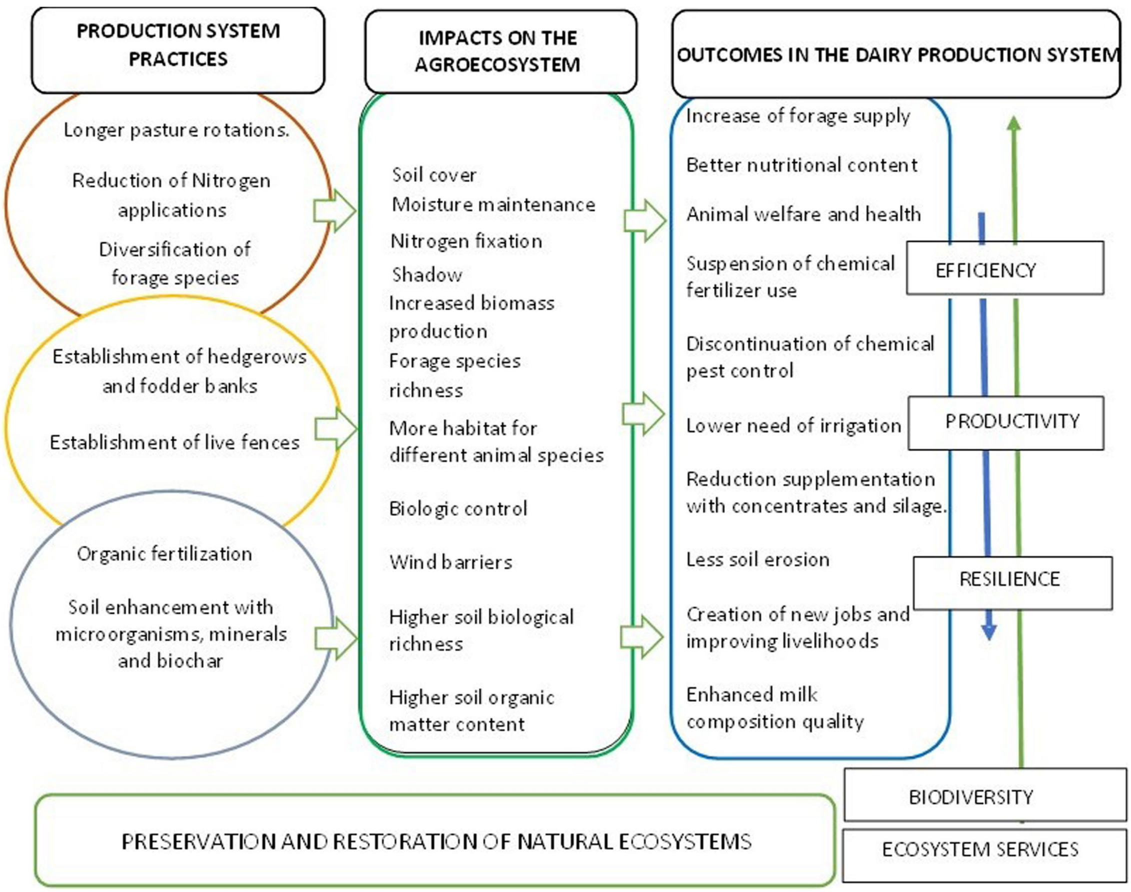


FIGURE 3
Production practices, impacts on the agrecosystem, and outcomes of agroecological and conservation management in high-altitude dairy silvopastoral systems. Source: Author's elaboration from Durana et al. (2022), Lopera et al. (2015), and Pezo and Ibrahim (1998).

Environmental feasibility and economic viability are complementary to the convenience or desirability of the system. Milk production in silvopastoral systems creates job opportunities, sustains livelihoods, and provides nutritional products without affecting the natural capital that supports it. By reducing the use of external inputs derived from non-renewable energy sources, pollution levels and GHG emissions decrease (Mahecha and Angulo, 2012; Montagnini et al., 2013; Chará et al., 2017; Giraldo et al., 2018; Silva et al., 2019; Aynekulu et al., 2020; Angulo-Arizala et al., 2021; Mahecha et al., 2021; Rivera et al., 2022). In silvopastoral systems aquatic habitats are protected and recovered (Chará and Giraldo, 2011; Galindo et al., 2017), and the welfare of animals is promoted (Broom et al., 2013). Silvopastoral systems reinforce the necessary conditions for biodiversity preservation, such as connectivity (Calle et al., 2012; Calle and Holl, 2019), while the capture of significant amounts of atmospheric carbon contributes to climate change mitigation (Chará et al., 2017; Peri et al., 2019; NAMA-Bovina Colombia, 2021; Rivera and Chará, 2021). Besides, agroecological production in silvopastoral systems integrated with preservation actions give a differential value to the product, no longer considered in the market as a basic commodity, but rather as a high-quality product, that improves human health, biodiversity, and ecosystem services.

## 4. Discussion

Current milk production systems in the high Andean tropics, especially on the slopes, face some problems of environmental feasibility, economic viability, and desirability, not complying with the precepts of sustainable development. Reducing reliance on external inputs lowers expenses, while the enriched agroecological base increases and sustains milk production levels in terms of quality and quantity (Lopera et al., 2015). In addition, in the current scenario of climate and market variability, it is necessary to develop adaptation strategies to maintain livestock production, competitiveness, and profitability. Agroecological production with silvopastoral systems and forest preservation has been proposed as a technological option that contributes to biodiversity preservation in fragile and strategic landscapes that also helps to prevent climate disturbances and maintain the agroecological and productive infrastructure (Figure 4).

Illustration of an idealized model representing the transition from a conventional milk production system to a silvopastoral system (SPS) in the high Andean region. Initially, there is a slightly decline in livestock production (brown line), and it is necessary to make an initial investment that impacts profitability (brown dotted line) (a). As the agroecological intensification is consolidated, it enhances the

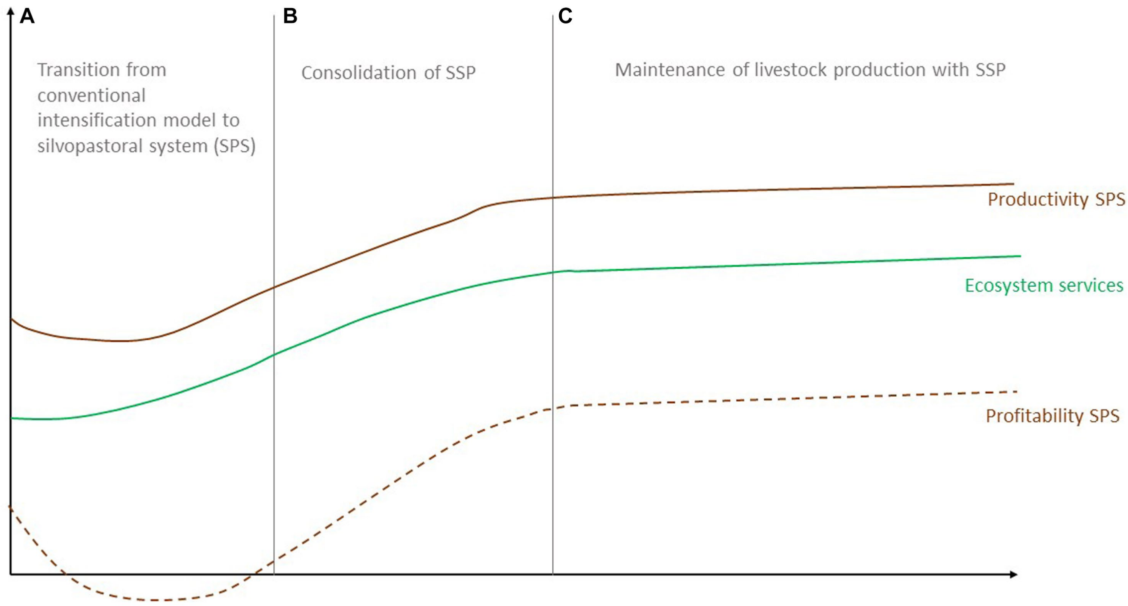


FIGURE 4
Behavior over time of the agroecological shift from a conventional model to a silvopastoral system. Source: Author's elaboration from Reyes et al. (2017), Lopera et al. (2015), and Pezo (2019).

productivity, improves profitability and ecosystem services (green line) (b). This situation is finally sustained over time and maintained in the face of external threats (c). The resilience of this agroecological intensification in the High Andean regions surpasses that of conventional models (Figure 2). This is because the "agroecological infrastructure" prevents the impacts of climate phenomena such as prolonged droughts or intense rains, due to soil and tree covers (Nicholls, 2013; León-Siccard, 2021).

The benefits described above lay out the need to scale up the transition toward agro-ecological dairy production in the High Andean region, considering the pace of changes in climate and markets (Calle et al., 2013; Durana et al., 2019; World Bank Group, 2019; Calle, 2020; MADR and MADS, 2021; World Bank, 2021). In Colombia, silvopastoral systems have been implemented in local and regional projects as well as in a national project called "Sustainable Colombian Livestock." This national initiative, led by the union and supported by both national and international organizations, has benefitted more than 4,100 small and medium-sized farms. It has also facilitated productive transformation across over 100,000 hectares in 12 Departments, including several experiences in the High Andean region (Giraldo et al., 2018; World Bank Group, 2019; Calle, 2020; World Bank, 2021).

However, silvopastoral systems in the high tropics are more recently developed than in the lower tropical areas and present some disadvantages related to the biophysical and environmental conditions of the mountains. Shrubs and trees in hedgerows and fodder banks, fences, and restorations grow and regrow slower than in lower-lying regions with higher temperatures and solar radiation. Frost is an important limitation for planting shrub fodder and other trees, especially in the first years. These, in turn, must compete with vigorous invasive herbaceous species, such as Kikuyu. For these reasons, the initial results of the silvopastoral system take longer, and the maintenance costs can be higher, which implies challenges for the acceptance, shift, and consolidation of the system. This requires a dedicated focus on providing technical assistance to the producers in administrative and livestock expertise, along with the application of agroecological principles, as well as economic support in the transition period. Furthermore, there is a need for more research on different fodder species, also on technologies for planting, utilizing, and maintaining trees and shrubs, the use of microbial strains, organic fertilizers, and biochar for soil improvement.

## 5. Conclusion

To promote agroecological transition initiatives involving silvopastoral systems integrated with natural ecosystem preservation and restoration, strong determination is essential. This entails implementing strategies that merge a systemic, socioecological, and interdisciplinary research approach together with the implementation of pilot projects, market-aligned certifications, and economic incentives to drive dairy farmers to adopt these changes, including mechanisms like payment for environmental services (Calle, 2020). Paying for milk based on specific quality criteria, which has already led to improvements in its composition and sanitation (Carulla and Ortega, 2016; Cadena et al., 2019), could also incentivize a shift toward sustainable livestock production (Durana, 2011). This change would be driven by price signals, along with the potential for technical assistance from dairy industries and cooperatives. Promoting sustainable farmer clusters in specific areas is a potential strategy that could contribute to joint territory management and the development of sustainable livestock landscapes featuring silvopastoral systems. These solutions need an innovative approach to change and a cultural transformation among farmers, their families, and rural workers. Furthermore, it requires a commitment from various sectors of society, especially academics and technicians, dairy processing companies, consumers, and the government.

## Author contributions

CD and EM contributed to conception of the study. CD contributed to the design and wrote the first draft. EM and BM wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Campesino and indigenous women conserve floral species richness for pollinators for esthetic reasons

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**Background:** Homegardens in agricultural areas are important refuges for pollinators and other valuable species due to the extensive plant diversity therein. Yet, plant diversity may strongly depend on the identity of the gardeners and their knowledge of plant identification and plant uses.

**Objective:** In this study, we used botanical surveys and homegardener interviews to explore plant diversity in homegardens in coffee-producing regions of Colombia, and to examine how homegardener identity influences their knowledge of plants, plant uses, and motivations for maintaining a homegarden.

**Methods:** We collected information in three villages in Cauca, Colombia and interviewed campesino ($n = 30$) and indigenous ($n = 30$) homegardeners. Half of the respondents from each social group were women and half were men.

**Results and discussion:** Of the 566 plant species that we detected in botanical surveys, the most recognized spontaneous herbs among homegardeners were "papunga" (*Bidens pilosa*, $n = 38$), "lechuguilla" (*Emilia sonchifolia*, $n = 32$), and "escoba" (*Sida acuta*, $n = 31$). Homegardeners identified multiple uses of spontaneous herbs including for food, material, medicine, plants for bees, and other environmental, conservation, or social uses. In addition, three different groups of gardeners emerged from social groupings and interview responses: (1) indigenous men with little knowledge of the uses of spontaneous herbs; (2) indigenous and campesino women who considered it beneficial to have flowers and crops for pollinators; and (3) male farmers who described detailed mutualistic plant-pollinator interactions that benefit crops, and who use spontaneous herbs to maintain soil moisture. In conclusion, homegardeners kept very diverse gardens and identified spontaneous herbs and pollinator functions, but this strongly depended on age, knowledge, and social group. Thus, homegarden presence within agricultural landscapes is of great importance to sustain functional biodiversity and ecosystem services in Colombian agroecosystems.

**Conclusion:** In conclusion, homegardeners kept very diverse gardens and identified spontaneous herbs and pollinator functions, but this strongly depended on age, knowledge, and social group. Thus, homegarden presence within agricultural landscapes is of great importance to sustain functional biodiversity and ecosystem services in Colombian agroecosystems.

KEYWORDS

**plant and pollinator conservation, ethnobotany, women in agriculture, floral visitors, homegarden biodiversity**

# 1 Introduction

Smallholder farmers in tropical agricultural regions often maintain gardens around their homes that provide important resources for biodiversity, including beneficial insects, especially in intensive agricultural landscapes. These family or rural gardens (hereafter "homegardens") are usually near the homes, are typically maintained by women members of farmer households, and provide microhabitats with a large variety of plants. Homegardens provide spaces to cultivate different vegetables, and may also contain tropical fruit or other trees, ornamental and medicinal plants, and other wild plants and spontaneous herbs. Because of this high plant diversity, homegardens can provide resources for visiting floral insects and animals (Eyzaguirre and Watson, 2002; Galluzzi et al., 2010), although the farmers may not be aware of this or of other benefits derived from the diversity of plants (Munyuli, 2011; Arango Gómez, 2019). Homegardens are considered spaces with the potential to become a reservoir for agrobiodiversity (Seid and Kebebew, 2022), especially in agricultural landscapes with predominantly intensive agricultural management. Although there is a tendency in Latin America to employ biodiverse traditional agriculture, especially in coffee producing regions, by using a variety of trees on the plantations (Perfecto and Snelling, 1995; Armbrecht et al., 2005), traditional coffee growing has almost entirely been replaced by intensive systems that require large amounts of chemical supplies (Jha et al., 2014; Harvey et al., 2021). Homegardens may be especially important for biodiversity conservation in tropical regions where coffee production is predominant, and where shade trees and other plants, such as spontaneous herbs, have been eliminated, as these practices limit domesticated and wild plant diversity, reduce floral resource availability for beneficial insects, and may limit the supply of ecosystem services (Potts et al., 2010).

Spontaneous herbs within homegardens guarantee floral diversity, provide resources for beneficial insects (e.g., floral visitors, pollinators, predators, and parasitoids), and may support ecosystem services like pollination and pest control (Blanco and Leyva, 2007; Nicholls and Altieri, 2013). Spontaneous herbs are often better known as weeds, and with that comes a negative connotation as pest plants (Fernández, 1982; Delgado and Romero, 1991). Yet, researchers have recognized that floral weeds fulfill roles of guaranteeing floral diversity in agroecosystems, providing resources and a refuge for insects (visitors, pollinators, among others), supporting pollination services, and some spontaneous herbs protect the soil and support hydrological or cultural services (Blanco and Leyva, 2007; Nicholls and Altieri, 2013; Bretagnolle and Gaba, 2015; Blanco-Valdes, 2016; Rivera-Pedroza et al., 2019). Pollination services, carried out by some flower-visiting insects, is an ecological function and a key economic, ecological, and social ecosystem service that is globally in decline (Daily, 1997; Klein et al., 2007; Potts et al., 2010). It is estimated that 35% of global crop production depends on animal pollination. In addition, the presence of pollinators not only increases crop productivity but also improves crop quality (Bailes et al., 2015), including in coffee plantations (Roubik, 2002; Ricketts, 2004). This ecosystem service is important both for agricultural production and in sustaining natural ecosystems in transformed landscapes. Nevertheless, pollinators not only provide services but also require resources (nectar, pollen, resin) to maintain their populations (Westrich, 1989; Roubik, 1992; Nates Parra, 2005). These resources can be provided by spontaneous herbs, crops, and other plants in homegardens and in natural habitats, such as forests.

Homegardens play an important role in the conservation of biodiversity and contribute to the survival of campesino families with monocultures by providing food products for family consumption or to sell (Eyzaguirre and Watson, 2002; Galluzzi et al., 2010). So, it is reasonable to expect that homegardens can conserve a high biodiversity of traditional ornamental, medicinal, and aromatic plants, both cultivated and wild, and also offer resources for pollinators in the area. In spite of this, traditional knowledge related to homegardens is threatened by a vision that tends toward favoring a homogeneous landscape and the idea that biodiversity in such a space is "dirty," or "weeds" that should be cut down. Moreover, homegardener knowledge may greatly differ depending on the social identities (e.g., based on social group, gender, age, or education, etc.) of people who inhabit agricultural landscapes where homegardens are common.

One axis of social difference that may influence homegarden management and plant diversity is gender (Reyes-García et al., 2010). Women play an important role in agriculture by contributing 43% of farm labor globally, and by providing for food security, care for the family and the home, obtaining income, and occupying themselves with the management of natural resources and biodiversity (García et al., 2006; Doss and Raney, 2011), and they use organic fertilizer (Reyes-García et al., 2010). Gardens and orchards managed by women more often support a variety of ornamental and medicinal plants than those managed by men (Reyes-García et al., 2010; Mahour, 2016), and women may demonstrate a greater awareness and desire to protect and conserve nature and its resources (Hunter et al., 2004). Women can have different perceptions and relations with floral spontaneous herbs than men. In other studies, scientists have documented that management of natural resources, and the use of fertilizer or herbicides is different between women and men in homegardens. These gender differences may translate into differences in homegardens. Traditional gardens are often creative places, a reflection of female identity and a space where sharing, learning, food production, and cultural and family life take place (Eyzaguirre and Watson, 2002). In our observations, we have noted that in rural gardens, the esthetic of the square garden, where biodiversity is submitted to open, monotone, geometrical forms, is broken down. In other words, homegardens usually have a different arrangement, which conforms to distinct feelings, knowledge, or social relations, beauty or artistic concepts, and can be a symbol of enrichment and decoration of the home with ornamental and other plants. Thus, women likely maintain high biodiversity with traditional vertical stratification in their gardens. Although it may seem disorderly to the common observer, women carefully plan each corner of the garden according to the microhabitat and availability of land. Throughout their lives, grandmothers, mothers, and daughters take an interest in maintaining and enriching their gardens and orchards by incorporating fruit, medicinal, aromatic, and ornamental plants. They also exchange seeds, buds and stems, and other offshoots with neighboring women or persons from other distant villages. This protective and loving attitude toward nature unconsciously creates conditions for a constant supply of flowers with pollen and nectar for pollinators. The history of women in the conservation of biodiversity reflects an underestimation of her role, just as of her role in agriculture (Kothari, 2003; García et al., 2006). Thus, studies must be carried out that begin to explore whether women are still continuing with this tradition of conserving biodiversity.

A second axis of social difference that may affect homegarden management is indigenous social identity. In Colombia, there are still various indigenous ethnic groups that manage homegardens in coffee-producing areas as well as campesinos, who are often relatives of the indigenous people, or referred to as mestizo. Social demographic information (e.g., age, education level) and behavior are the main characteristics that explain differences in the use of natural resources (Boster, 1986; Reyes-García et al., 2005). In Colombia, campesino and indigenous people have different lifestyles, languages, traditions, and cosmovisions, they live in nearby communities, and these differences may affect the homegarden management and homegardener knowledge about plant uses, as previously documented (Carr, 2008). In this study, we worked with the indigenous Nasa community, whose territory is in the northern to central-east Cauca department, extending from Caldono up to Popayán and Tierrandentro. They speak their own language, Nasa, as well as Spanish. They still practice their traditional rituals, and their primary economic activities are family agriculture and orchards for household rather than commercial consumption, but many also cultivate coffee. Colombian indigenous communities conserve a high diversity of cultivated plants in their homegardens (here, the Nasa community call it "tull"), which are established for household consumption (Sandoval Sierra and Chavez Servia, 2014).

We saw a great opportunity to interact with the campesino and indigenous communities to document these spontaneous herbs which do not have an economic value, but that may have a potential cultural value with benefits for health, rituals, agriculture, and nature conservation. The tools of ethnobotany may help in this issue to value the spontaneous herbs in homegardens and their potential for biodiversity conservation (Vicente and Sarandón, 2013).

We studied the diversity of floral spontaneous herbs (herbaceous plants) identified by and belonging to homegardeners in coffee production areas of southwestern Colombia. We completed botanical surveys, examined the knowledge of homegardeners from different social identities (e.g., women, men, campesino, and indigenous), and examined the biodiversity conservation potential of homegardens for pollinating insects. We specifically addressed the following research questions: (1) What are the social identities of interview participants? (2) How diverse is the plant composition in the homegardens? (3) Does social identity or demographic background influence plant species richness or knowledge about plants in homegardens? (4) What are the known uses of spontaneous herbs from homegardens?, and (5) Do spontaneous herbs provide a cultural value that promotes pollinator conservation in a Colombian coffee plantation landscape? We hypothesized that women in rural areas, more than men, without retribution or pay, protect and promote the flowers around their homes and, in this way, promote the biodiversity of the insects that visit coffee plantations.

# 2 Methods

## 2.1 Study site

This study was carried out in a coffee growing area in southwestern Colombia in the villages of El Rosal, El Pital, and La Isla, municipality of Caldono, Department of Cauca (2°49′44″ - 2°51′32"N y 76°34′8' – 76°33′25"W). Our study sites are located between 1,336 and 1,538 m elevation, and the area has a mean annual temperature of 21.5 C° and an annual rainfall of 2,191 mm. The region has two rainy seasons: April to May and October to November (Urrutia-Escobar and Armbrecht, 2013; Arenas-Clavijo and Armbrecht, 2019). The zone is dominated by mosaics of small coffee farms (with or without shade trees) mixed with corn, beans, plantains, yucca, and red pepper crops, among others. There are also small areas of land for cattle grazing.

Spontaneous herbs are often eliminated by agrochemical herbicides used in sun coffee plantations, although small coffee growers frequently still have spontaneous herbs in their homegardens due to a lack of money or of time to control them. In interviews, homegardeners often mentioned using natural fertilizers (guano, house compost), but some also use synthetic fertilizers (e.g., DAP, Triple 15, 20/24 or 24/25, or Cal Dolomita) and chemical herbicides (e.g., glyphosate). In contrast, the use of agrochemicals is less on shade coffee plantations and these crops are frequently associated with guamo trees, *Inga edulis* Martius, as well as the fruit and timber trees (Arenas-Clavijo and Armbrecht, 2019, obs. Pers. ALK and IA). The landscape is composed of small landholdings (*minifundios*) of up to 10 hectares each, usually with a house. The campesino and indigenous people establish their vegetable and flower gardens near the coffee crop. The women usually have a garden with flowers arranged in different densities and variety according to their taste or preferences.

## 2.2 Homegardener survey

We designed our surveys as semi-structured interviews (Parfitt, 2013) in order to discover the knowledge and perception of the homegardeners regarding the importance of spontaneous herbs, pollinator biodiversity, and their daily activities on the farms, as well as to determine their role in this context (Appendix 1). The survey was divided in three sections: (1) a social demographic section with questions about the background of the participants (education, age etc.), (2) a section with questions about management of the farm (with focus on coffee plantations for further studies), and (3) a section with questions about homegardener knowledge on the function and importance of spontaneous herbs, bees, and other pollinators as well as their motivations for gardening. We were primarily interested in assessing knowledge among women homegardeners, but men were interviewed as well so that we could compare plant knowledge and uses between genders. We conducted interviews with 60 people who were grouped in 4 groups: campesino women ($n = 15$), indigenous women from the Nasa community ($n = 15$), campesino men ($n = 15$), and indigenous men ($n = 15$). In some cases, we conducted surveys with more than one member of a household, but at different times, to avoid household members from influencing the answers of others. We later categorized all interview participants into three age groups: (youth 20–30 years, middle age 31–50 years, and adults over 51) as an additional possible axis of social difference among homegardeners.

## 2.3 Botanical survey of homegarden plants

While the interviews were being carried out, we collected information on the plant composition and species richness in the homegardens and other habitats (e.g., coffee plot, grazing area, other crops) within a 20 m radius surrounding the homes of the survey participants (Appendix 2). We took 1–2 h walkabouts with each survey participant, and during these walkabouts recorded the names of each of the plants (e.g., spontaneous herbs, flowers, herbs, grasses, crops, medicinal plants, others) that they recognized. Plants that survey participants recognized but did not have a name for were also recorded. The common names given were reviewed using a biovirtual platform (Bernal et al., 2017) to avoid species duplication, because the participants sometimes have different names for the same plant species. We took photographs of each plant seen during walks, and then used guides and keys (e.g., Pl@ntNet™ Copyright, 2014–2022; CENICAÑA, 2017; Salazar-Gutiérrez, 2020) to identify the scientific names of each plant seen.

## 2.4 Cultural valuation of spontaneous herbs and other plants in homegardens

The participants evaluated both the spontaneous herbs and the other plants used and recognized during the walkabout. We later categorized the plant uses provided into 11 use categories outlined by Cook (1995): (1) food, (2) spices/herbs, (3) animal food, (4) plants for bees, (5) building materials, (6) fuel, (7) social uses, (8) medicines, (9) conservation, (10) ornamental, and we added the category (11) spontaneous herbs (Supplementary Table S1). The sum of the values was used to compare the knowledge of campesino and indigenous women, and also to compare by gender. To calculate the cultural value of each ethnospecies (an ethnobotanical term for all plant species that the community in question related to use) recorded, we used the following formula (Reyes-García et al., 2006):

$$CV_e = Uc_e * Ic_e * \sum IUc_e \quad (1)$$

where $CV_e$ corresponds to the cultural value of an ethnospecies e and is calculated by multiplying the total number of uses reported divided by the potential uses for ethnospecies e ($Uc_e$), multiplied by the number of ethnospecies recorded from all of the participants ($Ic_e$), and the sum of the number of participants who mentioned each use of the ethnospecies e divided by the total number of participants ($n=60$; $\sum IUc_e$). The higher the calculated value of an ethnospecies, the higher the cultural value. This calculation was carried out using the "ethnobotany R" package (Whitney, 2021), and the tables were exported. We used the first 10 ethnospecies in the list of cultural values for all groups of the participants to generate an alluvial diagram by using the "etno_alluvial" function. This diagram helps to identify and visualize the knowledge and assigned importance of these 10 plants in the lives of the participants.

## 2.5 Data analysis

We categorized the answers about perceptions and knowledge of plants and pollinators, and we ran a cluster analysis with two packages in the R environment and language (R Core Team, 2022), "FactoMineR" (Le et al., 2008) and "factoextra" (Kassambara and Mundt, 2020). These analyses allowed us to combine demographic data (e.g., social group, gender, age, education), with the quantitative plant data from the botanical records, and with qualitative information from the interviews. Specifically, we chose five interview questions relating to uses of spontaneous herbs, pollinator function, and motivations for keeping a garden to characterize this information. We present the relative contribution of all quantitative and qualitative variables in dimension 1 and 2 in the multifactorial analysis in Supplementary Figures S1–S4. Further, the analyses allowed us to compare perceptions and knowledge about homegarden plants among the mentioned genders, social groups, and other demographic factors (e.g., age, education, working place).

We fitted eight GLMs, one for each of the following response variables: (1) richness of total reported plant species, (2) proportion of spontaneous herbs from total species richness, (3) proportion of ornamental plants from total species richness (4) proportion of other reported plant species from total species richness, (5) proportion of known reported plants, (6) proportion of known reported spontaneous herbs, (7) proportion of known reported ornamental plants, and (8) proportion of other known reported plants. For each model, we included the following factors: gender, social group, age range, education level, work location, hours per week spent in the garden, and homegarden manager gender. We list the information about factor levels in Supplementary Table S2. We did not include any interactions between factors. All statistical analyses were done using the R version 4.2.1. environment (R Core Team, 2022). Over-dispersion and values were calculated and transformed for error distribution from Poisson to negative binomial distribution with the "MASS" package (Venables and Ripley, 2002) for variable 1. For model 1 we used a Poisson distribution for the error but, because of certain over-dispersion, we changed to the negative binomial distribution. For models 2–7, which had a proportion as response variable, we used the quasibinomial distribution, and for model 8 the binomial distribution. For all models we conducted a stepwise elimination of not-significant factors starting with a complete model (all 6 factors included in the model). We chose the model with the best predictor variables using the information theoretic criterion, using the R function "stepAIC." To examine differences between mean values of the factor levels investigated, we run pairwise multiple comparisons of means using the "emmeans" function of the "emmeans" package (Lenth, 2022).

# 3 Results

## 3.1 Demographic distribution of participants

Our first study objective was to describe the social identities of the survey participants. The 60 participants represented two social groups: (1) indigenous members of the Nasa community ($n=30$), and (2) campesinos ($n=30$); half of each social group were women ($n=15$). The average age of campesinos was 56.9 and average age of indigenous participants was 46.2. Coffee growing was the main economic activity for both social groups. The indigenous families cultivated coffee as well as homegardens (or "tull") for home consumption. The entire family supported the work in the gardens and in the coffee areas, including time during the harvest. Indigenous women worked in the field and the "tull" and tended to the home and the children. Several generations live on the same farm and families have from two to four children. In contrast, there are few children on campesino farms, but sometimes grandchildren are present. Campesino children are usually already adults and work in neighboring cities, very few remaining with their parents to work on the farm. Campesino men generally worked in fields alone, sometimes with the support of the women or paid labor, both generally and at harvest time. Thus, campesinos work on their own farms and also on other farms to improve their economic situation. Campesino women generally were occupied with housekeeping, helping their husbands with the crops, and keeping their gardens. The women, in general, have no personal income, and may only have temporary work at harvest time. Some women work in the fields or take on other jobs (including cleaning other people's houses) in order to support themselves. There is also a small difference in education level. Most participants had not attended high school or had only studied a few years of elementary school. In general, the few young participants had already finished high school, but this was more common for campesino than for indigenous participants. Defined roles were noted in the two social groups and between genders. Both the indigenous and campesino women are dedicated to work near the home, but the indigenous woman dedicates more time to her vegetable garden (foods, spices, and medicinal plants) than to her flower garden (ornamental plants). The campesino men seem to see women's work as something pretty but unimportant since it produces no income for the home. Likewise, the indigenous men viewed women's work in maintaining ornamental flowers to be less important, but more highly valued women's work in the "tull" (pers. Obs. ALK). The women also answered questions about their work shyly, giving the sensation that they undervalued the time and hours spent working in the homegardens.

## 3.2 Participant knowledge of plants and pollinators

The multivariate analysis revealed relationships between demographic characteristics of homegardeners, botanical records, and plant functions (Figures 1, 2; Tables 1, 2; also compare with Supplementary Figures S1–S4). The variable that contributed the most to separate the cluster groups was knowledge of the function of pollinators in gardens. Campesino men more often identified the importance of pollinators in the gardens compared with indigenous men or both groups of women ($p < 0.0001$; Tables 1, 2). Another main variable was education. The low education level among the indigenous people was reflected in their very basic answers about the functions of spontaneous herbs and pollinators (Tables 1, 2). More women, in general, and campesino men recognized the functions of spontaneous herbs (Tables 1, 2).

The cluster analysis identified three groups (Figure 1). Group 1 was primarily characterized by indigenous men who had not attended school. This group of people recognized fewer ornamental plants and reported lower species richness in their homegardens. Those interviewed indicated not knowing the answers to questions regarding the function of pollinators in the garden and in the crop. The answer "medicinal" was most frequent when asking about spontaneous herbs uses or functions. Finally, this group had the fewest recorded ornamental plants. Group 2 was composed of indigenous women who had not attended school. In answer to questions about functions of pollinators in the garden as well as in the crop, these women said that these spaces represented a benefit to the crop and a resource for pollinators. These women also recognized that spontaneous herbs function as a fertilizer (improving soil quality). Group 3 was primarily characterized by campesino men with a middle to high education level and who worked both on their own farm and on those of others, but some campesino women ($n = 9$) also were included in this group. Members of this group had higher recorded richness of ornamental plants and total species richness. The most common answer regarding pollinators was that they were of benefit to both plants and pollinators due to mutual interaction. The campesino men interviewed demonstrated knowledge of the benefits of pollination by bees in their fields. Members of this group also reported that spontaneous herbs have a function in soil conservation against erosion and in keeping humidity in the soil.

Multifactor analysis (Figure 2) discriminated between campesino and indigenous people in terms of all selected social demographic data and questions and gender (Table 1). Both campesino and indigenous homegardeners had some overlaps between genders but were distinct from one another. Although there were answers in common for all groups, the analysis showed that there were social factors and life circumstances (gender, social group, age, and education level) that differentiate and identify each group as a whole (Table 2).

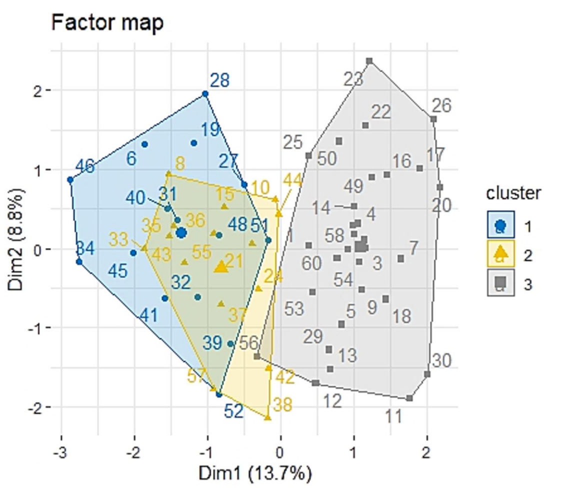


FIGURE 1
Two-dimensional factor map to illustrate pattern and distribution of cluster groups of homegardeners. The blue circles and their outlined area represent group 1 (lower educational level and less knowledge); the yellow triangles and their area represent group 2 (fewer ornamental plants); the gray squares represent group 3 (greater species richness and number of ornamental plants).

## 3.3 Plant species richness in homegardens

We recorded 2,936 individual plants and 566 different species of plants on the 38 homegardens and surrounding areas (23 homegardens in El Rosal, 12 homegardens in La Isla, and 3 homegardens in El Pital). We documented 166 species of spontaneous herbs (Supplementary Table S3). The homegardeners planted 264 ornamental plant species (Supplementary Table S4) and 136 species of other categories (e.g., crop or tree; Supplementary Table S5). The principal cultivated plants in homegardens were plantain (*Musa* sp.; several varieties; found in 44 homegardens), coffee (*Coffea arabica*; 33), yucca (*Manihot esculenta*in 33 homegardens), and other fruit trees. The main ornamental plants were *corona de cristo* (*Euphorbia milii*), *aloe vera* (*Aloe vera*), and geraniums (*Pelargonium peltatum*). The most recognized spontaneous herbs species were *papunga* (*Bidens pilosa*; found in 38 homegardens), *lechuguilla* (*Emilia sonchifolia* in 32 homegardens), and *escoba* (*Sida acuta* 31 in homegardens).

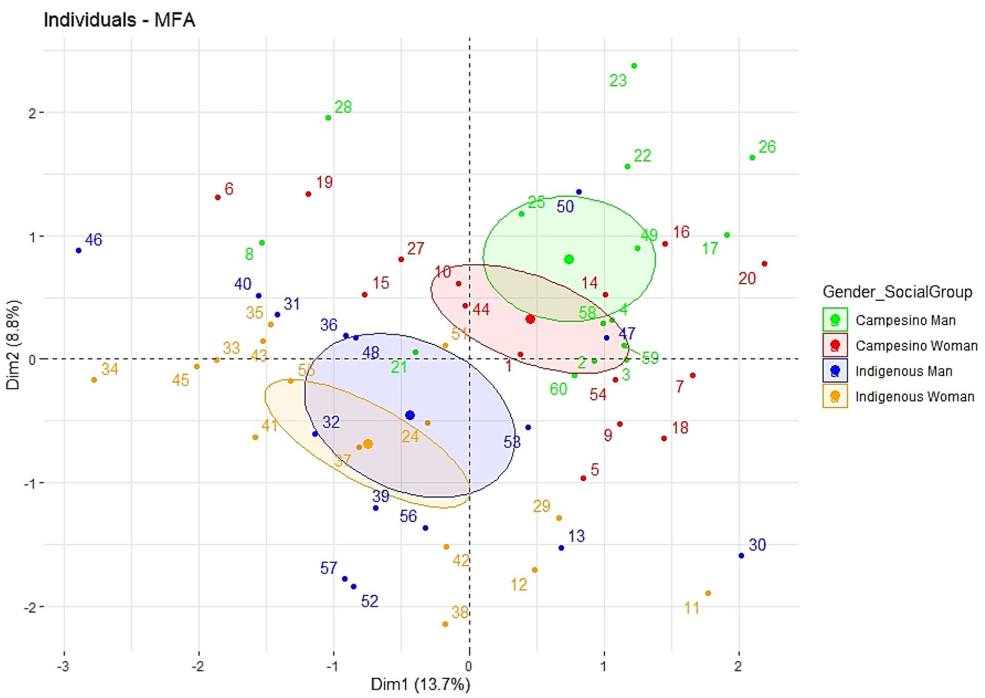


FIGURE 2
Multifactor analysis of the gender group variable and its contributions to the questions chosen to characterize the groups.

TABLE 1 Main variables obtained from multifactor analysis to produce cluster groups.

| Main variable | *p* value | *df* |
|---|---|---|
| Pollinator function (garden) | <0.0001 | 4 |
| Pollinator function (crop) | <0.0001 | 4 |
| Pollinator function (general) | <0.0001 | 6 |
| Educational level | <0.0001 | 4 |
| Spontaneous herb functions | <0.0001 | 8 |
| Gender – social group | <0.0001 | 6 |

We observed hundreds of plant species, including ornamental plants, crops, trees, and spontaneous herbs (Supplementary Tables S3–S5). Nevertheless, recorded plant species richness (Model 1) did not differ among participants and the best model for predicting plant richness did not include any predictor variables. Registered spontaneous herb species richness (Model 2) on the farms was best explained by education level and by who managed the homegarden. Unmarried men (where women were absent, $n = 6$) did not have homegardens or had homegardens with very low ornamental plant richness (pers. Obs. ALK), but a higher proportion of spontaneous herbs. People without formal education had a larger proportion of spontaneous herbs plants in their homegardens compared with those with high school education. In Model 3, reported ornamental plant species richness was explained by homegardener gender, social group, and educational level. Homegardens managed by women had more ornamental plant richness, and people with some formal education tended to maintain more ornamental plant species compared to those without formal education. Campesino women had more ornamental plants than indigenous men or women on their homegardens. Additionally, the factors kept in the model explained 28% of Model 4. The plants in the "others" category (crops and trees) showed more diversity on indigenous homegardens. More information about the coefficients and statistics of all models are in Supplementary Table S6.

## 3.4 Homegardener knowledge of plant species

Knowledge of plant names (total species) on the farms differed with social group and age (Model 5). Although the difference was only marginally significant, indigenous homegardeners tended to know more names of the plants on their homegardens than campesino homegardeners. Elderly homegardeners knew more plant names than middle-age homegardeners. Educational level and homegarden manager gender were important predictors of knowledge of spontaneous herbs (Model 6). These factors explained 29% of the variation of the proportion of recognized spontaneous herbs. Homegardeners with elementary school education knew the names of the spontaneous herbs more than homegardeners without formal education and women homegardeners knew more names than men. The knowledge of the names of ornamental plans in the garden (Model 7) was determined by age and gender. Women tended to have more knowledge of the ornamental plants than men, and elderly gardeners had more knowledge than middle age and young homegardeners. In Model 8, the "other plants" category did not indicate over dispersion and the best model was selected by AIC and BIC. In this case, the model with social group and educational level with the least AIC = 115.044 and BIC = 127.46 and a $p$ value of chi squared 0.02 was chosen (Table 3). Indigenous men and women knew more names of the crops and plants on their farms as did the elderly.

TABLE 2 Characterization of three groups of homegardeners based on survey responses about pollinator and spontaneous herb functions as well as gender and education.

| | Pollinator function (garden) | Pollinator function (crop) | Pollinator function (general) | Spontaneous herb functions | Gender-social group | Education level |
|---|---|---|---|---|---|---|
| Group 1 | Does not know/ have | Does not know/ have | Does not know/ have | Medicine | Indigenous Men | Does not have |
| *v* value | 4.666 | 4.262 | 2.978 | 3.619 | 2.067 | 3.854 |
| *p* value | <0.0001 | <0.0001 | 0.0029 | <0.0001 | 0.0387 | <0.0001 |
| Group 2 | Benefit for pollinators | Benefit for pollinators | Benefit for pollinators | Fertilizer | Indigenous Women | Does not have |
| *v* value | 5.728 | 4.707 | 4.322 | 2.046 | 2.689 | 2.052 |
| *p* value | <0.0001 | <0.0001 | <0.0001 | 0.0408 | 0.0072 | 0.0402 |
| Group 3 | Benefits by mutualistic interaction flower-pollinator | Benefits from pollinators for crop | Benefits from pollinators for crop | Benefits for soil and its humidity | Campesino Men | Primary / High School |
| *v* value | 5.892 | 5.118 | 4.111 | 4.705 | 2.622 | 3.105 / 2.375 |
| *p* value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0087 | 0.0019 / 0.0176 |

TABLE 3 GLM results showing which homegardener factors were the best predictors of different plant groups in homegardens.

| Model | Variation explained | Factor | Difference between factor levels | Estimate | SE | Z-Ratio | *p* value |
|---|---|---|---|---|---|---|---|
| 2 (proportion of spontaneous herbs) | 44% | Homegarden manager gender | women-men | −0.82 | 0.208 | −3.951 | 0.0001 |
| | | Education level | without -primary | 0.194 | 0.116 | 1.672 | 0.2161 |
| | | | without-graduated | 0.435 | 0.151 | 2.873 | 0.0113 |
| | | | primary-graduated | 0.241 | 0.15 | 1.608 | 0.2423 |
| 3 (proportion of ornamental plants) | 52% | Social group | Campesino-Indigenous | 0.445 | 0.14 | 3.191 | 0.0014 |
| | | Education level | without -primary | −0.311 | 0.142 | −2.191 | 0.0727 |
| | | | without-graduated | −0.416 | 0.178 | −2.335 | 0.0511 |
| | | | primary-graduated | −0.105 | 0.168 | −0.622 | 0.8081 |
| | | Homegarden manager gender | women-men | 0.93 | 0.273 | 3.402 | 0.0007 |
| 4 (proportion of other reported plant species) | 28% | Social group | Campesino-Indigenous | −0.405 | 0.15 | −2.7 | 0.0069 |
| 5 (proportion of known reported plants) | 27% | Age | young-middle | 0.148 | 0.306 | 0.483 | 0.8795 |
| | | | young-elderly | −0.371 | 0.284 | −1.307 | 0.3913 |
| | | | middle-elderly | −0.519 | 0.175 | −2.964 | 0.0085 |
| | | Social group | Campesino-Indigenous | −0.303 | 0.169 | −1.798 | 0.0722 |
| 6 (proportion of known reported spontaneous herbs) | 29% | Education level | without -primary | −0.527 | 0.18 | −2.933 | 0.0094 |
| | | | without-graduated | 0.0245 | 0.271 | 0.09 | 0.9955 |
| | | | primary-graduated | 0.5515 | 0.27 | 2.039 | 0.103 |
| | | Homegarden manager gender | women-men | 0.77 | 0.332 | 2.318 | 0.0204 |
| 7 (proportion of known reported ornamental plants) | 35% | Age | young-middle | −0.193 | 0.425 | −0.455 | 0.8923 |
| | | | young-elderly | −0.871 | 0.401 | −2.172 | 0.0761 |
| | | | middle-elderly | −0.678 | 0.256 | −2.646 | 0.0222 |
| 8 (proportion of other known reported plants) | – | Social group | Campesino-Indigenous | −1.12 | 0.39 | −2.884 | 0.0039 |
| | | Age | young-middle | 0.24 | 0.586 | 0.409 | 0.9119 |
| | | | young-elderly | −0.649 | 0.584 | −1.111 | 0.5074 |
| | | | middle-elderly | −0.889 | 0.395 | −2.252 | 0.0628 |

Recorded plant species richness was discarded (Model 1) because it did not differ between participants and therefore did not include any predictive variables.

On calculating the average of plants recorded and recognized by group, some tendencies were observed. For example, campesino women recognized more species of ornamental plants while indigenous women and campesino men recognized more spontaneous herbs plants. Indigenous men centered their knowledge on the names of crops and trees (Table 4), those species that provide income for the family.

## 3.5 Gendered perceptions of spontaneous herbs, pollinators, and the garden

There were no significant differences in the way men and women discussed spontaneous herbs, pollinators, and garden motivations. We nevertheless summarize observed differences by gender. Of the 60 persons interviewed, only 11 knew the term "*arvense*" – a Spanish language term equivalent to spontaneous herb – (campesino women = 3, campesino men = 11, indigenous women = 1, indigenous men = 0) while 57 persons recognized the term "*maleza*" – a Spanish language term equivalent to weed. In the interviews, the term "*planta del monte*," or "wild plant," was most often used to describe this group of plants (see Supplementary Figure S5). Women more often reported that spontaneous herbs were beneficial for people and have a biological function (see Supplementary Figures S6, S7). Women mostly related spontaneous herbs to medical uses but also as beneficial to the soil and as feed for animals and pollinators. Men identified spontaneous herbs more as a function in the crop as well as in conserving humidity and protecting the soil (see Supplementary Figure S8). Women expressed pleasure at having a garden. The reasons they gave were that it was good for their physical, mental, and spiritual health. Secondly, it decorated the farm. The men were more inclined toward the decorative aspect of gardens (see Supplementary Figure S9).

As to the questions regarding pollinators, men answered with more knowledge of the pollination process and its importance to the crop. Women, on the other hand, referred more to the benefits that the floral resources on the farm received from the pollinators (see Supplementary Figures S10, S11).

## 3.6 Plant uses and value index

At least one homegardener mentioned each of the 11 use categories for spontaneous herbs, but the most commonly mentioned uses were as weeds (49%), medicinals (18%), and ornamentals (13%; Figure 3).

The uses mentioned varied among participant groups (Figure 3). Campesino men mainly identified spontaneous herbs as "weeds" and tended to identify them less as ornamental compared to other groups. However, this was the group that most spoke of spontaneous herbs as plants for bees and as useful for the environment, including soil conservation. Campesino women focused more on ornamental and medicinal uses, as did the indigenous women. They were more inclined toward the social uses of some spontaneous herbs including, for example, educating children for bad behavior with a small hit with *Verbena* sp., and other plants are used for incense, and cleansing baths. Indigenous women were the group that most referred to the medicinal use of spontaneous herbs and very little to ornamental uses. They were the only group that used spontaneous herbs as food but did not associate them with conservation, just as the indigenous men (Figure 4).

All types of spontaneous herbs, ornamentals, and other plants were included to calculate the cultural value of the plants and to compare which plants had greater cultural value in this coffee growing region. The plants with the greatest cultural value index were spontaneous herbs: *Bidens pilosa* ($CV_e$ = 0.253), *Verbena littoralis* ($CV_e$ = 0.123), *Emilia sonchifolia* ($CV_e$ = 0.103), and *Cuphea racesoma* ($CV_e$ = 0.094). The spontaneous herbs are followed by *Inga* sp.*1* ($CV_e$ = 0.091), *Aloe vera* ($CV_e$ = 0.061), coffee ($CV_e$ = 0.061), *Pelargonium peltatum* ($CV_e$ = 0.061), *Psidium guajava* ($CV_e$ = 0.059) and different varieties of plantain *Musa* spp. I ($CV_e$ = 0.054). On making this cultural value calculation by community gender and social group, the values changed in between the different community groups and between the gender social groups (see Table 5; Supplementary Table S7). For example, *B. pilosa* showed different high cultural values in each group. The highest value was calculated for campesino man and indigenous woman. The lowest value this plant got was among campesino woman. Campesino woman more highly valued *Inga* sp.*1* ($CV_e$ = 0.162), *C. racesoma* ($CV_e$ = 0.114) or *Aloe vera* ($CV_e$ = 0.108). In contrast, the campesino man more highly valued spontaneous herbs. For all other listed species in Table 5, the indigenous women and men had lower cultural values than the campesino community; this was primarily due to calculating the values for each group separately (see Supplementary Table S8).

Homegardeners listed various uses for *B. pilosa* (food, conservation, for bees, and as 'maleza' or spontaneous herbs), *V. littoralis* (medicinal, material, ornamental, social, and for bees); *E. sonchifolia* (medicinal, feed for animals, ornamental, and conservation) and *C. racemosa* (mainly used as a broom, but also for material, medicinal, ornamental, social uses, and as a bee resource). The alluvial diagram (Figure 5) also included other very important plants such as *Aloe vera*, guamo, coffee to consume as food, and medicinal plants. *Pelagorium peltatum* was the only garden plant used mainly for ornamental purposes that is also as a medicinal plant.

# 4 Discussion

In our hypothesis we proposed that women in rural areas, more than men, without retribution or pay, protect, and promote the flowers around their homes and, in this way, promote the biodiversity of the insects that visit coffee plantation, and our results support this hypothesis. Even though we found a lack of knowledge, the valuation of spontaneous herbs and sometimes the woman's effort in the homegardens, and the awareness of relation between spontaneous herbs, gardening, and pollinators or other insects, all participants, more woman than men, contributing to plant diversity in homegardens, creating a beautiful home, and promoting biodiversity in this coffee landscape. In the following part we will discuss the results in detail to the questions.

In question 1, we asked about the social identities of interview participants with the aim of describing the socio-demographic characteristics of our study participants. We documented differences between the campesino and indigenous participants in terms of their education level and roles. Although we initially characterized our

TABLE 4 Mean species richness of plants recorded by the researchers and recognized by the indigenous and campesino survey participants.

| | Women | | Men | |
|---|---|---|---|---|
| Plant group | Campesino | Indigenous | Campesino | Indigenous |
| Total plant species richness | 52.1 | 46.7 | 50.4 | 42.9 |
| Standard deviation | 19.8 | 22.7 | 16.51 | 21.7 |
| Plant species recognized by participants | 33.5 | 32.9 | 30.2 | 26.9 |
| Standard deviation | 13.7 | 14.6 | 11.6 | 12.4 |
| Total spontaneous herb richness | 13.6 | 16.1 | 15.5 | 13.2 |
| Standard deviation | 5.8 | 6.9 | 5.1 | 9.3 |
| Spontaneous herb species recognized by participants | 6.7 | 8.3 | 7.7 | 5 |
| Standard deviation | 3.8 | 3.5 | 3.2 | 3.0 |
| Total ornamental plant richness | 24.2 | 15.1 | 21.3 | 13 |
| Standard deviation | 12.8 | 10.0 | 9.4 | 10.1 |
| Ornamental plant species recognized by participants | 13.3 | 9.3 | 9.6 | 5.9 |
| Standard deviation | 6.9 | 5.5 | 6.2 | 4.9 |
| Total species richness of other plants (crops and trees) | 14.3 | 15.5 | 13.6 | 16.7 |
| Standard deviation | 5.5 | 8.7 | 7.0 | 7.2 |
| Total other plants recognized by participants | 13.4 | 15.5 | 12.9 | 16.1 |
| Standard deviation | 5.5 | 8.5 | 6.4 | 6.8 |

For statistics, see Table 3.

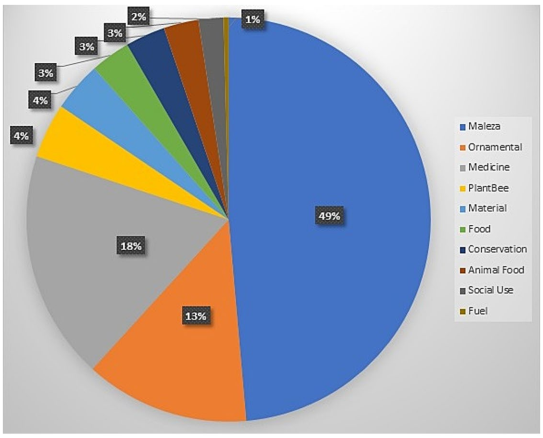


FIGURE 3
Spontaneous herb uses reported by homegardeners. Uses identified include: maleza (or "weed"), plants that grow naturally and are identified as dangerous or that have no function; ornamental, plants that are garden plants; plantbee, plants that represent flora resources for nectar and pollen for the bees; material, plants that are used in construction and furniture, among others; food, edible plants for human beings; conservation, plants that are beneficial to nature, crops and human beings; animal food, food for animals; social use, plants that have a social or spiritual use; and fuel, combustible plants.

participants into four groups, multifactor analysis based on identities, plant diversity, and plant knowledge formed three groups, not four. It turned out that the campesino women varied in their answers on plant species richness in their gardens and were split among multiple groups, although most of them were included in a group with campesino men that had a large number of ornamental plants in their gardens and more knowledge of plant functions and fertilizers. Indigenous participants, in contrast, did not always keep homegardens, and if they did, they were small. In a lifestyle aimed toward cultivating crops for household use, farm area is mostly used for commercial crops and vegetable gardens. Several plants for human consumption were found in homegardens and indigenous women indicated that planting ornamentals and having flower gardens was a luxury. They shared desires for floral diversity, if time and resources allowed, but their energies were concentrated on food and medicine. Single men had little time, had no or only a few ornamental plants, and did not think that having a homegarden was a priority. In contrast, households with women supported a variety of ornamental plants, spontaneous herbs, fruit trees, and spices for the kitchen. The overlap in the Figure 1 in both indigenous gender groups shows that there is not a large difference between them, with a bigger difference between social groups reflective of their education level and daily lifestyle.

The second question addressed the species richness and composition of homegarden plants. Here, we found that campesino women homegardens contained more ornamental plants than those of indigenous women who had very few ornamentals and instead cultivated more plants for food, medicinal, and other uses. Single men also placed more emphasis on food crops and had more grasses and/or spontaneous herbs.

Our third question addressed whether social identity or demographic background influence plant species richness or knowledge about plants in homegardens. We found, generally, that women recognized more plants, and specifically campesino women recognized more ornamental plants; indigenous women and campesino men recognized more spontaneous herbs, and indigenous men were more likely to recognize crops and trees. Importantly, this study emphasizes that farms with women have a greater diversity of

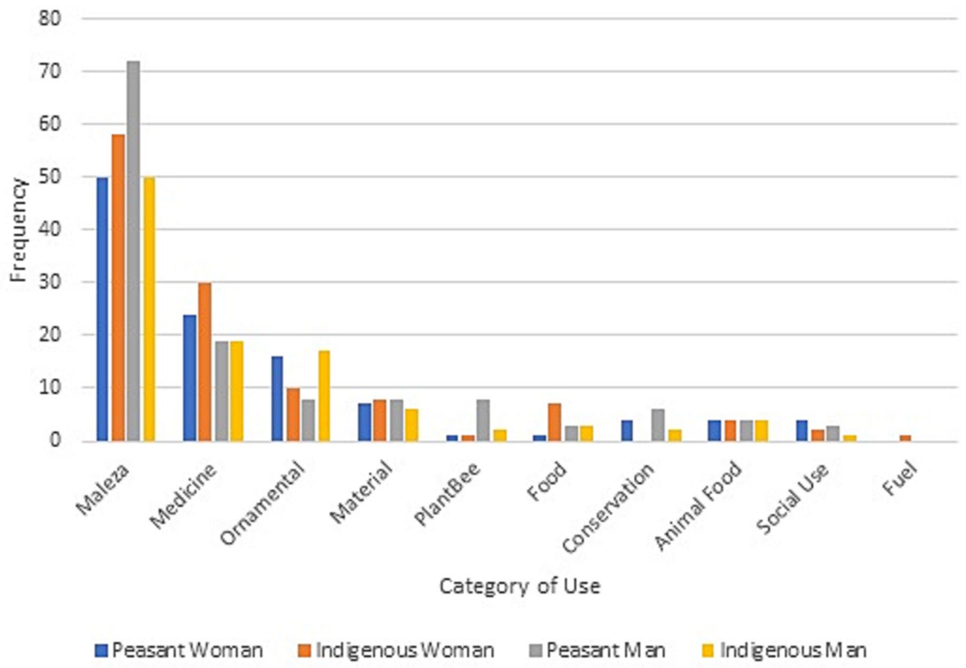


FIGURE 4
Number of species that each group of participants associated with a use. For the conventions of each use category, see Figure 3.

TABLE 5 Cultural values of ethnospecies ($CV_e$) grouped by ethnic groups of participants community: campesino and indigenous community and grouped by gender-ethnic groups of participants (first 10 ethnospecies).

| | Cultural value of ethnospecies ($CV_e$) | | | | | | |
|---|---|---|---|---|---|---|---|
| Scientific name | All | Campesino community | Indigenous community | Campesino woman | Indigenous woman | Campesino man | Indigenous man |
| *Bidens pilosa* | 0.253 | 0.23 | 0.222 | 0.05 | 0.256 | 0.367 | 0.128 |
| *Verbena littoralis* | 0.123 | 0.104 | 0.085 | 0.05 | 0.12 | 0.124 | 0.037 |
| *Emilia sonchifolia* | 0.103 | 0.168 | 0.04 | 0.16 | 0.037 | 0.132 | 0.018 |
| *Cuphea racemosa* | 0.094 | 0.161 | 0.009 | 0.114 | 0.011 | 0.072 | 0.007 |
| *Inga sp. 1* | 0.091 | 0.103 | 0.04 | 0.162 | 0.044 | 0.028 | 0.036 |
| *Aloe vera* | 0.061 | 0.089 | 0.019 | 0.108 | 0.022 | 0.036 | 0.016 |
| *Coffea arabica* | 0.061 | 0.08 | 0.022 | 0.089 | 0.022 | 0.072 | 0.022 |
| *Pelargonium peltatum* | 0.061 | 0.08 | 0.022 | 0.028 | 0.036 | 0.108 | 0.011 |
| *Psidium guajava* | 0.059 | 0.04 | 0.038 | 0.011 | 0.044 | 0.064 | 0.016 |
| *Musa x paradisiaca* | 0.054 | 0.049 | 0.059 | 0.064 | 0.044 | 0.036 | 0.075 |

The species are ordered depending on the relative importance of each one in the first column (to be continued in Supplementary Table S7).

ornamental plants as well as more knowledge of plants and their cultural uses. As far as motivation, occupation, and knowledge, similar results were found by Philpott et al. (2020) in the United States where it was found that women produced a greater variety of plant species in gardens, including ornamental and medicinal plants. Elderly people were also found to have more experience and knowledge of plants and their uses (Ladio and Lozada, 2004; Cruz et al., 2013; Bortolotto et al., 2015). Indigenous women knew more about the plant species in their homegarden, but botanical surveys revealed lower species richness of ornamentals and spontaneous herbs in their homegardens compared with campesino men and women. Perhaps, thus, spontaneous herbs, and trees were more useful for family survival due to their self-consumption lifestyle. Since indigenous women work with these plants daily, it was easier for them to recognize more plants. These results (knowledge of plant names, botanical registers, and cultural value of plants) reflected the existence of definite gender roles. Women recognized more plants and men who lived with women knew more about plants and their uses than the single men who usually did not garden or, if they did, had homegardens with low plant species richness. Single men, nevertheless, had more spontaneous herbs on their farms. Several men were able to identify medicinal plants, but women registered a deeper knowledge of medicinal plant uses than men (compared with Camou-Guerrero et al., 2008). On the other hand, since the campesinos were in the field all day, they likely had more contact with spontaneous herbs than the women. This observation was reflected in the cultural value lists. Additionally,

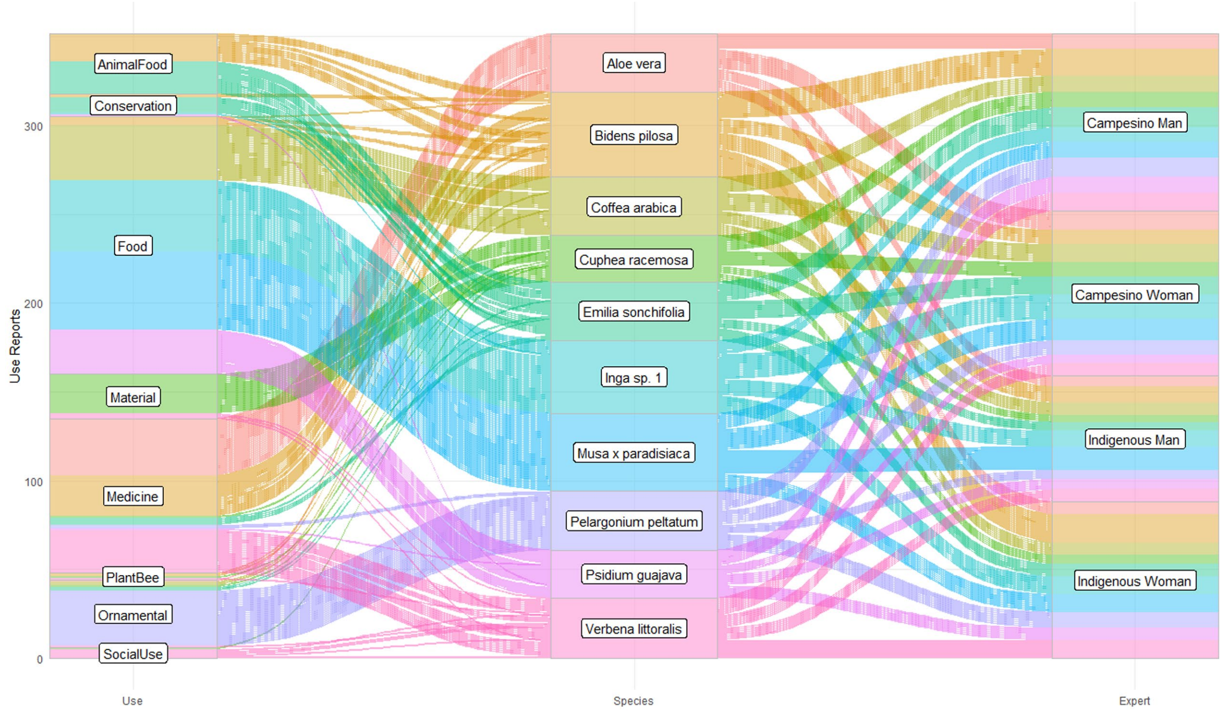


FIGURE 5
Alluvial diagram that relates use categories, plant species, and participant groups. In this diagram, the first 10 plants were selected according to the list of the highest cultural value. Plants are listed alphabetically. The conventions are ornamental, garden plants; food, edible plants for human beings; animal food, plants feeding animals; material, plants in construction, furniture, among others; medicinal plants; plantbee, plants that present floral resources for nectar and pollen for bees, conservation, plants that are beneficial to nature, crops and human beings; and social use, plants with a social or spiritual use.

campesino men and indigenous women registered more knowledge in this last category than campesino women who were busier with domestic chores or who worked in the fields.

Our fourth question aimed to examine the known uses of spontaneous herbs from homegardens. We found that spontaneous herbs were used for several purposes in this campesino and indigenous community. More specifically, 11 use categories were described in more detail. The most reported uses of spontaneous herbs were medicinal, ornamental, and as construction material (Vicente and Sarandón, 2013). *Bidens pilosa, Emilia sonchifolia, Sida acuta, Cuphea racesoma,* and *Verbena littoralis* were the spontaneous herbs with more different uses, as many as five different uses each. These plants were also the most common in botanical records and those most recognized by the campesino and indigenous communities. This resulted in high cultural index values for *B. pilosa, V. littoralis, E. sonchifolia,* and *C. racesoma*, plants that occupied the first places on the list of all of the plants in the study.

On comparing spontaneous herb plant use in other studies focused on edible or medicinal plants, various medicinal plants were found that the campesino and indigenous community identified as "weeds," but that had medicinal properties. For example, the Bussmann (2002) study in Ecuador that investigated the knowledge of healers collected a list of 142 medicinal species corresponding to the illness they cured. Of the list, 25 species appeared in the botanical records of the present study and also corresponded to medicinal uses. However, there are some species that have unrecorded medicinal uses. The same was true for other uses, such as bean plants for soil conservation, among other environmental benefits. These benefits were still not very related to spontaneous herbs. According to *Cenicafe* (Colombian National Center for Coffee Research), an important number of spontaneous herbs in the coffee producing area are classified as "noble arvenses," meaning that they are beneficial. Of these beneficial spontaneous herbs, 21 coincide with plants recorded in the present study (Salazar Gutiérrez and Hincapié Gómez, 2007; Salazar-Gutiérrez, 2020).

By assigning uses to the spontaneous herbs by all groups of participants, we expected to hear more often the uses for being a plant for bees or because it is a flower to be an ornamental plant in the view of the homegardeners. In our results we found that only 6% of spontaneous herbs are reported as plant useful for bees or ornamental. It seems to be that this awareness about the relationship between bees and spontaneous herbs and homegarden beauty are underdeveloped. Only after asking the participants in the walkabouts whether the plant is important for bees, mostly, they have answered with yes, when the spontaneous herb had a flower.

Finally, for our question 5, we examined whether spontaneous herbs provide a cultural value that promotes pollinator conservation in a Colombian coffee plantation landscape. We discuss two major findings related to this study question. First, our study detected a large gap between the knowledge and language used by scientists or agroecologists and rural farmers. The term "arvenses" (or Spanish term for spontaneous herbs) was still not well-known nor were their functions and benefits to crops and fauna. Yet the term "maleza" (or Spanish for weeds) preserves the image that wild plants or spontaneous herbs are damaging and of no use. Similar results were also obtained in other studies in Colombia demonstrating that spontaneous herbs were not important to campesinos (Arango Gómez, 2019). In contrast to Munyuli (2011), we found that indigenous people had the lowest knowledge of the benefits of pollinators for crops, with campesino women and men having a more detailed, or even functional understanding. Second, in general, we observed a low valuation of conservation actions for native wild plants. Several times during the walkabouts, women were seen pulling out spontaneous herbs, or weeding to clean their gardens. However, the ethno-botanical appreciation of these communities indicated a great potential for various uses of spontaneous herbs in their daily lives. Finally, a lack of education and awareness was observed with respect to connections between their work, the functions and benefits of pollinators, and their need to survive. The majority of the participants, more men than women, and more campesino men in general, demonstrated more knowledge of pollinators, but used chemicals to improve crop production and eliminate pests, an action that could negatively affect pollinators. Thus, it is necessary to improve information flow and education in these rural communities in order to conserve flora and fauna biodiversity and create more sensitivity regarding the role of conservation. According to the botanical records, this area seems to be very diverse in plant and floral resources thanks to the men and women who live and work there. Our study used ethnobotanical tools to provide a novel insight to the cultural value of spontaneous herbs. Although there is little literature on this topic, Arango Gómez (2019) is an important reference for Colombia and also indicates that very little attention has been given to the possible services of spontaneous herbs. Our study gives hope for changing the campesino community image of spontaneous herbs, an underestimated class of plants. But they have demonstrated great cultural potential with various uses in the daily life of the participants: medicinal uses, benefits to the soil and crops, and the very important conservation of bees and other beneficial insects.

## 5 Conclusion

This study documented high floral diversity in a coffee growing region that has been strongly modified by human beings. Homegardens supported an average of 48 species, including cultivated plants for commerce and self-consumption, ornamental plants, and native plants, such as spontaneous herbs, that represent a great potential for the conservation for pollinators. Garden installation, composition, and diversity varied depending on social demographic factors. Both social groups demonstrated a high degree of knowledge of plants and their uses, although knowledge of plants varied by occupation and according to social group and gender. Keeping a garden is still a symbol of luxury, especially for the indigenous community who cultivated medicinal and food plants, but few ornamental plants, and who were also busy with domestic and agricultural labors. Both indigenous and campesino farms, in general, were mostly family farms that shared the home with several generations and cultivated for self-consumption. An important number of campesino women belonged to the elderly group and were mainly housewives with more available time. They may have also had more economic resources to dedicate to their gardens. The campesino man tended to his crop alone or with the aid of workers. In reference to pollinators, men knew very little about insects, despite that campesino men knew more than other groups. The majority accepted the importance of pollinators once it was explained to them, but a large educational gap as well as the small amount of information flow from science to the rural population was observed.

Little recognition of the term "spontaneous herbs" confirmed this observation. The term was considered very technical and the native plants in this landscape were usually referred to as weeds or wild plants. Several potential uses were recorded for spontaneous herbs and the species with the highest cultural values were all spontaneous herbs. Thus, spontaneous herbs have been underestimated as to their presence, uses, and benefits to human beings, crops, and conservation of fauna and pollinators. Taking all this into account, it is clear that all participants contributed to conservation of plant diversity, but that women had a special role because of their diligence and dedication, using their imagination to create a space to beautify the home. Campesino and indigenous women pass their knowledge on to families, neighbors, and friends. There was not only a spoken exchange but an exchange of seeds or plants as well. Women brought flowers, beauty, and life to the home from a motivation that produces no income, but from a natural appreciation of doing. "Where there is a woman, there are flowers" was often heard during the interviews and is also reflected in the records. In conclusion, this study connected ethnobotany and the social aspect for a better understanding of the biological uses and benefits of spontaneous herbs and pollinators in order to increase awareness and make better decisions in favor of biological conservation.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

## Author contributions

AK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. SP: Supervision, Validation, Writing – original draft, Writing – review & editing. LR-P: Supervision, Validation, Writing – original draft, Writing – review & editing. IA: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1295292/full#supplementary-material

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# The main agroecological structure, a methodology for the collective analysis of the Mediterranean agroecological landscape of San Clemente, Region del Maule, Chile

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The simplification of the landscape as a consequence of the decrease in biodiversity and the adoption of monoculture production systems has led to a significant decrease in the provision of ecosystem services in the territory. The conversion of agroecosystems requires the adoption of agroecological techniques, which aim to design the agroecosystem as an integrated part of a vegetation matrix of the landscape, interconnecting the different production systems with the agricultural landscape. In order to measure the degree of connectivity of agroecosystems with the landscape, we used the Main Agroecological Structure (MAS) method, which was applied to 36 small agroecosystems of vegetable, livestock and fruit producers, which generally presented a low degree of connectivity. This allows us to evaluate the potential of these systems for agroecological transition, since being present in a moderately complex agricultural landscape gives important advantages over a more simplified system, allowing these producers to dispense with the use of many energy subsidies. This evaluation allows a first approximation to the quantification of the landscape matrix and will allow a comparison between agroecosystems or an evaluation of the evolution of the MAS over time. It is necessary to complement the MAS by quantifying the ecosystem services that may be associated with it.

KEYWORDS

**agriculture landscape, Mediterranean agroecosystem, agroecological transition, agroecological practices, ecosystem services**

## 1 Introduction

The intensification of agricultural systems has led to the simplification of landscapes, resulting in significant losses of biodiversity and associated ecosystem services (Gonthier et al., 2014; Campbell et al., 2017; IPBES, 2019; Sánchez-Bayo and Wyckhuys, 2019). A homogeneous landscape, ecologically simplified in structure and composition, results from large agricultural areas dominated by a few crop species (Margosian et al., 2009; Jonsson et al., 2015; Franzluebbers et al., 2020). The result has been the development of risk situations that exacerbate global food insecurity (Díaz-Hormazábal and González, 2016; Barrios et al., 2020; Bezner et al., 2021) because the poor provision of ecosystem services derived from the diminished biodiversity is subsidized through chemical inputs, which generate pollution to human and environmental health (Sabzevari and Hofman, 2022), soil fertility (Bünemann et al., 2018; Tibbett et al., 2020) and worsen pest and disease problems (Altieri and Nicholls, 2019).

The FAO urgently calls for the agroecological transformation of agricultural systems (FAO, 2018), as it will allow to increase the provision of ecosystem services to agriculture (Harrison et al., 2014; Tamburini et al., 2020) and ensure future food security (Bommarco et al., 2013) through agroecosystem designs that consider all levels or scales (Cappelli et al., 2022) for the integral development of the whole society (Vanbergen et al., 2020). The conversion of agroecosystems to agroecological management depends in part on the type of landscape matrix that surrounds them, since farm transformation involves the positioning of the agroecosystem and its connectivity relationship with the different types of semi-natural habitats that surround it (León-Sicard et al., 2018). Understanding the spatial and functional organization of this matrix of near-natural elements in interaction with agricultural structure is essential for promoting patterns and mechanisms which foster biodiversity and the provision of multiple ecosystem services by agricultural landscapes (Perfecto and Vandermeer, 2010; Marull et al., 2016, 2019; Cappelli et al., 2022).

Agroecology, through its methodological approach, initiates the analysis of agricultural sustainability from the farm scale [agroecosystem] (Guzmán and González de Molina, 2015), but it is necessary to scale this observation to spatial scales such as the landscape (Guzmán et al., 2018). The Main Agroecological Structure [MAS] of agroecosystems is an environmental index that includes ecosystem and cultural criteria, which allows visualizing some of the main relationships established between human groups [farmers] and their biophysical environment (Cleves-Leguízamo et al., 2017; Quintero et al., 2022). MAS uses metrics of composition, configuration, and heterogeneity of landscapes surrounding agroecosystems (León-Sicard et al., 2018), deriving key information to be taken into account when designing agroecosystems in the context of agroecological transition (Rudel, 2020; Vanbergen et al., 2020).

In this study, we use the MAS to perceive how the agrarian landscape is currently constructed and configured in the Chilean Mediterranean, a region where about 2 million people live in rural areas, occupying about 80% of the total land area (FAO, 2017; INE, 2017). This region of Chile has experienced profound geopolitical changes in the last four decades, which have reconfigured the landscape matrices in the region, as well as the agrarian structure and social relations (Kay, 1996, 2002), disrupting local economies, fragmenting and homogenizing the landscape, and exposing thousands of people to social and environmental risks in rural and surrounding urban areas (Armesto et al., 2010; Nahuelhual et al., 2012; Wratten et al., 2019).

In the face of growing evidence that agricultural sustainability at the agroecosystem scale largely depends on the management of the cultivated and uncultivated diversity of the surrounding landscape (Scherr and Mcneely, 2008; Garibaldi et al., 2016; Tamburini et al., 2020; Garibaldi et al., 2021), our hypothesis is that smallholder agroecosystems that use agroecological practices and are surrounded by a moderately heterogeneous matrix have better attributes to initiate the agroecological transition process at the community level. The objective of our study is to validate the MAS as a useful methodology for characterizing the landscape of the participating agroecosystems and how these are related to the application of agroecological practices, in a context of agroecological transition of a group of farmers in the Maule region, specifically the area near the commune of San Clemente, Chile.

## 2 Materials and methods

### 2.1 Study area

The Maule region is located within the Chilean Mediterranean (see Figure 1), and presents an area of 30296.1 km2, which represents 4.0% of the national surface, has a population of about 1 million inhabitants and a rich agrarian cultural diversity, where the rural population represents 33.6% of the regional total, about 330 thousand inhabitants (INE, 2017). It presents a warm and sub-humid climate of Mediterranean type, where there are four geomorphological zones: Andean Mountain range, intermediate depression, coastal mountain range and coastal plains. This allows the existence of native vegetation and the development of agricultural and forestry activities (ODEPA, 2018).

The area known as the intermediate depression, also known as the Central Valley, has a characteristic Mediterranean climate with cold, wet winters and hot, dry summers. It is considered a priority region for the conservation of world biodiversity (Myers et al., 2000) due to its high level of endemism and continuous habitat loss, as it is where most of the agricultural sector is located today. It is dominated by export crops, which occupy 90% of the land, out of a total of 811,480 ha available, and are represented in percentage terms by forestry plantations (60.8%), fruit trees and vineyards (12.4%), cereals (9.1%) and fodder crops (5.7%). With a much smaller area are vegetables, legumes, tubers and home gardens, which reach 22,236 ha planted, representing no more than 2.7% of the total regional area available (ODEPA, 2018).

### 2.2 Construction of MAS as an index of agrobiodiversity at the local scale

Satellite images [Sentinel 2] available for March 2022 (see list of images in the Supplementary material) were used to characterize the landscape by photointerpretation, and only for the identification of patches of native vegetation and water bodies present in the landscape, vector information corresponding to the CONAF vegetation cadastre (CONAF, 2021) was used (Table 1). Patch extent metrics and distances between patches and agroecosystems were processed and analyzed with Qgis and RStudio software using the sf, terra and rgdal libraries (QGIS Development Team, 2021; R Core Team, 2023).

In order to characterize and analyze the relationship between the agroecosystems of the Maule region, specifically the area near the municipality of San Clemente and the surrounding landscape, the methodology proposed by León-Sicard et al. (2018). Main

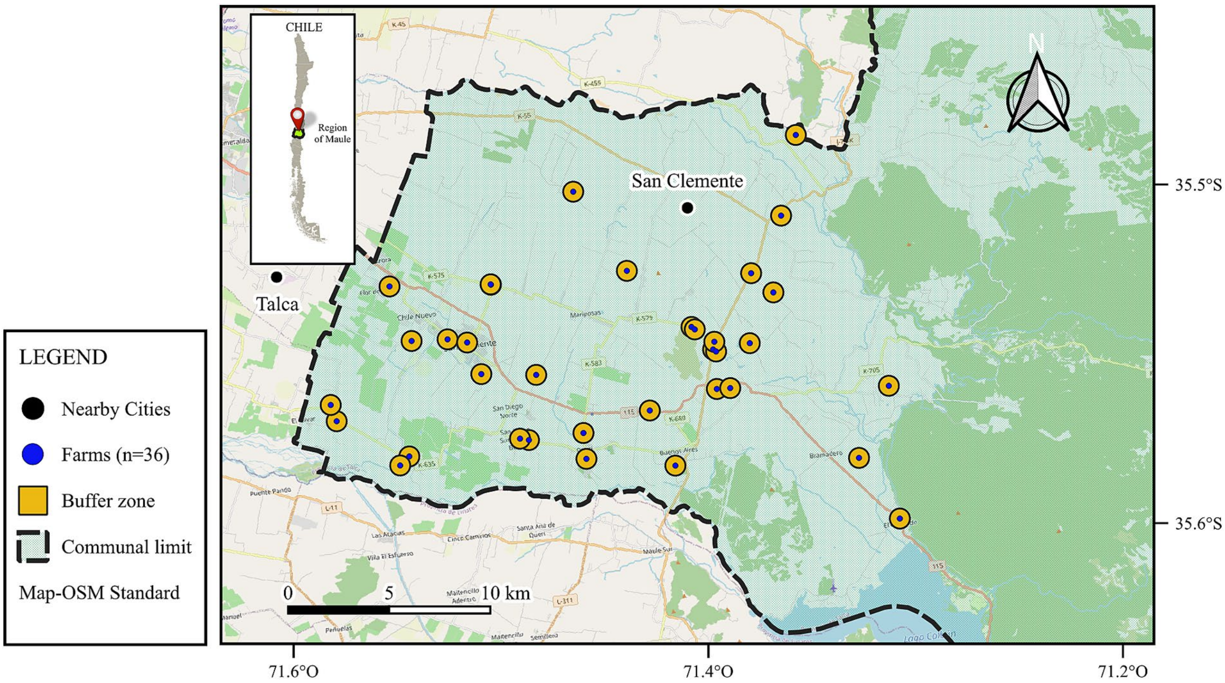


FIGURE 1
Study area, in blue point agroecosystem, the green buffer is landscape assessment.

**TABLE 1** Spatial information used, description and source.

| Type of information | Description | Source |
|---|---|---|
| Sentinel | Satellite information, raster type, with 10 m spatial resolution, 7 days temporal resolution and 13 bands spectral resolution. | European Space Agency (ESA) |
| Catastro Vegetacional | Vector information updated in 2016 and published in 2018, processed to have a minimum mapping unit of 0.5 ha for land use forests and water bodies. | Corporación Nacional Forestal (CONAF) |

Agroecological Structure [EAM], expressed in equation [1], is used to characterize the design of agroecosystems and their relationship with the surrounding landscape over time in an integrated manner. The Kruskal-Wallis test was used to assess significant differences between agroecosystem types.

$$MAS = CMELS + EEC + EIC + DEC + DIC + LU + WM + OP + PC + CA \quad (1)$$

This methodological tool allows us to look at the ecological, social and cultural links that exist between an agroecosystem and its environment [buffer zone], with an emphasis on water bodies, semi-natural areas and other non-productive uses. The buffer zone of [500 m] was defined as an area within which, for example, insect movements (Raymond et al., 2015) of interest to participating farmers and researchers could be distinguished. It was calculated using the agroecosystem perimeter and corresponds to a measure to normalize differences in total area between the types of agroecosystems studied (livestock, orchard, and horticulture). The index focuses on the quantitative and qualitative measurement of agrobiodiversity, particularly in terms of structure. The indicators used to construct the index are described in the Table 2.

## 2.3 Data collection

Qualitative and quantitative methods were combined to analyze the biophysical and agroecological conditions present in each agroecosystem. The following tools were used for data collection.

### 2.3.1 Workshop

Two extended workshops were held with a total of 65 farmers from the Maule region, specifically the area near the commune of San Clemente. This workshop defined the main problems and strengths of the group and some possible collective strategies for agroecological transition.

### 2.3.2 Focus group

Four group workshops were held with a balanced sample of the main crops present in the municipality. In the workshops, the variables and evaluation criteria of the main agroecological structure of the agroecosystems were diagnosed in a participatory way. For each agroecosystem and its buffer zone, a map was produced where the farmer identified the different types of soil, areas of native vegetation, water bodies and connections present (more details in the Supplementary material).

TABLE 2 Metrics evaluated, description and methods.

| Parameter | Description | Method |
|---|---|---|
| Connection with the main ecological landscape structure [CMELS] | Assesses the distance [m] of the farm in relation to the nearby fragments of natural vegetation, mainly forest covers and bodies of water. | GIS/focus group |
| Extension of external connectors [EEC] | Evaluates the percentage of the linear extension of live fences located in the perimeter of the farms. | GIS/focus group |
| Extension of internal connectors [(EIC)] | Evaluates the percentage of the linear extension of the rows of vegetation but internally. | GIS/focus group |
| Diversification of external connectors [DEC] | Evaluates the diversity of live fences or hedges located in the perimeter of the major agroecosystem. | GIS/ Interview/ focus group |
| Diversification of internal connectors [DIC] | Evaluates the diversification of internal live fences. | GIS/ Interview/ focus group |
| Use and Soil Conservation [USC] | This parameter evaluates the distribution percentage of different covers within the farm and the conservation of the soil (evidences of erosion). | GIS/ Interview/ focus group |
| Management of Weeds [MW] | Evaluates the management practices and systems of weeds. | Interview/focus group |
| Other management Practices [OP] | Is an indicator that expresses the type of production system (ecological, conventional or in transition) of each farm | Interview/focus group |
| Perception-Awareness [PA] | Evaluates the degree of conceptual clarity and awareness of producers regarding agrobiodiversity. | Interview/focus group |
| Level of Capacity for Action [CA] | Evaluates the capacities and possibilities of farmers to establish, maintain or improve their MAS | Interview/focus group |

TABLE 3 Weighting of the main problems according to farmers.

| Issues | Relative frequency |
|---|---|
| Lack of support from the state and its institutions for the development of more distribution and marketing channels for family agriculture with a focus on agroecological production. | 18% |
| Monocultures under greenhouses, pests, diseases and competition from weeds. | 17% |
| Devaluation of peasant knowledge, lack of practical technical knowledge to implement the agro-ecological transition of peasant family agriculture. | 16% |
| Very low yields and selling prices | 15% |
| High cost of agricultural inputs (fertilizer, feed, pesticides) | 14% |
| Climate change, drought and freeze damage | 13% |
| Lack of associativity among farmers in the same field or area. | 4% |

### 2.3.3 Surveys and semi-structured interviews

Surveys were conducted in each of the agroecosystems studied ($N = 36$), using a questionnaire consisting of closed multiple-choice questions and some open-ended questions (Córdoba et al., 2020). This allowed a greater degree of flexibility and depth in obtaining information (more details in the Supplementary material).

# 3 Results

## 3.1 Issues for the agroecological transition of agroecosystems

The workshops initially identified some of the problems that the group of participating farmers identified as priorities in their agroecosystem, see Table 3, including the lack of support for agroecological transition from the state and its agencies, technical difficulties such as pest, disease, and weed control, low yields, and low sales prices. The increase in external inputs and the general devaluation of traditional knowledge of the farmers were some of the most frequent observations made in the workshops held.

## 3.2 The main agroecological structure of the Mediterranean agroecosystems

The results show that, in general, the Mediterranean agroecosystems studied cover an average area of $1.96 \pm 0.1$ ha, with a low presence of native vegetation patches and water bodies within the agroecosystems and in the surrounding landscape, reaching no more than $4.0 \pm 0.2\%$ of the total area studied covered by native forest and $0.3 \pm 0.05\%$ of the total area with water bodies. Most of the native vegetation types present are of the renoval type of sclerophyll forest, with formations dominated by *Cryptocarya alba* (Chilean peumo), *Quillaja saponaria Mol.* (Quillay) and [*Lithrea caustica Mol.* (Liter) species]. The connection between the agroecosystems and the few

TABLE 4 Results metrics evaluated (mean ± error deviation).

| | Livestock (*n* = 14) | Orchards (*n* = 5) | Horticulture (*n* = 17) |
|---|---|---|---|
| Area (ha) | 3.17 ± 1.3 | 1.88 ± 1.1 | 0.86 ± 0.3 |
| Parameter | | | |
| Parch of Forests (%) | 8.9 ± 3.5 | 2.3 ± 1.4 | 0.9 ± 0.5 |
| Parch bodies of wáter (%) | – | – | 0.7 ± 0.2 |
| CMELS | | | |
| • *Distance between forest fragments (m)* | 42.5 ± 19.1 | 43.3 ± 36.1 | 18.8 ± 13.7 |
| • *Distance of forest fragments to the center of the farm (m)* | 137.8 ± 45.5 | 234.6 ± 95.7 | 128.3 ± 50.2 |
| • *Distance between bodies of water (m)* | – | – | 17.8 ± 5.6 |
| • *Distance of bodies of water to the center of the farm (m)* | – | – | 37.3 ± 28.4 |
| EEC | [Discontinuous perimeter-Moderately continuous perimeter] | [Strongly discontinuous perimeter-Discontinuous perimeter] | [Discontinuous perimeter-Moderately continuous perimeter] |
| EIC | [Very low connectivity-Low connectivity] | [Low connectivity] | [Very low connectivity-Low connectivity] |
| DEC | [Little diversified perimeter-Slightly diversified perimeter] | [Little diversified perimeter-Slightly diversified perimeter] | [Little diversified perimeter] |
| DIC | [Little diversified perimeter-Slightly diversified perimeter] | [Little diversified perimeter-Slightly diversified perimeter] | [Little diversified perimeter-Slightly diversified perimeter] |
| USC | Polycultures and agrosilvopastoral systems are present in a medium percentage of the covers | Polycultures and agrosilvopastoral systems are present in a low percentage of the covers | Polycultures and agrosilvopastoral systems are present in a medium percentage of the covers |
| WM | Weeds are not managed | Weeds are not managed | [Weeds are not managed] |
| OP | [Conventional management practices] | [Management practices in the reconversion process] | [Management practices in the reconversion process] |
| PA | Low or no degree of environmental awareness and knowledge of the role of biodiversity | High degree of environmental awareness—low or medium knowledge of the role of biodiversity | High degree of environmental awareness—low or medium knowledge of the role of biodiversity |
| CA | High possibilities of action | Medium possibilities of action. | High possibilities of action |

surrounding patches of native vegetation or water bodies present was low or zero, as can be seen from the average distance between the patches and the center of each agroecosystem [DFFCF DBWCF], where only for horticulture patches of water bodies and native vegetation were found.

In general, distances between native vegetation patches and water bodies were smaller in vegetable agroecosystems, but the presence of patches in the buffer zone was significantly higher in livestock systems. Mean distances between native vegetation patches were low for all three agroecosystem types, with a mean of 31.4 ± 1.8 m. The distance between water body patches was 17.8 ± 5.6 and the distance from the center of the agroecosystems to the water body patches was 37.3 ± 28.4 (see Table 4).

The MAS of the evaluated agroecosystems can be considered as slightly developed, with a calculated mean of 52.6 ± 0.27. Livestock agroecosystems received the highest and lowest scores for the main agroecological structure, i.e., agroecosystems with important proportions of native forest and water bodies in the buffer zone, which were also connected by vegetation edges, and others that did not have any of these types of patches were characterized. As there were no statistical differences between the types of agroecosystems assessed (Kruskal-Wallis, $p = 0.14$), the distribution of observations can be seen in Figure 2. The mean was calculated for livestock (53.4 ± 3.2), orchards (55.7 ± 2.9) and horticulture (49.5 ± 1.8) (More details in the Supplementary material).

## 3.3 Agroecological practices and their contribution to the collective construction of the landscape

The research process allowed us, through the application of the MAS methodology, to know in detail the management that each

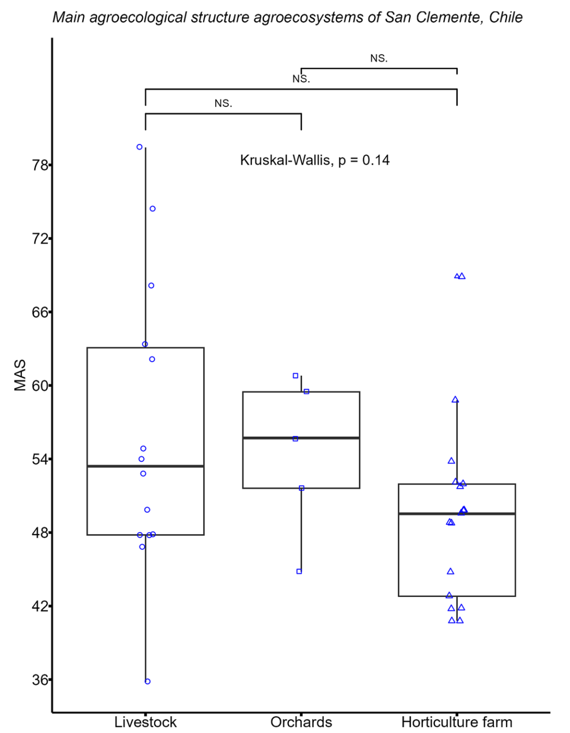


FIGURE 2
Boxplot by type of agroecosystems evaluated.

farmer carries out in his agroecosystem. A set of 11 practices was identified (see Table 5), recognized for their positive contribution to key ecological functions for Mediterranean agricultural systems, soil fertility, natural regulation of pest organisms and weed control. At least 50% of the agroecosystems studied use spatial and temporal diversification as a strategy to maintain soil fertility. These strategies include at least 3 agroecological practices, crop rotation [85.3%], crop diversification in the agroecosystem [73.5%] and integration of the animal component [67.6%], whether it is sheep, cattle or poultry production systems.

Natural pest regulation is another key element in agroecosystems with Mediterranean, in the group no strategies developed to optimize this ecological process were identified, however, at least 50% of farmers use, crop association [70.6%] and the inclusion of aromatic plants [55.8%]. It is important to highlight the use of chemical products in an important group of agroecosystems [76%] to replace the ecological processes of soil fertility and natural pest regulation.

# 4 Discussion

## 4.1 Contributions to the use of MAS in practice and methodological adaptations

In this study, the methodology proposed by León-Sicard et al. (2018) was used, as at the time of the fieldwork, the update of the methodology carried out in 2022 had not yet been officially published. The work of Quintero et al. (2022) promotes an equitable weighting, through the aggregation or balanced summation of each of the parameters involved in the construction of the MAS, which included the metrics of composition, configuration, heterogeneity, and landscape management practices used in each agroecosystem (Fahrig et al., 2011). Given the apparent link between management practices and ES provision (Palomo-Campesino et al., 2018, 2022), it is crucial to identify which agroecosystems have the potential to contribute to ES provision and which do not, as illustrated in Figure 3 and highlighted by Sirami et al. (2019). The MAS values recorded ranged from 35 to 79, indicating a gradient between the agroecosystems studied, with one group with a poorly developed agroecological structure and considerable cultural potential, and another group with an agroecological structure in a moderately developed state, with management differences observed between the agroecosystems studied and a high degree of isolation from the ecological structure of the surrounding landscape.

The use of maps and other GIS tools allowed for a participatory characterization of the landscape surrounding the agroecosystems studied, working together with farmers to identify strengths and weaknesses at the landscape scale. In this context, the MAS methodology allows aspects of landscape composition and configuration to be observed in an integrated manner, allowing for the standardization and local refinement of the landscape metrics used (Liere et al., 2017). Including the perspective of the farmers' group (PA) on what they perceive as environmental degradation and biodiversity loss, which was little developed at the beginning of the workshops conducted. On the other hand, farmers also recognize an important individual and collective capacity for action (CA) that could significantly improve what is done in their production units.

Particularly in this region, the agriculture landscapes show a high homogeneity from an agricultural point of view, dominated in the last 20 years by the increase of forest plantations and agricultural export crops (Díaz-Hormazábal and González, 2016; Tapia and Morais, 2020). It is therefore not surprising that the valorization of the extension (EEC; EIC) and diversification (DEC and DIC) of the external and internal connectors of the agroecosystems are mostly low, since these agroecosystems do not have an established agroecological design, which is reflected in external connectors at the periphery that are abandoned and in some cases non-existent, internal connectors with low or no connectivity between the different areas within the agroecosystem, and in both cases, external and internal connectors, with a low diversity of tree and shrub plant species present. In this territory, agroecosystems play an important role in the conservation of organisms in an important global biodiversity hotspot (Henríquez-Piskulich et al., 2021).

A transversal characteristic of the agroecosystems studied is the integration of the animal component, which in practice is observed as different land uses (USC) in the agroecosystem, where these agrosilvopastoral subsystems are included, using an average area of less than 50% of each farm studied. Management of Weeds (MW) is mostly conventional, where mechanical control and the use of herbicides for weed control predominate. In general, the agroecosystems are characterized by conventional management, which includes at least 5 practices that, if properly applied, could serve as a basis for conversion to agroecological systems.

The use of landscape metrics for the construction of MAS, through methodological tools such as the creation of collective maps, makes it easier for farmers to understand the importance of the internal and external connectivity of the biodiversity of each agroecosystem with the agricultural matrix that surrounds it (Cattaneo et al., 2018). In addition, these tools allow researchers and

TABLE 5 Practices used by type of agroecosystem.

| | Livestock (*n* = 14) | Orchards (*n* = 5) | Horticulture (*n* = 17) | (*N* = 36) |
|---|---|---|---|---|
| Managements | | | | |
| Animal Breeding | 71% | 40% | 73% | 67.6% |
| No/natural fertilizers | 36% | 60% | 20% | 32.3% |
| Crop rotation | 71% | 80% | 100% | 85.3% |
| Crop diversification | 57% | 20% | 93% | 73.5% |
| Fallow | 43% | 20% | 40% | 38.2% |
| Light tillage | 36% | 40% | 47% | 44.1% |
| Crop association | 64% | 40% | 80% | 70.6% |
| Aromatic plants | 42% | 60% | 67% | 55.8% |
| Nest-boxes for insects | 7% | – | 7% | 5.9% |
| No/natural pesticides | 43% | – | 13% | 23.5% |
| No/natural herbicides | 29% | – | 7% | 14.7% |

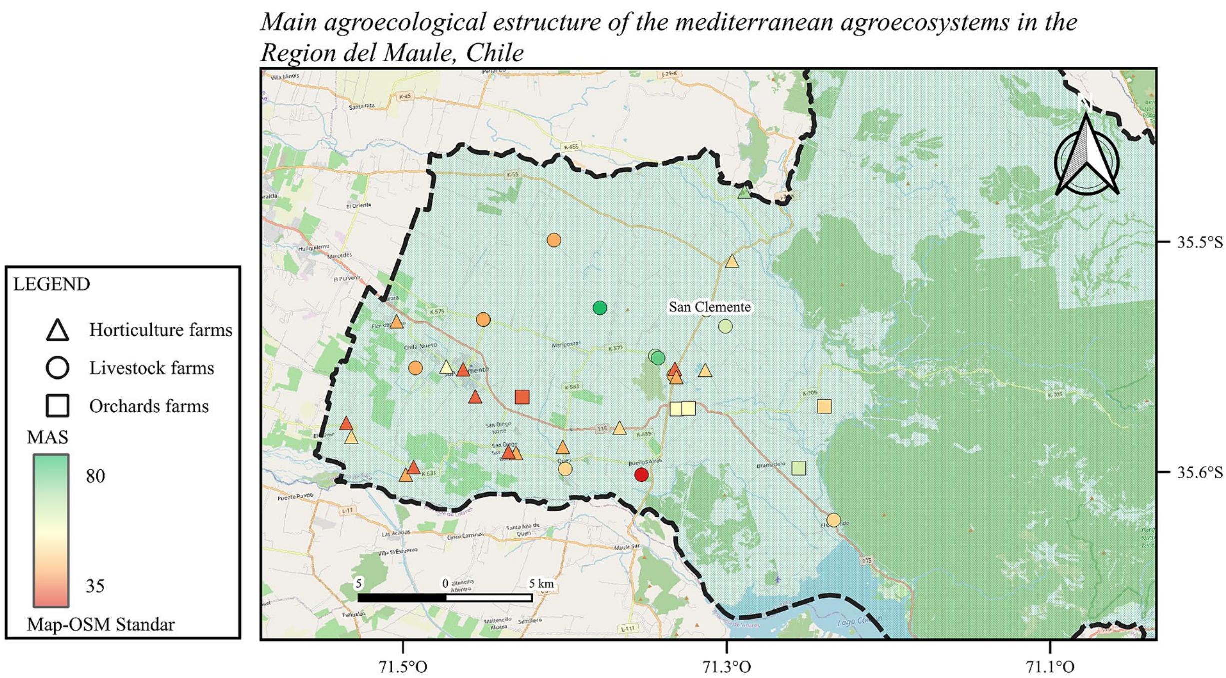


FIGURE 3
Geospatial location and assesment MAS of Mediterranean agroecosystems in the Region del Maule, Chile.

other stakeholders to visualize some of the most common and necessary technical issues that need to be addressed in each context.

## 4.2 Perspectives for future research at local level

In order to promote the agroecological transition and expand the scale of agroecological experience (González de Molina et al., 2017), it is important to work with farmers through the use of practical, horizontal evaluation methods that take into account different scales, from the agroecosystem (Nicholls et al., 2020; Tamburini et al., 2020) to the landscape (León-Sicard et al., 2018; Vanbergen et al., 2020), which allow a better understanding of the impact of management on the agroecological landscape of all actors involved in this research, a complex and non-linear process that requires attention.

To achieve agroecological landscapes, it is crucial to understand the biodiversity patterns, biological interactions, and mechanisms of the natural ecosystems present in the territory (Brauman et al., 2020; Jeanneret et al., 2021), and to engage farmers in a bottom-up, context-specific approach to improve services at the landscape scale (Barrios et al., 2020; Brauman et al., 2020). In addition, it would be important to assess at the local scale the contribution that the portions of native vegetation cover [native forest or scrub] in the landscape adjacent to the agroecosystems included in this study could make to the provision of ecosystem services, such as natural regulation of pests and diseases at the landscape scale (Wratten et al., 2019). Considering that only a proportional 20% of the total area devoted to non-agricultural land could significantly improve the impact on local biodiversity and ES provision, reducing dependence on agricultural inputs by up to 50% (Garibaldi et al., 2021).

The MAS methodology is a useful collective planning tool in the process of socio-ecological transition, allowing the involvement of different actors of the territory (Quintero et al., 2022). Since participatory and quantitative methods are used in a combined way, accurate and relevant assessments of agroecological transitions can be made (Teixeira et al., 2018). This also allows a future work plan in terms of planning, seeking an integral connection of the environment of each agroecosystem, which can even be replicated and extended to peri-urban and urban production systems (Vaarst et al., 2018). In addition, successful cases of farmers were identified to become beacons that stimulate and guide the adoption of agroecological practices and principles in local communities of the area, where the recovery of traditional agricultural systems and their management, which have historically offered promising models of sustainability and resilience, can be observed (Nicholls and Altieri, 2018).

## 5 Conclusion

This study allowed us to characterize the main agroecological structure of the agroecosystems of the Maule region, specifically the area near the commune of San Clemente. The MAS methodology was useful to understand the partial complexity of the agroecosystems and their surrounding landscapes, which are generally in a slightly developed state. This evaluation is an important first input for a second level of research, whose objective is to answer if indeed the agricultural systems surrounded by a complex landscape matrix and that correctly apply agroecological practices present a better provision of ecosystem services in their properties. And where the MAS plays a valuable role in facilitating a complex learning process between the different actors of the territory.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

AS-R conceived and designed the experiments, analyzed the data, wrote the manuscript, prepared the figures and tables, and authored or reviewed drafts of the paper, approved the final draft. RC-H conceived and designed the experiments, authored or reviewed drafts of the paper, approved the final draft. MA conceived and designed the experiments, authored or reviewed drafts of the paper, approved the final draft. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1241648/full#supplementary-material

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# Agroecological planning of productive systems with functional connectivity to the ecological landscape matrix: two Colombian case studies

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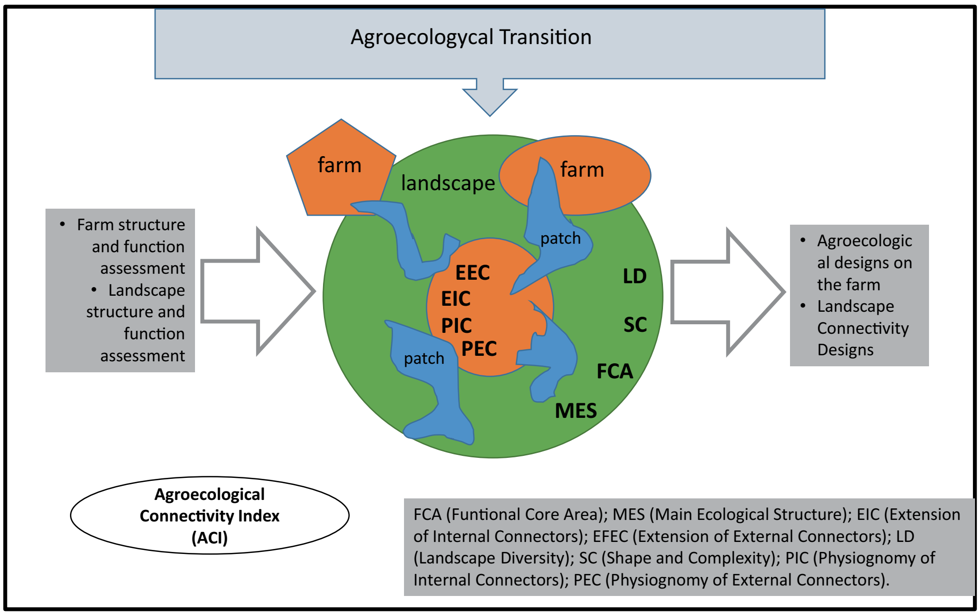
Given the need for agricultural system management under sustainability principles, identification and quantification of the landscape structure surrounding production systems is a tool that allows farmers to make their agroecological transition processes more appropriate. An ACI with eight indicators was proposed for farm assessment. This ACI is focused on functional connectivity both at farm and landscape levels. Two Colombian farms with different connectivity characteristics were evaluated under the index. Tosoly presented a stronger ecological structure and higher connectivity and diversity. Villa Alicia showed a weak ecological structure and low connectivity and complexity. From a systemic approach, the ACI allows an analysis of landscape structural conditions that promote ecological functions of pollination and biological controllers. With landscape structural conditions, it is possible to analyze the quantity and quality of the habitat for designing agroecological transition programs focused on obtaining productive agroecosystems that simultaneously comply with conservation strategies.

KEYWORDS

**agroecological transition, biodiversity, agroecosystems, ecosystem functions, agroecological governance**

## 1 Introduction

Agriculture is the human activity that has generated the greatest transformation of ecosystems worldwide (Millennium Ecosystem Assessment, 2005; Zimmerer et al., 2019). Agricultural technological intensification has negatively impacted ecosystems, compromising their conservation over time (Liere et al., 2017; Thrupp, 2004). Due to its relevance and predominance, agriculture should not only be concerned with production but also the preservation of wild biodiversity and ecosystem functions: the latter determines the continuity of the former. Biodiversity is essential for agricultural production and also for technological innovations, food security, and environmental conservation (Thrupp, 2004). For this reason, it is urgent to manage the biodiversity of agricultural landscapes through ecologically-based farming approaches (Scherr and McNeely, 2009).




GRAPHICAL ABSTRACT

Agroecology has emerged as a methodological approach for transitioning to sustainable production systems (Nicholls et al., 2016) that guarantee environmental functions conservation in agroecosystems (Acevedo-Osorio, 2016). However, in many cases, the transition from conventional to agroecological agriculture only means a mere input substitution. The result of this substitution cannot be classified as an actual agroecological system but, at most, as a proposal for organic production. Agroecology is based on returning unbalanced systems to stable ecological conditions that allow farms to drastically reduce their dependence on exogenous inputs (Gliessman, 2002). To achieve this, agroecology focuses on maximizing the benefits that local (farm level) and regional (landscape level) biodiversity can provide to agriculture (Altieri and Nicholls, 2007).

This research proposes a tool, adapted from already established landscape indexes, to assess the degree of functional connectivity between productive systems and the landscape matrix. This assessment is aimed to be integrated into agroecological transition processes based on the redesign of productive systems with particular emphasis on pollination as an ecological regulation process. To do this, it is necessary to achieve specific objectives that allow gathering the required data to calculate the indicators linked to each farm. These objectives are (1) to identify the land covered and land uses, (2) to establish patches with functional area, and (3) to calculate neighborhood metrics (extension and physiognomy of the internal and external vegetation connectors) and the similarity of each patch to a circle through the shape and complexity indicator.

## 1.1 Planning the agroecological transition

Agroecological systems are sets of spatial and temporal arrangements or designs of biotic and abiotic components (Martínez, 2002). These arrangements are dynamic and can take different technological patterns depending on both biophysical and socioeconomic circumstances and the interests of each producer (Altieri and Nicholls, 2012; Noguera-Talavera et al., 2019). Agroecological systems should be understood as continuous transformation processes towards adapted and resilient systems at the farm, landscape, or organizational and market systems levels that contribute to food system sustainability (Noguera-Talavera et al., 2019).

A careful design process is needed to constitute agroecological systems. This process intends to integrate existing ecological components in order to increase biological efficiency while the productive and self-sufficient capacities of the system are maintained (Noguera-Talavera et al., 2019). The transition to agroecological systems is usually a slow but steady process in a three-step sequence (Gliessman, 2002; Marasas et al., 2014). The first is oriented toward the efficient use of inputs, while the second focuses on substituting these inputs. The third aims to redesign productive systems through optimal distributions of crops and livestock that promote interactions so that the agroecosystem can manage processes related to soil fertility, natural pest control, and crop productivity (Hill and MacRae, 1996). Emphasis has been placed on the fact that this process must go beyond the change of isolated practices, which implies an investment in time, knowledge, and a systemic vision. It also requires the application of agroecological principles instead of general rules since it assumes the particularity of each system.

An adequate transition process guarantees the development of environmental functions that favor the system's self-regulation. These functions, in turn, form the basis for establishing more balanced productive systems that depend less on external inputs. Working on distinct levels (parcel of land, farm, and territory), a highly diverse landscape structure, reflects a greater possibility of natural control of herbivores due to a higher presence of their natural enemies (Altieri and Nicholls, 2007).

From an agricultural production perspective, the most crucial ecosystem functions include processes related to the soil (mineralization and nutrient recycling, organic matter decomposition, soil aggregate stabilization, organic matter formation, and water regulation), trophic web complexity (food sources for other species, and pest, disease, and weed control), gene flow (pollination), and production increase (food and materials) (Altieri, 1999; Moonen and Bárberi, 2008).

## 1.2 Studies on landscape connectivity

According to landscape ecology, human actions alter natural habitats, the landscape, and the functioning of ecosystems (Calabuig, 2013). For example, if the movement of pollinators, dispersers, or other natural biological control agents is curtailed by fragmentation, the remaining forests might become genetically and demographically isolated units (Calabuig, 2013; Gutiérrez-Chacón et al., 2020). In this sense, a fragment might be extremely isolated to the point that the populations of seed dispersers or pollinators might not reach it, causing the local extinction of certain species (Forman, 1995; Murcia, 1995).

Functional connectivity corresponds to the degree to which the landscape facilitates or prevents the movement of specific biota between habitat fragments as a result of the interaction between behavioral ecological processes and the landscape's physical structure of the landscape (Taylor et al., 1993; Crooks and Sanjayan, 2006; Alonso F et al., 2017). Functional attributes such as high levels of biodiversity, the exchange of species between cultivated and uncultivated lands, and resilience require the maintenance of connectivity between the ecosystem elements in order to linger over time (Swift et al., 2004).

Depending on the degree of intensification linked to different agricultural systems, there are several effects on the fragmentation of habitats and the loss of biodiversity; monoculture is one extreme of this spectrum. Farm mechanization and modernization bring uniformity to the landscape, erase bordering zones, increase pesticide use, among other changes (Altieri, 1999). The result corresponds to the creation of systems considerably open to matter and energy exchanges, influenced heavily by external conditions, and with clear cultural control (Gómez, 1993; Ramírez and Hernández, 2013).

Landscape connectivity allows the enhancement of the ecological functions of the landscape with agroecological production practices, and therefore, it can be evaluated spatially in terms of composition and function (Bennet, 1999; Taylor et al., 2006). To assess the potential of agricultural production systems and take advantage of the ecological structure, León-Sicard et al. (2018) proposed a useful methodology that begins with the Main Agroecological Structure (MAS) as a concept. This refers to the arrangements of internal and external connectors in farms that might be related to the likelihood of resilience or adaptation of the agricultural systems to different ecological disturbances. Through these arrangements, it is possible to establish design options for adapting to and mitigating the changing weather and other daily risks in agricultural systems (Cleves 2018). Considering that this methodology analyzes aspects of the structure (for example, how a production system connects with the surrounding landscape through vegetation cover or bodies of water), it is necessary to complement this analysis with data about the types of covers that determine the functionality that those connectivity covers might provide to both the production system and the landscape.

It is fundamental to develop studies on landscape structure and its implications in the intensification of ecosystem functions to the scope of planning agroecological production systems. This is the contribution this research aims to make to this field. Therefore, the purpose of this article is to address, from a functional connectivity perspective, landscape studies based on known and new indicators related to the farm's internal and external structure to facilitate production and conservation designs that improve the sustainability of long-term agricultural production.

# 2 Methodology

The methodology in this research was based on the Agroecological Connectivity Index (ACI) which integrates a set of eight indicators and 12 variables (landscape metrics) that aim to collect different ecological, biological, and agricultural key aspects of the landscape and the farm (Table 1).

Land measurements were made in the open-source software Qgis 3.14, and land cover maps were digitized using Google Earth images (2020), obtained from the service connection tool XYZ Tiles, using as reference the descriptions of the CORINE Land Cover methodology as reference adapted for Colombia (IDEAM, 2010a). A minimum mappable area of 0.01 ha was chosen because the size of the area of influence of the farms and the available satellite images allowed such a level of detail. In addition, field verifications were carried out based on observation and the georeferencing of borders between covers, which allowed us to refine each cover polygon to subsequently assign the current land use to each identified cover.

Two case studies were selected due to the contrasting conditions of land use between cultivated land inside the farm and the configuration of the area of influence of the landscape. The farms are located in the departments of Santander and Cundinamarca (Colombia; Figure 1). The first farm, called Tosoly, is in the village of Morario, municipality of Guapotá, Santander, with an average temperature of 21.7°C and average annual precipitation between 2700 and 3000 mm. The 8.54 ha farm is located between 1480 and 1535 m.a.s.l and integrates elements of conservation and agroecological production with an emphasis on energy cycling. The second farm, called Villa Alicia, is in the village of La Playa, municipality of Carmen de Carupa, Cundinamarca, with an average temperature of 12°C and average annual precipitation between 500 and 1000 mm (IDEAM, 2010b). The farm covers an area of 18.23 ha and is located between 2800 and 2900 m.a.s.l. It is mainly intended for the conservation of the remnants of a secondary-growth forest, pastures for extensive stock farming, and some subsistence crops.

The indicators, based mainly on the MAS (León-Sicard et al., 2018), were weighted according to their estimated degree of specific importance for the agroecological connectivity between the farm and the landscape. Subsequently, the ACI was obtained.

The criteria for the indicators' weightings were determined following data from scientific articles related to these indicators (Peña et al., 2005; Fahrig, 2013; UNU-IAS, et al., 2014; Hilty et al.,

TABLE 1 Indicators and metrics for the agroecological connectivity index (ACI).

| Indicator | Metric | Reference |
|---|---|---|
| LD: Landscape Diversity | Area and density | UNU-IAS, Biodiversity International, IGES and UNDP (2014) |
| FCA: Functional Core Area | Fragment functionality measured by the internal buffer | Matteucci (1998); Peña et al. (2005) |
| MES: Main Ecological Structure | DFF: Distance between Forest Fragments | Matteucci (1998); León (2010, 2012); Pantoja et al. (2014); Cleves (2018) |
| | DCLCF: Distance between Core Areas of the Landscape - Core Areas of the Farm | |
| | DBW: Distance between Bodies of Water | |
| | DBWLF: Distance between Bodies of Water Landscape and Farm Functional Core Areas | |
| | DNN: Distance to the Nearest Neighbor | |
| EEC: Extension of External Connectors | Evaluation of the linear extension and surface of vegetation in living fences in the perimeter of the farm | |
| EIC: Extension of Internal Connectors | Evaluation of the linear extension and surface of vegetation in internal vegetation that connects the subsystems of the farm | |
| PEC: Physiognomy of External Connectors | Evaluation of the similarity in composition (diversity) and structure to the reference forest in the studied area | Senanayake and Jack (1998); Meijboom (2007); IAFN-RIFA (2016) |
| PIC: Physiognomy of Internal Connectors | Evaluation of the similarity in composition (diversity) and structure to the reference forest in the studied area | |
| SC: Shape and Complexity | Shape of the fragments | Matteucci (1998) |

2020) as well as previous experiences of the authors (1). Two indicators proved to be more relevant compared to others: (1) the Main Ecological Structure (MES) because of its effect on the assessment and the complete analysis of the connectivity networks of the landscape-farm and (2) the identification of the edge effect (core area) due to its influence over the behavior of animals and plants populations in the short term. The following is the final equation that illustrates all the weightings for the eight indicators:

$$\begin{aligned} ACI = {} & 0.09(ILD) + 0.23(FCA) + 0.23(MES) + 0.09(EEC) \\ & + 0.09(EIC) + 0.09(PEC) + 0.09(PIC) + 0.09(SC) \end{aligned} \tag{1}$$

The values of the eight indicators were obtained from ratings, resulting from normalizing measurements on a scale from 1 to 5, according to the perceived level of agroecological connectivity: 1 as undesirable and 5 as desirable.

## 2.1 Landscape diversity (LD)

For this indicator, the area of influence of the landscape over the farm was calculated. To do so, first, the area of a circle drawn from the center of the farm was obtained, following the equation $R = 2Y$, where Y is the measurement of the longest possible diagonal between the borders of the farm, and R corresponds to the radius of the circle (León, 2010; 2012). Then, the inner area of this circle was subtracted from the total area including the outer limits of the farm, resulting in the area of influence. The CORINE Land Cover methodology adapted for Colombia was used to carry out the inventory for vegetation cover and land use. The methodology was also used to characterize, classify (IDEAM, 2010a), and compare the two sites and, with this information, know the degree of similarity between the covers that make up the landscape (dominant matrix and fragments). Subsequently, the equitability of the covers was established, counting the existing fragments for each class. Finally, the total area and density were calculated as the percentage of each cover in relationship with the total area of the circle. This value was normalized in the numerical scale from 1 to 5.

## 2.2 Functional core area (FCA)

This indicator evaluates the edge effect. Following Peña et al. (2005), we defined an edge effect of 20 m corresponding to the distance of the internal buffer zone that can be plotted for each of the natural vegetation fragments. Fragments with a functional area (fragments with a remaining inner area after eliminating the edge effect) were selected as functional fragments for the index. Then, through the relation $a / A * 100$, the corresponding numerical values for the functional fragments were calculated, with A the total area of natural fragments and a the total area of the functional nuclei.

## 2.3 Main ecological structure (MES)

Neighborhood metrics are defined by the MES: these metrics assess the distances between the fragments with natural covers of landscape and bodies of water and the farm (León-Sicard et al., 2018). A spatial and temporal analysis was considered, framed in both the hypotheses of fragmentation-island biogeography (Hilty et al., 2020)

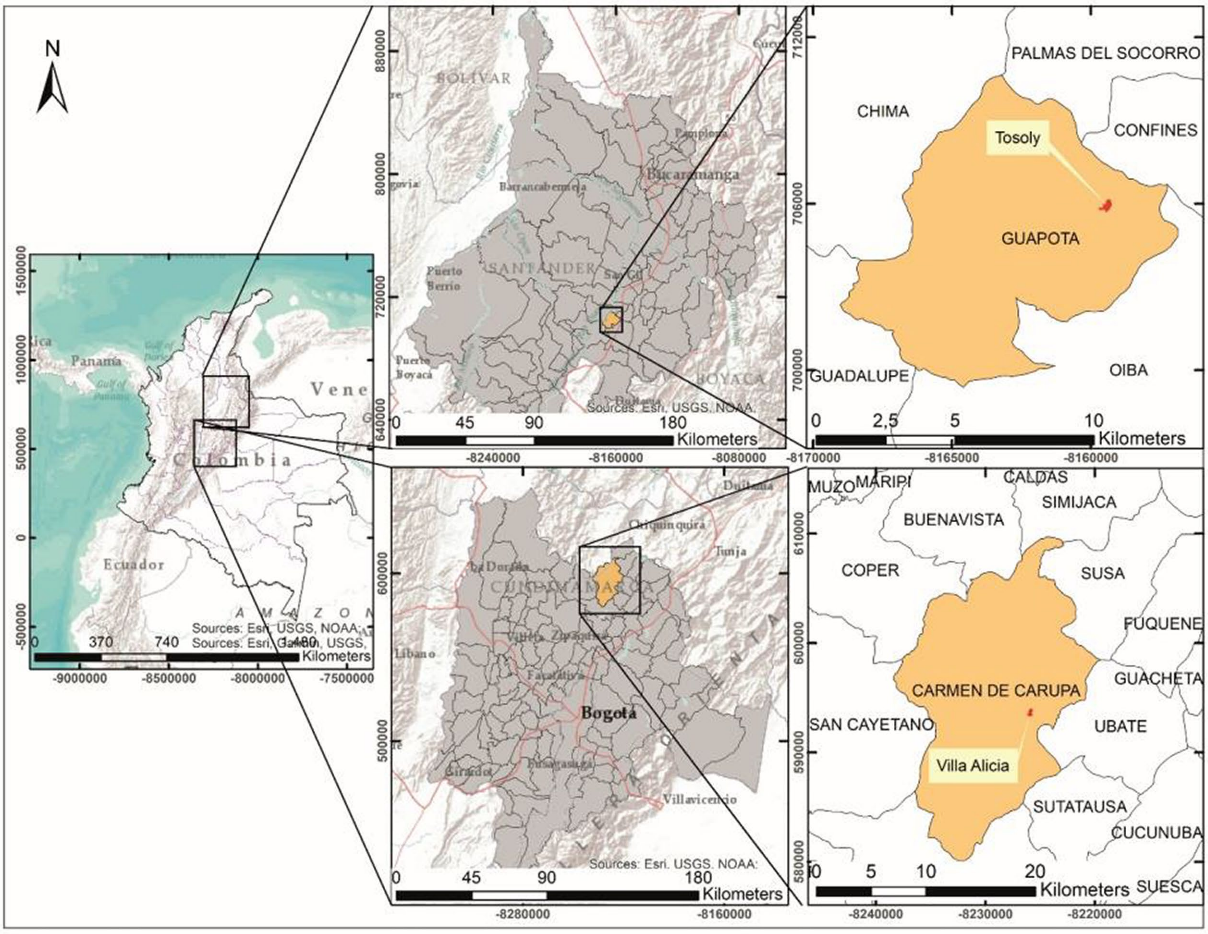



FIGURE 1
Location of the studied farms.

and the habitat's quality and quantity (Fahrig, 2013) as determinants of the density and richness of the associated biodiversity.

The weightings for each component in the MES equation are derived from fieldwork conducted by the authors and the literature linked to these metrics. The Presence of Native Forest Fragments (%F) corresponds to the native forest cover of each area reflected in the habitat's quality and quantity (Fahrig, 2013; Hilty et al., 2020). DCLCF shows the connectivity network between the landscape and the farm. DNN uses native covers (%F) to exhibit the connectivity network among the vegetation fragments that offer the ecosystem services necessary for ecological balance (Fahrig, 2013; Hilty et al., 2020). DBWLF presents the routes of the associated fauna to obtain water resources and the network of connectivity between vegetation fragments and their connections with bodies of water. The complete MES equation and the definitions for each parameter needed for its calculation are presented next.

$$\begin{aligned} MES = {} & 0.175(\%F) + 0.1(DFF) + 0.175(DCLCF) + 0.175(DNN) \\ & + 0.1(\%BW) + 0.1(DBW) + 0.175(DBWLF) \end{aligned} \quad (2)$$

Presence of Native Forest Fragments, expressed as a percentage (%F), is the sum of the vegetation cover areas comparable in structure and diversity to the native ecosystems in the studied area.

Distance between Forest Fragments (DFF) is the average distance to the closest functional fragment of any cover. Modeling and creation of ecological corridors are its base. Therefore, it is measured based on the likelihood and minimum distance criteria.

Distance between Core Areas of the Landscape and Core Areas of the Farm (DCLCF) is based on the connection network created for DFF, and it corresponds to the average of the distances between the functional fragments of the farm and those of the landscape.

Distance to the Nearest Neighbor (native forest) (DNN) is related to a temporal analysis, as it evaluates the average distance of the connection between forest fragments and native vegetation (existent from the past). It aims to include the habitat's quantity and quality hypothesis in the methodology and assessment.

Distance between Bodies of Water (DBW) corresponds to the connections network created between natural and artificial bodies of water in the landscape and the farm. Their lengths are averaged.

Distance between Bodies of Water and Landscape and Farm Functional Core Areas (DBWLF) corresponds to the average distance species should travel from functional fragments to the closest body of water. Only straight measurements followed by an animal to access a network of connectivity with the water resource are calculated.

TABLE 2 Symbols for coding each stratum in the reference formula and on the external and internal connectors.

| Basic growth forms | Symbol | Vegetation height classes (m) | Symbol |
|---|---|---|---|
| Trees (woody) | | >35 | 8 |
| Evergreen broadleaf plants | V | 20–35 | 7 |
| Deciduous broadleaf plants | D | 10–20 | 6 |
| Evergreen leafy plants in needles | E | 5–10 | 5 |
| Deciduous leafy plants in needles | N | 2–5 | 4 |
| Evergreen compound leaf | T | 0.6–2 | 3 |
| Deciduous compound leaf | W | 0.1–0.5 | 2 |
| Aphyllous trees (no apparent presence of leaves) | O | < 0.1 | 1 |
| **Other forms of growth (non-woody)** | **Symbol** | **Vegetation cover classes** | **Symbol** |
| Palms | P | Continuous (> 75%) | c |
| Rhizomatous plants (banana, plantain, etc.) | R | Interrupted (51–75%) | i |
| Bamboo (considered individually for its size and growth shape) | B | Fragments (26–50%) | p |
| Succulents (cactus) | S | Rare (6–25%) | r |
| Rosette plants (agave, terrestrial bromeliad) | K | Sporadic (1–5%) | b |
| Ferns | F | Almost absent (< 1%) | a |
| Climbers / Creepers | C | | |
| Epiphytes | X | | |
| Lichens and mosses | L | | |
| **Herbaceous plants** | **Symbol** | | |
| Grasses | G | | |
| Annual herbaceous plants | A | | |
| Perennial herbaceous plants | H | | |

Source: IAFN-RIFA (2016).

Presence of Bodies of Water expressed as a percentage (%BW) is the percentage of the areas of natural and artificial bodies of water found in the studied area.

Since MES is an indicator that is formed of five metrics, the following scale has been defined for its numerical assessment: MES between 20 and 14 = **5**; MES between 13 and 11 = **4**; MES between 10 and 7 = **3**: MES between 6 and 4 = **2**; MES between 3 and 1 = **1**.

## 2.4 Extension of External Connectors (EEC)

It corresponds to the percentage of the perimeter of the farm covered with vegetation, either natural or planted, native or introduced, with elements >1 m in height.

## 2.5 Extension of Internal Conectors (EIC)

It refers to the percentage of patches of vegetation comparable to the natural ecosystems corresponding to the study area connected by linear plant formations with elements >1 m in height, regardless of whether they are natural forest extensions or products of intentional farm management (León-Sicard et al., 2018; Castell and Almarales, 2021).

## 2.6 External Connectors (PEC) and Internal Connectors (PIC)

These indicators correspond to an approach to assess the structure and the basic forms of growth of the species existing in the external and internal connectors. Analog forestry methodology is their base (Senanayake and Jack, 1998; Meijboom, 2007; IAFN-RIFA, 2016), and their calculation uses a reference equation linked to the natural ecosystem area.

For the construction of this equation, we worked by height strata. To each stratum, a symbol was assigned (Table 2) following three characteristics: basic forms of growth, height, and approximate cover percentage of this basic form of growth. The symbols of the external and internal connectors of the farm strata were obtained, and each of these symbols was contrasted with the symbols of the reference formula. Then, a weight equal to 12.5 was assigned to each stratum. A comparison between referential strata and the existing strata (external and internal connectors of the farm) in the current physiognomy was carried out: total code match corresponded to a total value of the stratum (12.5); partial match of at least the first letter of the code equaled half the value of the stratum (6.3); and, no match in the first letter corresponded to zero.

TABLE 3 Interpretation of the agroecological connectivity index.

| Degree of connectivity | Numerical value |
|---|---|
| High connectivity | 4.4–5.0 |
| Moderate connectivity | 3.6–4.3 |
| Light connectivity | 2.8–3.5 |
| Weak connectivity | 1.9–2.7 |
| No connectivity | 1.0–1.8 |

TABLE 4 Land uses in Tosoly and Villa Alicia farms.

| Class | Tosoly area (ha) | Percentage in relation to Tosoly farm area | Villa Alicia area (ha) | Percentage in relation to Villa Alicia farm area |
|---|---|---|---|---|
| Reservoir | 0.00 | 0.00 | 0.05 | 0.27 |
| Discontinuous urban factory | 0.18 | 2.11 | 0.06 | 0.33 |
| Orchard | 0.01 | 0.12 | 0.06 | 0.33 |
| Confined livestock | 0.04 | 0.47 | 0.11 | 0.60 |
| Shrubland | 0.04 | 0.47 | 0.51 | 2.80 |
| Parcel mosaic | 1.31 | 15.34 | 1.04 | 5.70 |
| Secondary vegetation | 0.88 | 10.30 | 3.29 | 18.05 |
| Dense forest | 0.94 | 11.01 | 9.72 | 53.32 |
| Rice | 0.24 | 2.81 | 0.00 | 0.00 |
| Riparian forest | 1.16 | 13.58 | 0.00 | 0.00 |
| Coffee | 1.11 | 13.00 | 0.00 | 0.00 |
| Shade grown coffee | 1.14 | 13.35 | 0.00 | 0.00 |
| Channel | 0.29 | 3.40 | 0.00 | 0.00 |
| Cane | 0.75 | 8.78 | 0.00 | 0.00 |
| Artificial body of water | 0.22 | 2.58 | 0.00 | 0.00 |
| Guadua plot | 0.07 | 0.82 | 0.00 | 0.00 |
| Gardens | 0.06 | 0.70 | 0.00 | 0.00 |
| Seedbeds | 0.01 | 0.12 | 0.00 | 0.00 |
| Inactive land | 0.09 | 1.05 | 0.00 | 0.00 |
| Peas | 0.00 | 0.00 | 0.09 | 0.49 |
| Confined crops | 0.00 | 0.00 | 0.02 | 0.11 |
| Fruit trees | 0.00 | 0.00 | 0.32 | 1.76 |
| Vermiculture | 0.00 | 0.00 | 0.01 | 0.05 |
| Wooded pastures | 0.00 | 0.00 | 2.22 | 12.18 |
| Clean pastures | 0.00 | 0.00 | 0.73 | 4.00 |
| Total | 8.55 | 100.00 | 18.23 | 100.00 |

## 2.7 Shape and complexity

Shape has been considered another edge effect indicator because there is a positive relationship between circular patches and tree species richness (Matteucci, 1998; Torras et al., 2008).

For calculations, each of the eight quantitative indicators was normalized on a scale from 1 to 5, according to the perceived level of Agroecological Connectivity: 1 as a minimum and 5 as a maximum value of each indicator. The results were also interpreted on a scale from 1 to 5 (Table 3). The evaluation implied a perceptual consensus of those who participated in the evaluation to provide an adequate level of objectivity to the analysis.

# 3 Results

## 3.1 Characteristics of production systems and regions

Tosoly farm presented nineteen uses, most of them linked to crops (53%), followed by forests and secondary vegetation (25%; Table 4).

TABLE 5 Covers of the fragments of interest for connectivity in influence area of Tosoly and Villa Alicia farms.

| Class | Tosoly landscape area (ha) | Percentage in relation to Tosoly landscape | Villa Alicia landscape area (ha) | Percentage in relation to Villa Alicia landscape |
|---|---|---|---|---|
| Dense forest | 58.73 | 23.68 | 60.52 | 15.40 |
| Channel | 0.56 | 0.23 | 7.11 | 1.81 |
| Forest plantation | 2.25 | 0.91 | 8.92 | 2.27 |
| Reservoir | 6.55 | 2.64 | 0 | 0.00 |
| Total | 68.09 | 27.45 | 76.55 | 19.47 |

In the area of influence determined in the landscape (248.05 ha), four land uses were associated with the fragments of interest for Ecological Connectivity, with dense forest as the dominant land use (Table 5). The landscape matrix of the area of influence is mostly formed of wooded and clean pastures and crops. However, out of the 248.05 ha of the plotted circle, 68.09 ha have usable covers for connectivity purposes, including forest plantations.

In contrast, Villa Alicia presented 14 land uses linked to the dense forest (53%), secondary vegetation (18%), and wooded pastures (12%): the cultivated land is quite reduced (only 8%) (Table 4). The landscape matrix of the area of influence was 380.98 ha and was dominated by pastures and bare soil. There are 76.55 ha of fragments of interest for connectivity purposes (Table 5).

## 3.2 Evaluated indicators

Both Tosoly and Villa Alicia presented low landscape diversity (LD) (Table 6). For Tosoly's influence area, the percentage of fragments with vegetation cover comparable with the original natural nearby ecosystems ranged between 20 and 29.9% of the total farm area. This range allowed an LD rating equivalent to 3 (on a 1 to 5 scale). An advantageous feature of such fragments is that they mostly correspond to dense forests (Table 5), representing a secure feeding source for fauna, with a lear possibility of further expansion of the vegetation cover. For Villa Alicia's influence area, the percentage of fragments with vegetation cover comparable with the original natural nearby ecosystems ranged between 10 and 19.9% of the total farm area. This range corresponded to an LD rating of 2. Similarly, as for Tosoly, most of these connectivity-related fragments are dense forest relicts (around 60 ha - Tables 5).

The landscape FCA for Tosoly (Figure 2) was higher than for the fragments in Villa Alicia, which are much narrower and separated from each other (Table 7). This is because Villa Alicia is located in the province of Ubaté, which is considered one of the main dairy regions in the Department of Cundinamarca. About 4% of the total milk production in Colombia comes from this province, with great pressure on the natural ecosystems of the area. These natural ecosystems have been transformed for livestock use and, to a lesser extent, for potato, wheat, and barley cultivation. Additionally, there is a high susceptibility to laminar erosion (Municipal Council of Carmen de Carupa, 2000). It is worth mentioning that fragments with useful covers for connectivity that do not have a Functional Core Area can be considered in planning as stepping stones that facilitate movement from one fragment to another. Therefore, these fragments were also registered.

The Distance between Forest Fragments (DFF) (Table 8) showed a degree of difficulty in achieving an inter-species matter and energy exchange (Figure 3) three times greater in the Villa Alicia landscape in comparison with Tosoly. This matter and energy exchange was assessed considering the criteria of a real possibility of creating future and parsimony connectors which is equal to taking the closest connection option in the landscape.

The Distance between Core Areas of the Landscape and Core Areas of the Farm (DCLCF) revealed that Tosoly had better structural connectivity, with an average distance nearly three times shorter than that in Villa Alicia (Table 8). In the latter, the area of influence almost lacked natural ecosystems and very scarce Functional Core Areas, especially to the south and west.

When plotting the waterbody connection network, the Distance between Bodies of Water (DBW) for both farms showed a low score: there were not enough areas with this element to encourage fauna movement towards the farms. However, for Tosoly, at least three bodies of water (0.51 ha) were identified with riparian buffer zones, including forests or agroforestry crops. In contrast, Villa Alicia only had a waterbody (0.05 ha) within the property: one of these waterbody's edges limits with a clean pasture cover. This situation reduces the likelihood of fulfilling its long-term ecosystem function if no protection strategy is implemented.

The Bodies of Water percentage (%BW) is low for both landscapes. However, for Tosoly, there was greater protection in the riparian buffer zones. For Villa Alicia, there was a lower availability of surface water, and the riparian buffer zones were also more unprotected. Both aspects increase waterbody exposure to contamination by agrochemicals and high concentrations of organic matter, which is common in Ubaté (Concejo Municipal de Carmen de Carupa, 2000).

The Distances required to connect the Bodies of Water with the Functional Core Areas (DBWLF) for Villa Alicia (Figure 3) were more

TABLE 6 Ratings for the eight indicators composing the agroecological connectivity index (ACI) for Tosoly and Villa Alicia farms.

| Farm | *LD* | *FCA* | *MES* | *EEC* | *EIC* | *PEC* | *PIC* | *SC* | TOTAL | Connectivity |
|---|---|---|---|---|---|---|---|---|---|---|
| Tosoly | 3 | 4 | 3 | 5 | 5 | 3 | 3 | 3 | 3.59 | Moderate |
| Villa Alicia | 3 | 3 | 2 | 5 | 5 | 1 | 1 | 2 | 2.68 | Weak |

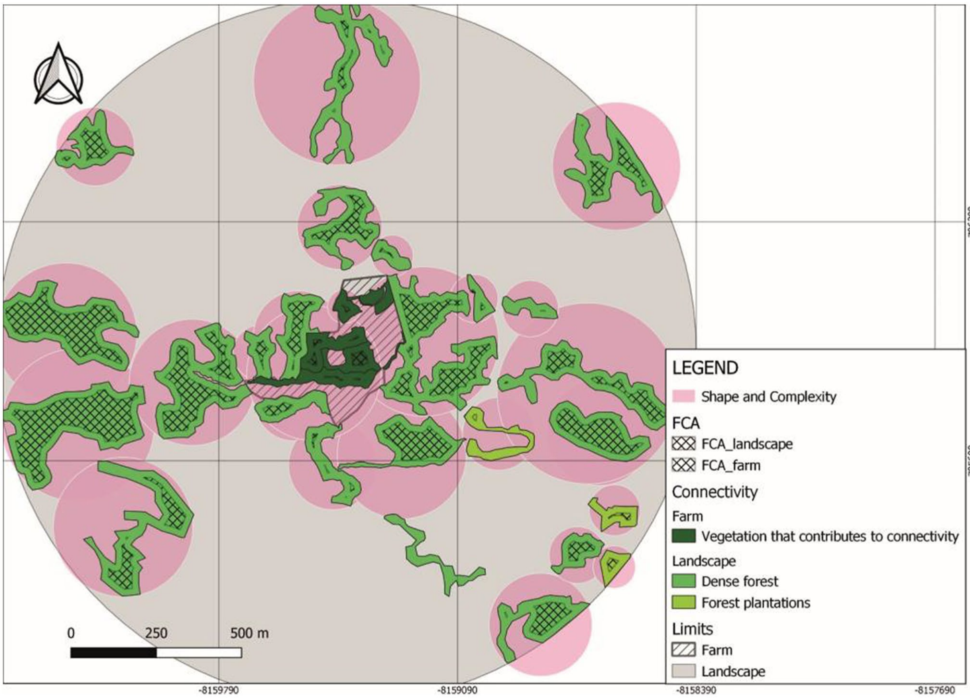



FIGURE 2
Functional core area (FCA) and shape and complexity (SC) indicators in Tosoly farm and its surrounding landscape.

TABLE 7 Area of fragments that contribute to connectivity and functional core areas for Tosoly and Villa Alicia farms.

| Farm | Area of fragments that contribute to connectivity (ha) | Functional core area (ha) | Functional core area percentage (%) |
|---|---|---|---|
| Tosoly | 65.13 | 19.84 | 30 |
| Villa Alicia | 79.67 | 22.42 | 28 |

TABLE 8 Assigned values to the metrics composing the main ecological structure (MES) for Tosoly and Villa Alicia farms.

| Farm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tosoly | Metrics | *%F* | *DFF* | *DCLCF* | *DNN* | *%BW* | *DBW* | *DBWLF* |
| | Value | 24.5 | 59.22 | 62.71 | 65.76 | 3.1 | 179.78 | 36.18 |
| | Score | N/A | 4 | 4 | 4 | N/A | 2 | 5 |
| | MES equation (2) | (24.5)(0.175) + (4)(0.1) + (4)(0.175) + (4)(0.175) + (3.1)(0.1) + (2)(0.1) + (5)(0.175) = 7 | | | | | | |
| Villa Alicia | Metrics | *%F* | *DFF* | *DCLCF* | *DNN* | *%BW* | *DBW* | *DBWLF* |
| | Value | 18.6 | 192.63 | 182.53 | 195.0 | 1.9 | 203.83 | 80.75 |
| | Score | N/A | 1 | 1 | 1 | N/A | 1 | 4 |
| | MES equation (2) | (18.6)(0.175) + (1)(0.1) + (1)(0.175) + (1)(0.175) + (1.9)(0.1) + (1)(0.1) + (4)(0.175) = 4 | | | | | | |

than double compared to Tosoly. However, the scores for the farms were high since the measured distances were not even half the maximum distance (180 m) required by pollinators to move from one fragment to another.

Finally, the Distance to the Nearest Neighbor (DNN) was high for Tosoly because there was a higher density of dense forest fragments compared to Villa Alicia. In the latter, the low density of dense forest fragments meant that their distances were three times greater than in Tosoly.

Both farms presented the highest rating for the External and Internal Connectors (EEC and EIC) (Table 9) because there was continuity with living fences or forest remnants in most of the property boundaries since their managers decided to plan the conservation of these connectors.

Shape and Complexity were low in both production systems (Table 10), especially for Villa Alicia where the fragments of interest for connectivity were extremely elongated (between 0.6 and 0.8). This shows both low structural complexity and high edge effects. Tosoly

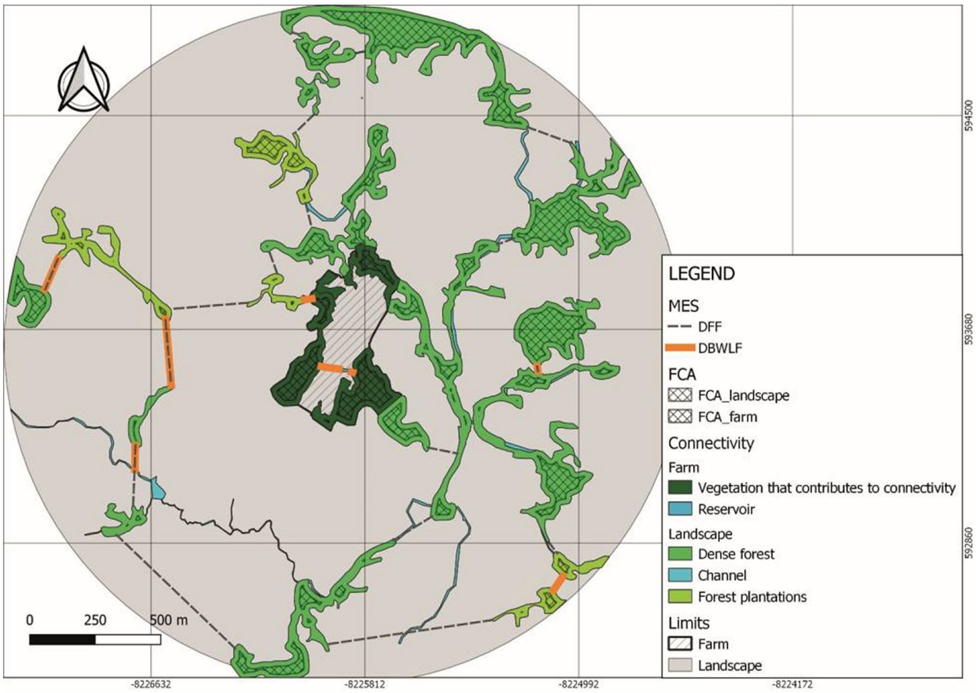



FIGURE 3
Distance between forest fragments (DFF) and distance between bodies of water and landscape and farm functional core areas (DBWLF) (variables of the Main Ecological Structure [MES]) neighborhood metrics in Villa Alicia farm and its surrounding landscape.

**TABLE 9** Extension of external and internal connectors for Tosoly and Villa Alicia farms.

| Farm | *EEC* | | | *EIC* |
|---|---|---|---|---|
| | Perimeter (m) | Living fence (m) | Living fence (%) | |
| Tosoly | 1,643 | 1,233 | 75.0 | Between 75% and 100% of the internal areas of the farm are connected with living fences |
| Villa Alicia | 2,140 | 1,920 | 95.00 | |

**TABLE 10** Fragment shape and complexity indicator for Tosoly and Villa Alicia farms.

| Farm | Number of fragments | Average SC value |
|---|---|---|
| Tosoly | 26 | 0.58 |
| Villa Alicia | 20 | 0.74 |

might be roughly considered as circular (between 0.4 and 0.6, respective to 0 as the referential value), and its fragments were more likely to contribute to the connectivity network by providing greater complexity, supporting more biological interactions.

Regarding the complexity of the fragments, the physiognomic formulas for the two corresponding referential forests were established.

According to the symbology in Table 2, the referential formula for Tosoly contained the physiognomy of eight strata (identified while touring the area). The most representative species are shown in Figure 4. Table 11 shows the similarity values with the referential formula for each stratum. The highest stratum W8b did not exist in any of the connectors, which is why it was assigned a value of 0 in all columns. The next stratum V7c was shared thoroughly by connectors CE1 and CI1 (12.5) and partially shared by connectors CE2 and CI2 (6.3). Then, by adding the values of each connector and weighting them using its distance, the rating values for all external (47.7) and internal (48.4) connectors were obtained. Only one of the external connectors CE1 presented a high similarity with the referential forest. However, it is the most extensive connector covering 57% of the farm perimeter, providing greater weighting to the diverse physiognomy of this connector. In addition, CE1 was shared over its entire length with the internal connector CI1, and therefore, the same value of 41.2 was given to the internal connectors.

Similarly, the referential formula was established for Villa Alicia. Species such as *Cedrela* spp. and *Quercus* spp. and families such as Arecaceae, Bromeliaceae, Piperaceae, Loranthaceae and other hemiparasites and epiphytes were found. Each stratum was compared with the existing physiognomy (Table 12). Only the presence of broadleaf deciduous trees was shared, but there were no more shared elements, not even tree height: this value in the referential forest reached the range between 10 and 20 m, while in the existing connectors, this value did not exceed 5 m. Even when an external connector shared its

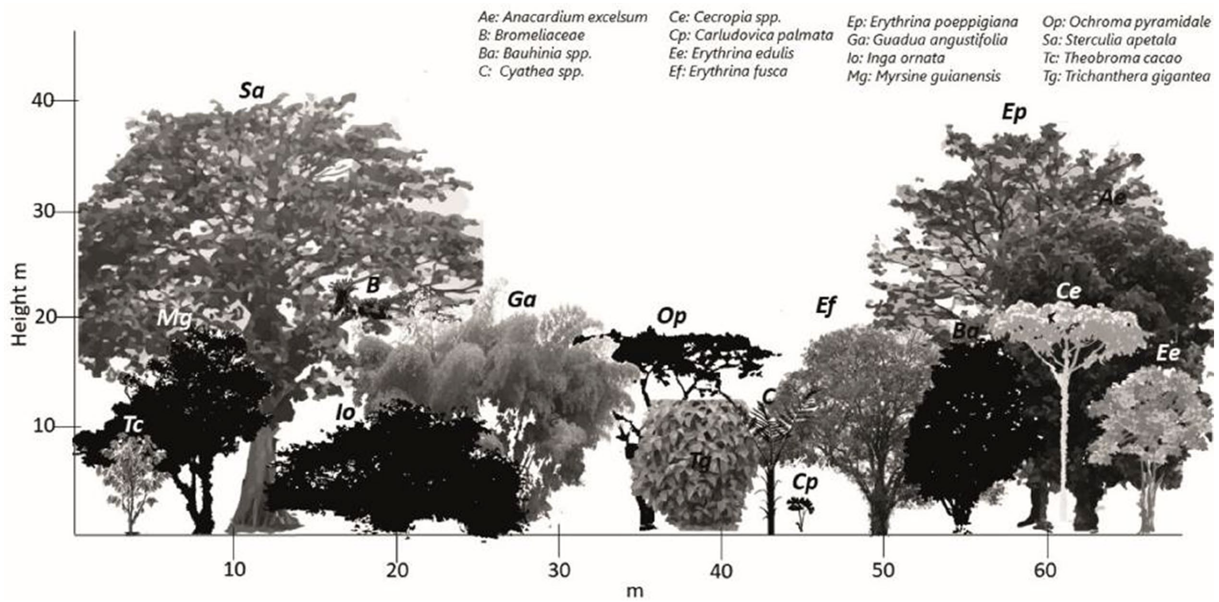



FIGURE 4
Reference forest profile for the physiognomy formula for Tosoly farm.

TABLE 11 Comparison between each external and internal connector of Tosoly farm and the reference forest formula and weighting according to the percentage extension of each connector.

| Reference formula | Maximum% possible | Rating in% for each stratum when comparing the connectors with the reference formula | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | EC1: V7c; V6i; F6a, X6p; V5p, E5r; L4b | EC2: V7b; V6r; V4r | EC3: G6c | EC4: V6b; C5p; V4i; V3r | IC1: V7c; V6i; F6a, X6p; V5p, E5r; L4b | IC2: V7b; V6r; V4r | IC3: V6b; C5p; V4i; V3r |
| W8b | 12.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| V7c | 12.5 | 12.5 | 9.4 | 0 | 0 | 12.5 | 9.4 | 0 |
| D7p | 12.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| V6i | 12.5 | 12.5 | 9.4 | 0 | 9.4 | 12.5 | 9.4 | 9.4 |
| X6p | 12.5 | 12.5 | 0 | 0 | 0 | 12.5 | 0 | 0 |
| F6r | 12.5 | 9.4 | 0 | 0 | 0 | 9.4 | 0 | 0 |
| V5p | 12.5 | 12.5 | 6.3 | 0 | 6.3 | 12.5 | 6.3 | 6.3 |
| L4b | 12.5 | 12.5 | 0 | 0 | 0 | 12.5 | 0 | 0 |
| Total | 100.0 | 71.9 | 25.1 | 0 | 15.7 | 71.9 | 25.1 | 15.7 |
| Weighing | | | | | | Total | | |
| EC | | 41.2 | 3.9 | x | 2.6 | 47.7 | | |
| IC | | 41.1 | 1.8 | 5.6 | x | 48.4 | | |

length with an internal one (finding up to four vertical strata), no strata were similar to the referential forest, which is why this farm obtained the lowest possible score for this indicator.

## 3.3 Comparative connectivity

The comparative analysis between both production systems indicates how Tosoly farm showed planning and management focused on sustainable practices that strengthened the functional connectivity network and the exchange of matter and energy with natural ecosystems (Figure 5).

Although both farms had similar values for the Landscape Diversity indicator, the edge effects (Functional Core Areas) and the spatial distribution (shortest Distance between Fragments) showcased a connectivity network with more parsimony. Therefore, there is a higher possibility of maintaining and offering ecosystem services to the farms and their productive units.

TABLE 12 Comparison between each external and internal connector of Villa Alicia farm and the reference forest formula and weighting according to the percentage extension of each connector.

| Reference formula | Maximum % possible | Rating in % for each stratum when comparing the connectors with the reference formula | | | |
|---|---|---|---|---|---|
| | | EC1: V5i; D5r; V4b; D4b | EC2: V4i; D4i | IC1: V5i; D5r; V4b; D4b | IC2: V4i; D4i |
| W6r | 11.1 | 0 | 0 | 0 | 0 |
| D6p | 11.1 | 5.6 | 5.6 | 5.6 | 5.6 |
| P6p | 11.1 | 0 | 0 | 0 | 0 |
| F6r | 11.1 | 0 | 0 | 0 | 0 |
| X6i | 11.1 | 0 | 0 | 0 | 0 |
| L6i | 11.1 | 0 | 0 | 0 | 0 |
| K6p | 11.1 | 0 | 0 | 0 | 0 |
| C5b | 11.1 | 0 | 0 | 0 | 0 |
| H3r | 11.1 | 0 | 0 | 0 | 0 |
| Total | 100.0 | 5.6 | 5.6 | 5.6 | 5.6 |
| Weighing | | | | Total | |
| EC | | 5.3 | 0.3 | 5.6 | |
| IC | | 5.0 | 0.5 | 5.6 | |

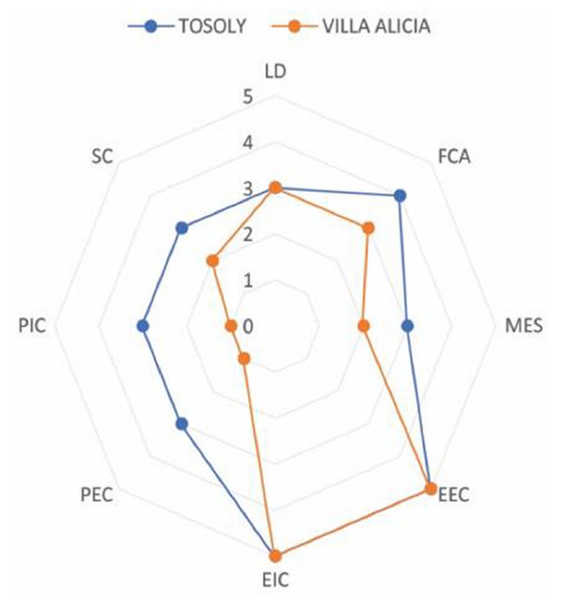



FIGURE 5
Comparative analysis of the agroecological connectivity index (ACI) for Tosoly and Villa Alicia farms.

Due to the initiatives of Tosoly's managers, wild vegetation native greenhouses have been established. In these greenhouses, seeds from the same native forests of the region are collected, preserved, exchanged, reproduced, and germinated to nurture the conservation areas and build the external and internal connectors of the farm. These actions contrasted with the substantial transformation of the landscape in Villa Alicia, resulting in marked differences in the numerical values of the indicators for the physiognomy of internal and external connectors.

## 4 Discussion

A paradigm based on biodiversity management for sustainable agriculture represents enormous potential to face many of the current agricultural challenges because it could increase environmental and socioeconomic resilience (Jackson et al., 2007) of production systems and agricultural territories. This paradigm considers biodiversity management as creative, pragmatic, and planned but mostly as a key component of the agro-productive designing processes.

The expansion of the agricultural frontier implies the destruction of extensive areas of wild biodiversity with a direct impact on the attributes of the forest (Safar et al., 2022). However, there are more rational alternatives to landscape modification that do not radically disturb ecological attributes and, on the contrary, guarantee the spatial flow of ecosystem services varying according to landscape structure (Assis et al., 2023). Agroecology proposes the application of transitional principles towards sustainability based on biodiversity management for the transformation of productive systems (Nicholls et al., 2016). Such management allows biodiversity use, conservation, and enrichment at the farm level, increasing productivity and reducing pressure on the landscape (Thrupp, 2004). However, productive strategies (use of living fences, covers, crop association, agroforestry, and composting, among others) are not enough to enrich biodiversity within productive systems (Nicholls et al., 2016) since farms undoubtedly interact with ecosystem components surrounding them. Therefore, agroecological planning is not only exclusively inherent to the farm but also involves the landscape. In its conceptual and methodological evolution, agroecology has integrated a larger scope into its analysis, moving from the plot and farm to the landscape unit (Wezel et al., 2020).

There is increasing scientific evidence for the need to closely link landscape ecology with agroecology to move towards the transformation of agricultural systems (Batáry et al., 2020). This study proposed the Agroecological Connectivity Index as a diagnostic and planning tool that considers the ecosystem and agroecosystem structure of both landscape and production systems from the perspective of ecological structure functional connectivity. Its operation allows adequate farm planning for the production of healthy food and biodiversity conservation.

## 4.1 Environmental ecological functions and connectivity

In an analysis carried out on more than 172 agricultural production projects worldwide, Mijatovic et al. (2013) showed how biodiversity contributed to landscape resilience through ecological restoration practices, productive diversification, and soil and water management, and all activities promoted by agroecological approaches. Ecological functions developed by agroecological processes in agriculture have valuable repercussions for sustainable production, especially for the protection of pollinating populations and natural enemies considered critical ecological services for agricultural systems (Liere et al., 2017). Functional connectivity represents a particularly pivotal issue in agricultural landscapes where the Green Revolution agriculture has intensified. This is because monoculture trends in large areas have made remaining patches of biodiverse wild vegetation scarce. In addition, such trends do not guarantee the continuity of functionally desirable species for agriculture (Harvey, 2009). However, projects such as those mentioned above, carefully planned, and with property design processes manage to reactivate these essential functions for a more balanced operation of production systems.

Connectivity is a function of the distribution and types of natural vegetation patches in the agricultural landscape (Hilty et al., 2006) evidenced in the indicators used for the ACI and applied to Tosoly and Villa Alicia. In general, landscapes with a high degree of functional connectivity, those maintaining large areas of natural vegetation with short distances between remaining patches while having extensive corridor networks that facilitate species mobility, have the greatest likelihood of preserving species populations (Bennet, 1999). In that sense the farm Tosoly is an example of higth functional connectivity because have short distances beetwen patches of natural vegetation and can provide a network of corridors. Blann (2006), Castell and Almarales (2021), Liccari et al. (2022), and Miñarro, et al. (2023) ratify how the different land uses in the surrounding landscape and the degree to which a patch is connected to similar patches determine not only the abundance and richness of species but also ecological processes associated to them (seed dispersal, prey–predator interactions, and pollination, among others). The sole presence of tree corridors of a single species does not guarantee adequate connectivity and flow of species through them. Thus, conserving patches and corridors with vegetation comparable to the native one found in the region enables the highest flow of pollinators, biological controllers (Saunders, 2016), as well as native microfauna that require exclusively unmodified habitats (Sanabria et al., 2016). The scarce structure of the connectors for Villa Alicia was related to land uses in the surrounding landscape. A historical look at the landscape transformation showed that, for at least two decades, only 19% of the covers might have potentially contributed to connectivity. The rest have been transformed into clean pastures or monocultures. This limits any possibility of connectivity and expansion of ecosystem functions within the region.

It is well-founded to integrate ecological connectivity into the planning processes of the farm and the landscape through diverse biological corridors (Gutiérrez-Chacón et al., 2020). These corridors expand the insect trophic networks and promote exchanges of associated fauna and flora due to their high capacity to fulfill ecosystem functions that can be useful for agricultural production processes. However, this does not occur immediately after the establishment of the corridor but, along the restoration process of the physiognomy of local ecosystems. Knowledge of the complexities between landscape ecology and agroecology allows a comprehensive vision of the ecosystems' spatial distribution. Additionally, being able to recognize the connections of the ecosystems with human activities allows and improves their conservation and management.

## 4.2 Landscape analysis based on connectivity indicators

The study of the landscape in terms of agroecological connectivity and environmental functions that can be used by agroecosystems must be analyzed from a systemic approach. For landscape studies, the importance of natural vegetation fragments is no longer questionable: what is important now is to develop a comprehensive and detailed understanding of when and how fragmentation matters (Rybicki et al., 2020). In this case, this understanding is necessary for procuring an ecosystem balance at the productive system level.

In this regard, two components influence the potential connectivity for a species, community, or ecological process: the structural and the functional (Fahrig et al., 2011; Ana Milena Alonso et al., 2017; Liere et al., 2017). The structural component corresponds to the spatial connection of different types of habitats in the landscape, and the functional component refers to the spatial arrangement and composition of the habitats, which generates a behavioral response of individuals and species towards the landscape's physical structure. Thus, the ACI incorporates indicators related to these two crucial landscape components.

One of the structural indicators is the landscape diversity (LD) which makes an inventory of covers and uses and focuses on characterizing the fragmentation degree of the landscape to identify whether the matrix is governed by natural fragments (when it is greater than 50%) or not.

The main ecological structure (MES) integrates five landscape metrics to measure the distances at which fragments of natural vegetation and bodies of water can be found. Its interpretation scale was structured for pollinators, considering that wild bees do not fly beyond 180 m from their hives and, therefore, the effective pollination ecosystem service cannot occur outside this range of action (Pantoja et al., 2014).

The functional core area (FCA) analyzes the edge effect as an important characteristic in vegetation patches in fragmented landscapes that generates changes at different levels due to the transition between diverse ecosystems. For example, at the microclimatic level and within the physical soil conditions, the edge effect makes the composition and structure of the vegetation different in the perimeter and inside the forest (Fox et al., 1997). Consequently, it also affects insect diversity (Harvey, 2009). The fragments that show a Functional Core Area (those that exceed the edge effect) are taken into account for connectivity networks and the calculation of other indicators. The fragments that do not show this characteristic are regarded as "stepping stones" but are not mandatorily included in the neighborhood connections in the connectivity networks. FCA does not take into account riparian forests since the edge effect is null when limited by a waterbody (Granados-Sánchez et al., 2006). No limitation was determined in the size of the Functional Core Areas since it has been shown that small tree covers (≤1 ha) within agricultural matrixes are essential to maintain landscape connectivity as they have different functions (perching places, "stepping stones," dispersal routes, and additional habitats for the associated fauna). This proves even more critical for animals that move daily for short distances (Saura et al., 2014; Cadavid-Florez et al., 2020).

Shape and complexity (SC) is another structural indicator related to the edge effect. It detects thin and elongated patches compared to a hypothetical circle, which is considered as the desirable shape, since it reduces said effect by the minimum (Patton, 1975; Saura and Carballal, 2004) and facilitates the balance of ecosystem relationships within the fragments (Fox et al., 1997). The relevance of the indicator is higher when the landscape matrix generates stronger resistance to the movement of fauna or dispersal of flora. This is the case of a matrix dominated by clean pastures and constant livestock and monoculture dynamics, as for Villa Alicia.

Other structural indicators are the extension of connectors, both internal and external (EIC, EEC). They identify the connection routes between natural fragments through which their functions extend. For example, soils of these connection routes act as more effective repositories of organic carbon, promote infiltration and reduce run-off, and increase the diversity of organisms such as earthworms and even arbuscular mycorrhizae (Holden et al., 2019). They also contribute to the restoration of fragmented agricultural landscapes (Francesconi et al., 2011). In the internal connectors at the farm level, there may be more controlled management and more rigorous monitoring through the implementation of basic agroecological practices that favor pollination and biological control.

The functionality of the landscape analyzes the functional value of the fragment in relationship to its size. The quality of the fragment refers to how much its structure and floristic composition has been modified, that its structure and floristic quality have had. Therefore, the more modified or degraded the fragment is, the lower its quality is (Kennedy et al., 2003). In the ACI, this characteristic is analyzed through Physiognomy Indicators of Internal and External Connectors (PIC, PEC). These Physiognomy Indicators are based on the analog forestry methodology (Senanayake and Jack, 1998; Meijboom, 2007; IAFN-RIFA, 2016), and they describe the physiognomy (external appearance) of the vertical structure of the fragments that serve as connectors.

This comparative analysis of Physiognomy Indicators is carried out considering that agricultural modifications in an ecosystem can be established while trying to imitate the initial ecosystemic architecture. In this sense, it is possible to maintain many of the initial natural ecosystem functions (Scherr and McNeely, 2009). The analysis begins with a description of a referential forest by direct observation: a nearby patch is highly preferable, but if it is not available, the description can be established using local knowledge and secondary information about the biome, life zone, and vegetation inventories of the natural ecosystem comparable to the analyzed area. This referential forest description is then compared to the external and internal connectors, and even future monitoring might be carried out. The descriptions should primarily focus on the species' adult forms (IAFN-RIFA, 2016). Analyzing the proximity of fragments of similar composition is crucial because specific species might move between patches of vegetation in the landscape if they are similar and relatively close to each other. However, if those patches are considerably distant, such mobility can be hampered. In this way, landscapes are functionally connected when wild species can move freely from one patch to another within the same landscape (Harvey, 2009).

Several studies on the ecological structure of the landscape and its effects on agricultural processes have been conducted in Colombia. The use of the MAS index applied to high Andean regions dedicated to livestock and milk production has shown how a landscape structure with high connectivity is directly related to the increase in agrobiodiversity and positively related to functions, such as the increase of soil organic matter (Quintero et al., 2022). The MAS index has also been applied to citrus cultivars, finding that a greater ecological structure improves the resilience capacity of agroecosystems against climate variability phenomena (Cleves 2018). Another study demonstrated how forest and waterbody connectivity reduces the incidence of the two main pests of oil palm in highland regions (*Opsiphanes cassina* and *Rhynchophorus palmarum*) (Gómez et al., 2023).

## 4.3 Planning the agroecological transition

Agroecological designs do not only enrich biodiversity within the farm but simultaneously enhance functions between fragments of natural habitat (Vandermeer and Perfecto, 2007). For this reason, it is important to act inside and outside the production system. Within the production system, one of the essential activities is to promote connectivity restorative practices such as the use of living fences, agroforestry crops, crop association, cover crops etc. Such practices should be strategically located to enhance both structure (fragment size) and functionality (fragment quality) of the farm. Additionally, these practices benefit the services of the agroecological production process, especially pollination and biological control of pests, diseases, and weeds (Altieri, 1999; Crowder and Jabbour, 2014). Agroforestry and silvipastoral crops deserve special attention as they correspond to strategies that increase above-ground biodiversity and activation of ecosystem functions. A study carried out with silvipastoral systems based on *Leucaena leucocephala* in the Colombian Andes showed a higher number of native ants compared to treeless grasslands (Rivera et al., 2013).

While agroecological connectivity within the farm represents a process over which the managers of the productive system have absolute control, connectivity outside the productive system implies a negotiation process with other actors. The result of this negotiation escapes the decision of a single agroecological producer. In this way, when assuming the agroecological transition outside the productive system, the construction of community agreements for an adequate territorial intervention is quintessential. This is known as the territorial agroecological governance process (Camacho et al., 2020). This process requires closer articulation and effort at institutional and community levels to guarantee action-oriented policies for agrobiodiversity conservation that provide public benefits (Thrupp, 2004).

# 5 Conclusion

Agroecological farm planning based on the functional connectivity in the farm and landscape is in a paradigm context different from the one associated with a productivist farm and territorial planning since it analyzes the structure and functions of the landscape from a systemic approach and takes advantage of them for restoring the ecosystem balance. From this perspective, the landscape is an agroecological matrix with natural vegetation fragments and agroecosystems that retain the functionality of natural ecosystems in favor of agroecological production processes at the farm and the regional level.

Agroecology must not be understood as limited to reducing the use of synthetic inputs or substituting biological and organic inputs. Therefore, the agroecological transition process must be reconsidered: it begins with a complete redesign of the productive system, articulating it to the landscape. The authors argue that such a transition must start from recognizing the connectivity status within the productive system and the area of influence of the landscape over the farm. Essentially, the transition must be carried out inside and outside the production system.

The ACI incorporates landscape indicators and metrics that show aspects of both the structure and functionality of the landscape. In the Colombian case studies analyzed, Villa Alicia, located in Cundinamarca, showed a weak ACI index (2.59 on a scale between 1 and 5): the farm presented fewer productive uses, both in its interior and in the landscape. This situation translated into a low main ecological structure and reduced complexity and physiognomy of its connectors. In contrast, Tosoly, located in Santander, showed moderate functional connectivity (3.59) due to a good MES and a high score of functional core areas. The suggested methodology allowed the analysis of the fragmentation and quantity and quality of the habitat, which supported the design of productive agroecosystems that simultaneously comply with conservation strategies.

In future studies, it is necessary to analyze the relationship between the ACI and the dynamics of populations of pollinating insects and organisms that control pests and diseases. The purpose of such analysis is to establish incidental relationships between the introduced indicators and the ecological processes that are triggered by the structure and operation of the connectivity elements present or included in the productive systems and the landscape.

From the social perspective, it is decisive to change individual and community attitudes to ensure collective action to conserve the ecosystem. The transformation of the landscape matrix is undoubtedly achieved from the transformation of each of its segments (farms) while constantly avoiding the interruption of connectors and planning connectivity through the farms to recover the regional ecological structure. One question is open to debate here: how much are the farmers aware and willing to contribute to a coordinated effort in the territorial transformation when productive planning, in general, is done individually and disjointed?

Additionally, community action on the landscape must be strengthened with public policies that promote collective connectivity actions. Social action (participatory governance) and public action (institutional policies) can create a new order which is capable of recovering and invigorating the ecosystem balance needed for agroecological production.

# Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

# Author contributions

ÁA-O: Formal analysis, Investigation, Supervision, Writing – review & editing. JC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. AM-P: Formal analysis, Investigation, Methodology, Writing – original draft.

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# Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

# Publisher's note



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# Community gardens for inclusive urban planning in Padua (Italy): implementing a participatory spatial multicriteria decision-making analysis to explore the social meanings of urban agriculture

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Urban agriculture is recognized as a worthy resource to support a growing population as well as to provide other positive effects on urban ecosystems and their citizens. In this context, community gardens are considered key topics in terms of food production and food security, in both developing and developed countries, as well as in terms of social inclusion and participation. The general aim of this study was to assess the main spatial criteria recognized and shared by stakeholders to identify suitable and inclusive areas for community gardens by testing and developing a participatory process. Because of its size, population, and urban fabric, Padua (northeast Italy) was selected as a representative and emblematic case study for mid-sized cities in Europe. The methodology was based on field surveys of key informants and spatial multicriteria decision-making analysis in the open-source geographic information system environment of QGIS. The results identified neighborhoods to be prioritized in the design of new community gardens according to three scenarios: the distance index, the social index, and the combination of the two (overall index). To conclude, this study highlighted the importance of adopting a decision-making methodology to support local policymakers and municipal agencies that are interested in implementing other community gardens in Padua. The case study and the methodology adopted could also serve as important guides for cities by providing step-by-step processes that can be directly applied.

KEYWORDS

**urban agriculture, community gardens, participation, urban ecosystem services, spatial multicriteria decision analysis, MCDA, GIS, urban planning**

## 1 Introduction

### 1.1 Urban agriculture and community gardens

Worldwide, one of the major issues of the next few decades is how to feed a growing population (Fouilleux et al., 2017). This topic is particularly exacerbated in urban contexts, where it is estimated that most people will live in the next few decades. In this framework, the strict dependency to supply food among cities and rural areas could become unsustainable in future (Bloem and de Pee, 2017). However, the space for food in cities is limited for two main reasons. First, until recently, urban planning allocated primarily the hinterlands as areas for food production to prevent public health issues (Mubvami and Mushamba, 2006). Second, nowadays, competition to take land and soil among settlements, transport areas, and green areas is sharply increasing, thereby reducing the potential space for food (Olsson et al., 2016; Peroni et al., 2022b).

In this framework, urban agriculture is recognized as a worthy resource for food supply, as urban areas are producers of 15–20% of the world's food (Worldwatch Institute, 2011). They can provide fresh and local food to urban dwellers by supporting a healthy diet and fostering food security at the same time (Cabannes and Marocchino, 2018; Siegner et al., 2018).

In addition, urban agriculture has other positive effects on urban ecosystems and their citizens, such as supporting climate change resilience and adaptation, which is in accordance with the European Green Deal, providing different urban Ecosystem Services (ES), and contributing to the network of green infrastructures and nature-based solutions of a city (Sanyé-Mengual et al., 2018; Peroni et al., 2022a). Urban agriculture plays an important role in mitigating urban heat islands, addressing the soil sealing phenomenon, regulating water runoff, and providing benefits for pollinators, due to plant variety (Matteson et al., 2008; Gittleman et al., 2017; Pristeri et al., 2021; Romanovska et al., 2022).

Scientific literature has also recognized the added value of urban agriculture in terms of human wellbeing and quality of life by improving the living environment through recreational and cultural activities (Harada et al., 2021; Ilieva et al., 2022). Urban agriculture is likewise identified as a worthy alternative to the reuse of vacant and abandoned land as, for example, reported by Newell et al. (2022) in a Detroit case study.

The integration of agriculture into the urban planning of cities should represent a fundamental strategy in sustainability agendas (Bartolome et al., 2022). Therefore, it should be of paramount importance for local policymakers to plan, allocate, and manage potential areas designated for agriculture in cities. In this framework, Singapore is a good example; despite the city-state ranking first in the global food security index, local production is fostered through policy support, particularly by increasing self-sufficiency by 2030 to meet 30% of the country's food demand (Diehl et al., 2020).

Urban agriculture currently encompasses different categories: urban forests, rooftop gardens, residential and community gardens, guerrilla gardens, vertical farms, balconies, schoolyard greenhouses, and vacant lands (Oda et al., 2018; Goodman and Minner, 2019). In this context, community gardens are considered key topics in urban agriculture in terms of food production and food security, in both developing and developed countries, as well as in terms of social inclusion and participation (Kafle et al., 2022). To date, there is no uniform and unique definition of community gardens. According to Zheng et al. (2023), eight main definitions of community gardens are not always able to encapsulate the different meanings attributed to them by participants of community gardens. Comparing the different literature definitions with the types of community gardens investigated in this study, we chose to describe them following Kingsley et al.'s (2009), p. 209 definition: "plots of land allocated to individuals to create gardens of their choice in a communal environment."

## 1.2 Benefits of community gardens and the identification of their best and fairest locations

Community gardens have been recognized as providing multiple benefits to local communities and urban dwellers. Besides their main documented role in guaranteeing food security, they play an important role in environmental restoration, biodiversity support, and environmental education (Caneva et al., 2020). Their supportive roles in social inclusion and integration (Turner et al., 2011; Christensen et al., 2019), the maintenance of physical and mental wellbeing (Lampert et al., 2021; Litt et al., 2023), community empowerment and development (Cumbers et al., 2018), and the promotion of social interactions across generations (Yotti Kingsley and Townsend, 2006) have also been reported.

Overall, the scientific literature has extensively studied the siting of urban agriculture resources in relation to food security, nutrition, and the social dimensions of community gardens, while less attention has been given to their contributions as green infrastructure to the urban ecosystem. In a recent bibliometric analysis of urban community garden systems, how community gardens are defined as nature-based interventions is among the emerging research topics (Zheng et al., 2023). The incorporation of both the social and environmental dimensions to identify the best locations to be prioritized for the siting of a community garden could therefore be challenging despite the large availability of remote-sensing technologies, such as high-resolution aerial images and Geographic Information System (GIS) technologies.

In this context, multicriteria decision analysis (MCDA) coupled with GIS, which improves the spatial dimension (spatial MCDA, hereafter sMCDA), could be a useful tool for supporting local stakeholders and policymakers when deciding where to locate community gardens. According to Smith et al. (2021), systematic and quantitative methods, such as MCDA, for strategic siting have received less attention, and few community garden studies that specifically call for the application of MCDA as a means of siting community gardens have been identified. However, MCDA has been widely adopted in decision-making processes for other decisions (Smith et al., 2017; Boggia et al., 2018; Cinelli et al., 2020).

It is also important to highlight that many studies have mainly investigated distance criteria (Kyoi, 2023), for example, by examining how far the site of urban agriculture is from the houses of urban dwellers (Bergstrom et al., 2009) or the spatial distance between green spaces and residents in Berlin (Bertram and Rehdanz, 2015), with less consideration of involvement of stakeholders (Bousquet et al., 2023).

## 1.3 Objectives

In this context, the general aim of this study was to assess the main spatial criteria shared and recognized by stakeholders to identify suitable and inclusive areas for community gardens. These criteria will incorporate both social and environmental dimensions. The specific aims were as follows:

1. To test and develop a participatory process for spatial criteria definition and weighting for locations of democratic community gardens.

2. To identify suitable and prioritized urban areas for community urban gardens in public spaces.
3. To understand the main reasons why urban dwellers are encouraged to cultivate community gardens.

## 1.4 Study area

The study area identified in this research is the city of Padua, located in northeast Italy. Figure 1 shows the municipality boundaries and the 40 urban units (hereafter UUs, the sub-urban division used for management and statistical purposes).

Because of its size, population, and urban fabric, Padua was selected as a representative and emblematic case study for mid-sized cities in Europe characterized by a medieval downtown. The municipal territory of the city occupies an area of 93.3 $km^2$, with approximately 211,000 inhabitants (Comune di Padova, 2021).

The city is ranked among the top five Italian cities with the highest soil sealing (Munafò, 2022); indeed, 50% of the urban territory is covered by impervious surfaces (Pristeri et al., 2020). As a result, the competition for land among different stakeholders is intense, and there is a high risk of reducing the space for the implementation of new community gardens.

It is important to highlight that, as in other European and North American cities (Anguelovski et al., 2022), Padua faces potential green gentrification focused on fostering and implementing green spaces with the enactment of the New Urban Plan (Piano degli Interventi); the plan adopts an afforestation strategy, which is characteristic of the Boeri architecture studio (Comune di Padova, 2020). The New Urban Plan for the city is mainly focused on this green approach without considering the agricultural issue as well as on more specific community garden interventions. Most of these interventions will be implemented in low-income and disadvantaged neighborhoods of the city, where the presence of community gardens to foster local food production should be implemented.

Moreover, a new Municipal Green Plan was approved at the beginning of 2022. It is a planning tool complementary to local urban planning, containing a strategic vision of urban and peri-urban public green and agricultural areas in the medium to long term (Comune di Padova, 2022). This plan, unlike the New Urban Plan, is not binding.

At present, the majority of the agricultural areas of the city are located in the hinterlands, occupying 28.8 $km^2$ of the total city area (Pristeri et al., 2021). In this context, since the 1990s, Padua has been promoting the creation and allocation of new community gardens, whose number, to date, has reached 710 lots distributed in 19 sites in different municipal areas around the city (Figure 2).

The periodic calls for allocation have also seen a development in the types of target citizens, such as associations and schools, and not only individuals, as well as in aims, such as promoting the sharing of benefits, environmental education, and organic farming.

# 2 Materials and methods

Spatial and statistical data for Padua municipality were searched and collected, together with reports and publications concerning the topics of interest, to accomplish the aims of this study. Structured and semi-structured interviews were developed, tested, and carried out, and different sMCDA scenarios were created. Concerning the spatial dimension of community gardens' locations, we considered two spatial scale levels that are useful for spatial planning purposes: the 40 UUs level and the green areas administrated by the municipality. In particular, for green areas, we used the spatial database provided by Padua municipality, which consists of over 12,000 polygons; the data were filtered by area size by considering only polygons over 500 $m^2$ in size (considered the minimum area suitable for community garden creation) and selecting only categories that are useful for community gardens' locations (e.g., excluding green areas inside roundabouts), obtaining a total of 476 areas.

## 2.1 Participatory survey and workflow

### 2.1.1 Interview definition and preparation

Two types of interviews were structured and carried out. First, semi-structured interviews were conducted with the community garden office staff of the municipality to obtain an overview of the state of the art of Padua community gardens and their histories as well as to select possible criteria for the sMCDA simulations on the basis of the respondents' opinions, statistics, and the spatial data available. Second, structured interviews were carried out with the gardeners of the community gardens.

The structured interviews with the gardeners consisted of five parts. Sections 1 and 2 were related to the respondents' personal data (i.e., age, residence, and employment) and general information (i.e., knowledge of the different kinds of community gardens in Padua and preferences for different typologies), while Section 3 investigated the habits of the users (i.e., how many times a week they visited their plots and how they reached them). The fourth section was about defining criteria, divided into two main categories (see Table 1), which were (i) distance features (six criteria), or the distance from some feature of interest (i.e., cycle paths and parking), and (ii) socioeconomic and cultural characteristics (hereafter social characteristics, with five criteria; i.e., number of families and presence of migrants). Finally, Section 5 included some questions to understand the people's approval of community gardens (i.e., the surfaces of the lots, production, and services). The structured interview format was socialized and tested with the community garden office staff of the municipality.

### 2.1.2 Interview administration

In total, 7 of 19 representative community gardens were selected, and email and phone contacts were obtained with the support of the community garden office. The community gardens chosen were well distributed around the city and were located in different neighborhoods. Each representative was contacted to determine their availability for the study and to agree on a possible day for the interview. The selected sites were as follows (see Figure 2): Orti sociali di Via Induno (San Carlo community garden in the north of Padua), Orti delle Meraviglie (Camin community garden in the east of the city), Orti dei Salici (Guizza UU near the center of Padua), Orti del Parco Mela Rossa (in the southwest of the city), Orti Verde Mamiani (Stanga UU in the northeast of Padua), Orti Mondorto (Montà UU in the west of the city), and Orti Vengo e Vango (Voltabarozzo UU in the

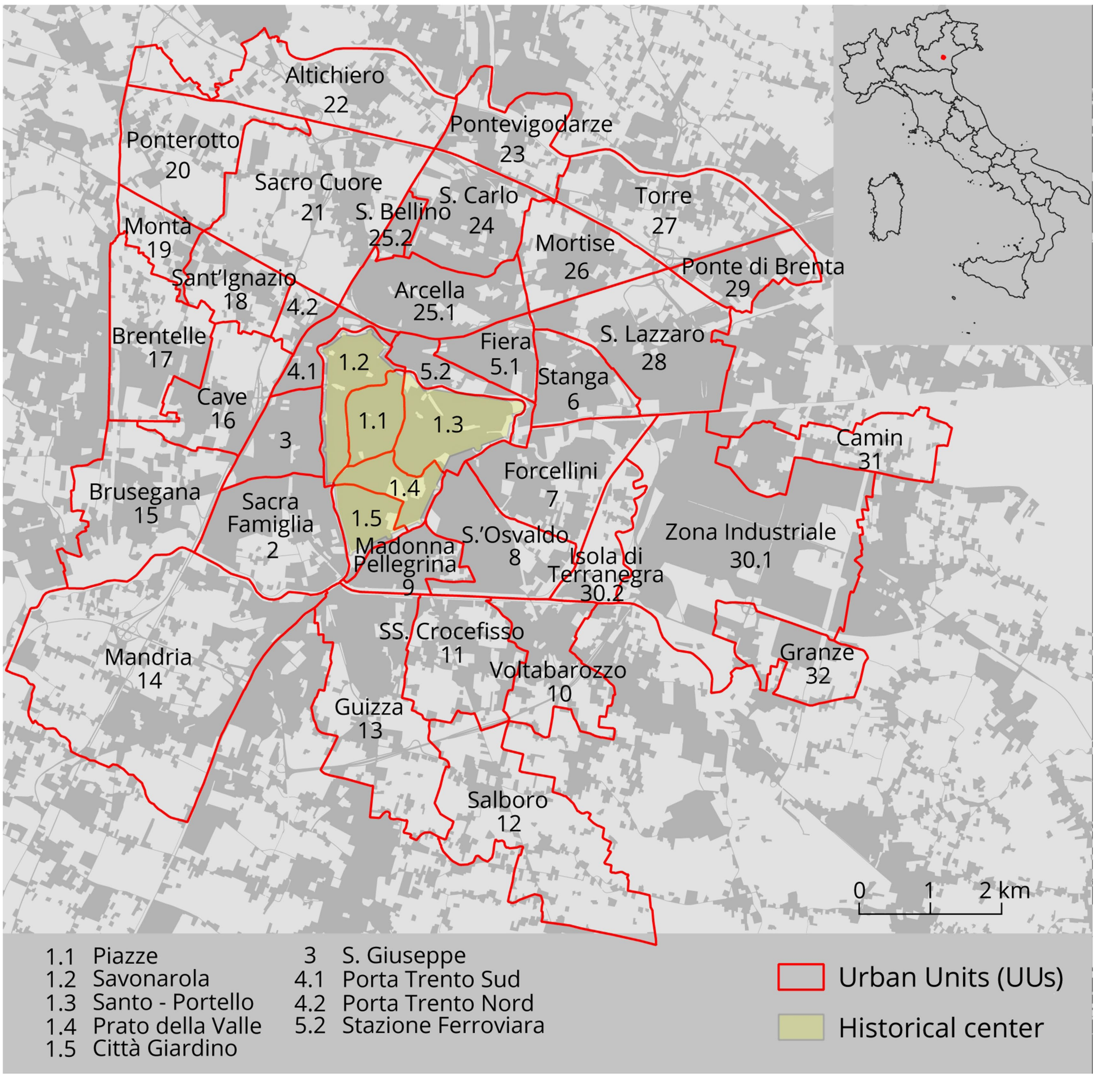


FIGURE 1
Map of Padua (the study area) and its location in Italy. The figure highlights the 40 urban units (UUs) and the historical center.

southeast of the city). Interviews were carried out between June 2023 and September 2023 in each community garden; the users verbally answered the questions shown to them in a paper interview, and their answers were registered simultaneously by the interviewer on the online version of the interview. In Section 4, in the part related to criteria assessment, laminated tags were prepared to increase interaction with the respondents; for each categoy, a color was chosen (green for distance features and yellow for social characteristics), and the interviewees were requested to order them, one category at a time, from the most important at the top to the least important at the bottom, according to their opinions. The final ranking was then recorded in the online system. Tags were blended every time to reduce the influence of the previous ranking.

## 2.2 The sMCDA approach and workflow

Multicriteria decision analysis refers to a series of approaches and techniques used to combine criteria of different types (e.g., social, environmental, and economic) in order to rank a series of alternatives for improving decision-making using a rational process that highlights better alternatives (Adem Esmail and Geneletti, 2018). The approach can be carried out using spatial criteria in a GIS environment to support territorial decision-making. Participation in MCDA is usually guaranteed by the definitions of the criteria, the preferences for them [i.e., an increase in the value of a criterion makes the alternative better (as a gain or benefit) or worse (as a cost)], and their relative weights, which express their relative importance for stakeholders. For this study, we used the TOPSIS approach in open-source QGIS software through the geoTOPSIS module of the vectorMCDA plugin (Massei, 2013).

The overall workflow is presented in Figure 3 and briefly explained here, following the typical MCDA steps. (1) Two types of alternatives, namely, the UUs ($n = 40$) and the selected municipality green areas ($n = 476$), were defined. (2) Meetings with key actors and spatial and available statistical data were used to select and create two types of criteria, which were distance from features of interest, such as cycle paths or residential buildings, and social criteria, such as density of

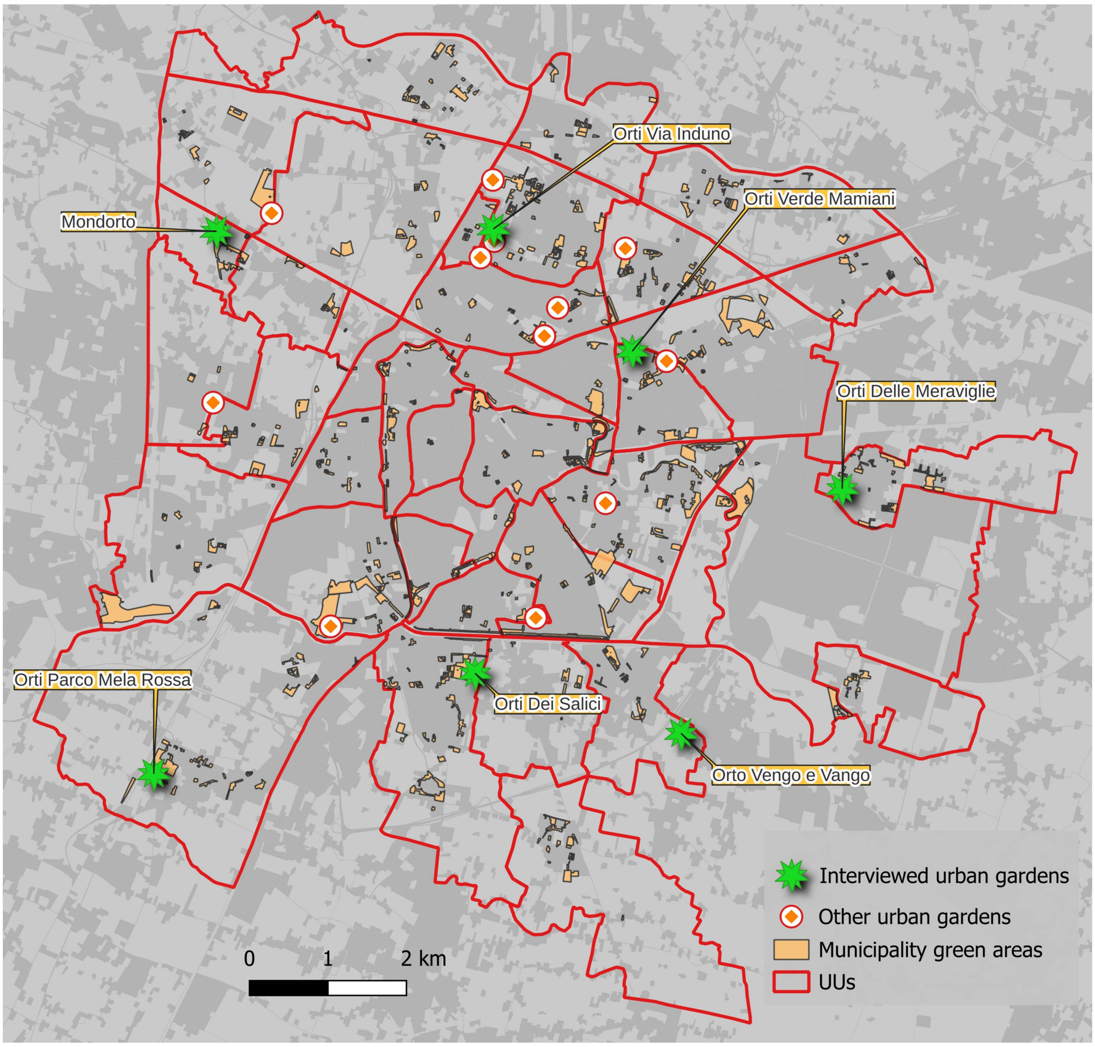


FIGURE 2
Spatial location of the 19 existing community gardens, categorized using different symbols that distinguish between the seven interviewed community gardens and the others. The map also reports the green areas of the municipality selected in the study.

families and percentage of private gardens per UU. (3) The decision-making geodatabase (i.e., the quantitative values of each criterion for each alternative were calculated for the UUs and green areas) was then created. (4) Two geoTOPSIS simulations were carried out using the relative weights between criteria derived from the interviews—one called distance index and the other social index. (5) Finally, a final geoTOPSIS simulation, which combined the two previous simulations using the same weights, was performed in order to obtain a final overall index. The criteria and their characteristics are presented in Table 2.

# 3 Results and discussion

## 3.1 Interviews with the community garden office staff of municipality and data collection

Interviews and data collection from the community garden office offer a general framework of the past and present situations of municipality community gardens and their localizations. Since the end of the 1990s, only some social (for people over 60 years old and low-income individuals) community gardens have been created; since 2021, with the advent of new municipality regulations and the creation of new areas, two public tenders (in 2021 and 2023) have included social and traditional (for every citizen of Padua over 18 years old) community gardens. Other types of community gardens (didactics and therapeutics) are listed in the regulation and derived from the example of past or current municipality or civil society association projects/experiences; however, they have never been implemented with continuity. Currently, the overall assignee compositions tend to be quite different between the two types (i.e., social and traditional community gardens). In social community gardens, almost all users are elderly Paduan citizens, as they are the main targets of this category, while in traditional community gardens, individuals over the age of 60 represent 75% of the total, and those in their 50s are the second most-represented group. The presence of migrants is quite frequent: 15% are non-European Union, but this percentage reaches 20% when considering also those coming from outside Italy. The

TABLE 1 Ranking of the key features and characteristics to consider for the selection of new areas for community gardens, divided into three macro categories.

| Aspect | All | > 60 | < 60 |
|---|---|---|---|
| **Distance features** | Rank | | |
| As close as possible to where the assignees live | 1 | 1 | 2 |
| As far away as possible from contaminated places (busy roads) | 2 | 2 | 1 |
| As close as possible to cycle paths | 3 | 3 | 3 |
| As close as possible to open-air public services (urban parks, playgrounds, dog areas, etc.) | 4 | 4 | 4 |
| As close as possible to bus/tram stops | 5 | 6 | 5 |
| As close as possible to parking | 6 | 5 | 6 |
| **Social characteristics** | | | |
| Promote neighborhoods where the possibilities of having private vegetable gardens are lower | 1 | 1 | 1 |
| Promote neighborhoods where there are more people with limited economic opportunities | 2 | 3 | 2 |
| Promote neighborhoods where there are more elderly people | 3 | 2 | 4 |
| Promote the most populous neighborhoods | 4 | 4 | 3 |
| Promote neighborhoods where social cohesion is stronger (for the management of community gardens) | 5 | 5 | 5 |

proportion of male and female users is balanced, settling approximately 45% for females and 55% for males; this is due to the fact that most users manage the plots with the help of their families, often represented by their wives or husbands.

If a plot is unmanaged for a long time by the assignee, the municipality can rebuke the user, sending two warning letters reminding him/her to take care of the plot. If no change occurs, the plot assignment is revoked, the turnover procedure starts, and a new assignee is chosen from the current waiting list. It is worth noting that almost all users tend to give up spontaneously because of a lack of time or interest (94%); in a few cases, turnover is related to changes in the city of residence (1%) and health problems (5%), especially among the elderly. Based on the experiences of the community garden office staff, the best size of a community garden area is approximately 30 plots, considering financial and management issues. Additional plots usually present organizational problems or a decrease in social cohesion and participation, along with an increase in conflicts between users, whereas fewer plots usually present higher creation and maintenance costs.

The criteria used by the municipality for the allocation of new community gardens comprise spatial issues, such as proximity to other green areas, particularly urban parks, and to other services, such as sports centers. Moreover, community gardens should be preferred in highly populated neighborhoods, where water sources are available and connected to local municipal aqueducts, and where car parks, pedestrian ways, and cycle paths are located. Particular attention is given to those areas located in neighborhoods near the city center, where the demands are higher because of the lack of spaces to have one's own vegetable garden, and new assignees are also chosen for their proximity to a community garden. However, no GIS spatialized or multicriteria analysis and/or the use of a participatory approach appears to be carried out to define siting, thereby limiting the analysis to the spatial knowledge of the city by decision-makers, the requests of citizens, or the number of people in the waiting list. Other more technical criteria are related to soil quality and fertility, which can be evaluated through on-site analyses.

## 3.2 Interviews with the community garden users

Interviews were conducted in seven community gardens (see the map in Figure 2) among the 19 existing in the municipality, for a total of 56 completed interviews. Of the respondents, 29% ($n=16$) were female and 71% ($n=40$) were male; 61% ($n=34$) were over 60 years old, 39% ($n=22$) were aged 30–60 years, and only one person was under 30 years old. Regarding education level, 5% ($n=3$) had primary education, 64% ($n=36$) graduated from secondary school, 27% ($n=15$) graduated from university, and 4% ($n=2$) had a master's/PhD degree. In terms of employment, 54% ($n=30$) of the respondents were retired, and only one person was unemployed. The majority of the interviewees were Italian citizens, while three were migrants. Dwellings were also considered: 20% ($n=11$) lived in private houses, of which 82% ($n=8$) had backyards, while 80% ($n=44$) lived in flats, of which 35 had terraces.

Almost 95 and 79% of the interviewees knew of the existence of traditional and social gardens in Padua, respectively (Figure 4). These high percentages confirm the only two typologies of community gardens listed in the "Municipal Regulation for the Assignment and Management of Community Gardens" (Comune di Padova, 2019) that were put out to tender by the municipality. However, even if Padua does not manage other types of community gardens at present, most people pointed out the presence of didactic community gardens and gardens for associations (64 and 48%, respectively) as well as therapeutic and innovative gardens (21 and

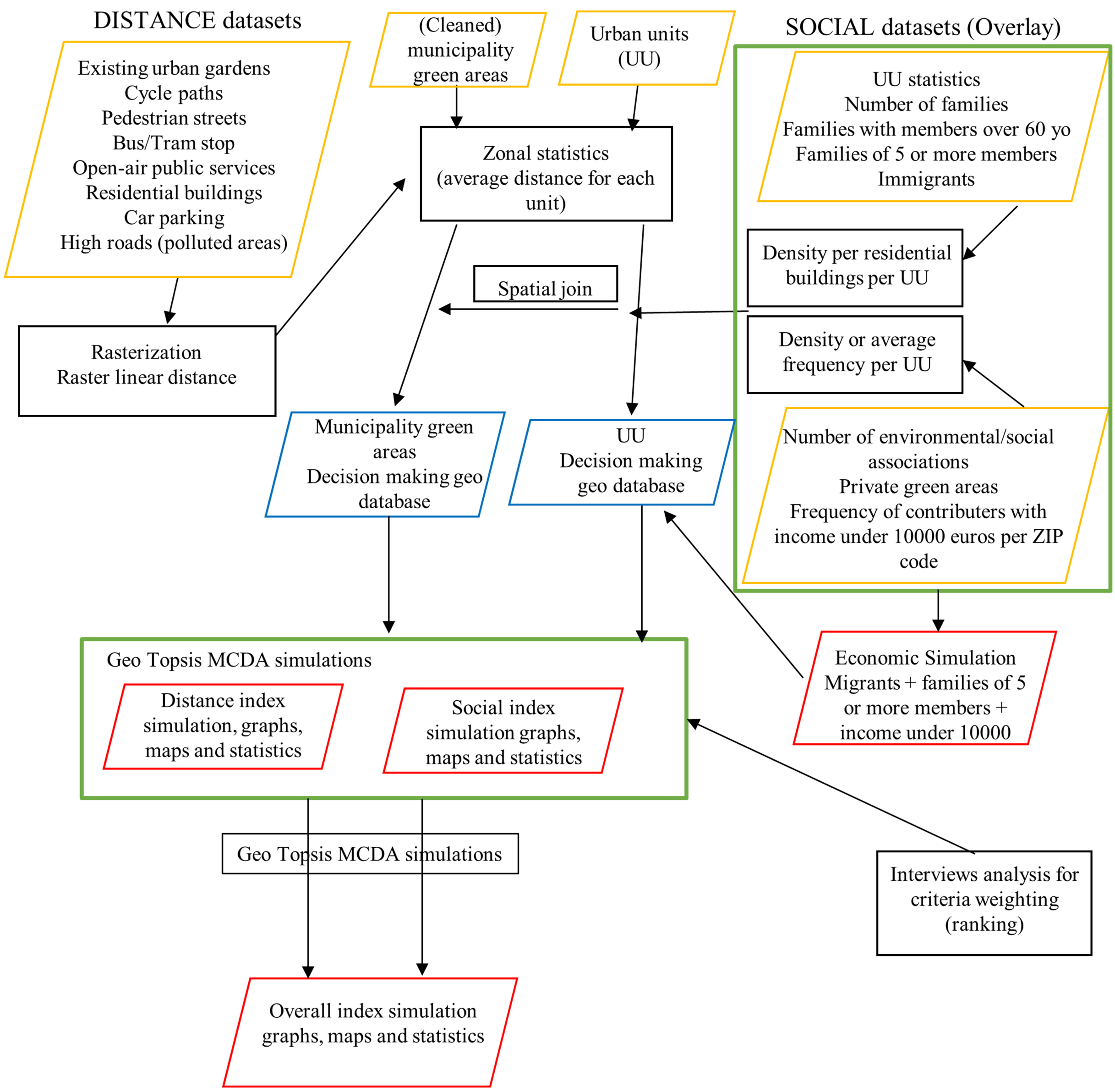


FIGURE 3
Workflow of the sMCDA analysis. Yellow boxes contain the main input dataset, black boxes contain the main geo-processing, blue boxes contain the intermediate output, and red boxes contain the final output.

26%, respectively); six individuals (10%) also mentioned food forests, a category not included in the municipal regulation. Based on some interviews, the mention of these typologies of community gardens is probably due to the interviewees' knowledge of past or current garden or fruit tree projects carried out by the municipality or associations in some areas or with schools, besides the presence of some plots managed by associations. Among the desirable typologies (i.e., those that should be promoted/increased in Padua; each respondent could give a maximum of three answers. See Figure 4), the interviewees highlighted their interest in increasing traditional community gardens (64%) and their preferences for the didactic (50%) and therapeutic (41%) categories. This finding is consistent with that of Caneva et al. (2020), showing how community gardens, more recently, can also play an important role in environmental education to increase citizens' awareness of biodiversity issues. It is important to highlight that these last two preferences show how citizens are also interested in cultural ES not directly related to food provision.

The importance of cultural ES associated with community gardens is highlighted in Figure 5, which presents the question, "Why did you choose to cultivate a community garden." Answers related to cultural ES, for example, "stay in nature/open air" and "cultivate the land" as a hobby, accounted for over 50% of the responses, while "cultivate relationships" accounted for 30%. Provisioning ES and food security, which can be associated with the answers "be autonomous in food production" and "economic advantage/save money," both accounted for less than 10% of the total responses. Attention to the quality of food consumed (healthy food) was also a key focus, comprising 46% of the preferences. This finding is consistent with those of other works

TABLE 2 Data input, criteria description, sources, preferences (cost or gain), ranks, and weights.

| Data input | Criterion | Source | G/C | Rank | Weight |
|---|---|---|---|---|---|
| **Distance index** | | | | | |
| Residential buildings | Average distance in UU or of green areas from clusters of residential buildings | OSM and Veneto Region | cost | 1 | 0.222 |
| Existing community gardens | Average distance in UU or of green areas from community gardens | Municipality | gain | 2 | 0.194 |
| High roads (contaminated roads) | Average distance in UU or of green areas from contaminated roads | OSM | gain | 3 | 0.167 |
| Cycle paths | Average distance in UU or of green areas from cycle paths | Municipality | cost | 4 | 0.139 |
| Pedestrian streets | Average distance in UU or of green areas from pedestrian streets | OSM | cost | 5 | 0.111 |
| Open-air public services | Average distance in UU or of green areas from leisure elements | OSM and municipality | cost | 6 | 0.083 |
| Parking | Average distance in UU or of green areas from car parking | OSM | cost | 7 | 0.056 |
| Bus/tram stops | Average distance in UU or of green areas from bus/tram stops | OSM | cost | 8 | 0.028 |
| **Social index** | | | | | |
| Private green areas | % of private green areas/number of families per UU | Pristeri et al. (2020) | cost | 1 | 0.333 |
| Families with five or more members | Families with five or more members/area of residential buildings per UU | Municipality | gain | 2 | 0.267 |
| Migrants | Migrants/area of residential buildings per UU | Municipality | gain | | |
| Contributors with income under 10,000 euros | Average of contributors with income under 10,000 euros/total contributors per UU | MEF | gain | | |
| Families with members over 60 years old | Families with members over 60 years old/area of residential buildings per UU | Municipality | gain | 3 | 0.200 |
| Number of families | Families/area of residential buildings per UU | Municipality | gain | 4 | 0.133 |
| Number of environmental/social associations | Number of associations/UU area | Municipality | gain | 5 | 0.067 |

OSM, stands for OpenStreetMap and MEF, for Ministry of Economy and Finance.

in other urban areas, such as Detroit (Newell et al., 2022). In the case of Padua, the interviewees represented mostly people living in flats or houses without gardens in a typical mid-sized city in a developed country or individuals who value having their own open spaces for the cultivation of their hobbies and for eating healthy food. However, some respondents underlined that cultivating their own food is not so economical compared with buying from discount markets, so they value more the production of their own handmade healthy food.

Cultivating relationships is an important aspect confirmed by the graphs in Figures 6, 7. Figure 6 shows that 61% of the respondents worked on the plots with the help of relatives or friends, even if this help was occasional for 23% of them, while 39% worked without the support of family or friends; of the latter, 71% of the users were over 60 years old. It is worth noting that the municipal regulation allows the management of plots only at the family level, a limitation seen in a negative light by many gardeners, as they wish to have the right to involve whomever they want. Other than this, almost all interviewees agreed or strongly agreed that mutual help and sharing of work existed between gardeners, indicating that the community gardens are appropriate spaces to create new relationships and foster cooperation and mutual learning, as shown in Figure 7.

The graphs in Figure 7 also present the opinions of the interviewees concerning the key aspects of the usefulness and adequacy of community gardens and their plots. More than 53% of the gardeners agreed that community gardens were not sufficient in the areas where they lived, which is evidenced by the number of requests for community gardens and the current waiting list. However, 29% believed that the number of community gardens was enough, perhaps due to the presence in each community garden of some plots that were abandoned or not well managed by their users. The opposite is the case with plot size (usually 30 $m^2$), which was perceived as adequate by 60% of the respondents, even if some gardeners think that they should be at least 50 $m^2$ in size to meet their families' needs. This finding on plot size could confirm the lesser importance of community gardens for food security compared to other benefits, as perceived by the respondents. Some users' answers to these two questions were interesting because they highlighted the need for a more flexible municipal regulation, particularly related to abandoned plots that should be reassigned quickly and/or should possibly be given to other gardeners in order to manage them while waiting for their new users. More than 50% of the users agreed that, due to the community gardens, they were able to increase the variety of vegetables they consumed, a finding that could be related to the importance they accord to healthy food consumption, and they were able to decrease their expenses for vegetable consumption.

The questions presented in Figure 8 and Table 1 are related to the definition of the criteria and weights for their uses in the sMCDA (Chapter 3.2). Figure 8 shows the results of two questions related to the distance and the means of transport used to reach the community garden; 73% of the interviewees lived within a distance of 2 km from the community gardens, and only 5% (3 users) had to travel more than 5 km. It is worth highlighting that most users who lived more than 3 km from the gardens were from one peripherical community garden (Orti delle Meraviglie, located in the east sector of Padua in a UU close to the industrial zone, with 62% of the interviewees living 3 km or more from the gardens). The users usually preferred to walk to the community gardens at a maximum distance of 2 km, but most of them (80% of the 15 respondents) were within a distance of 500 m or less. A bicycle is used mainly for a distance between 500 m and 4 km, a car is used mainly for 500 m or more, and it has become the most used means of transport starting from 3 km of distance. Some

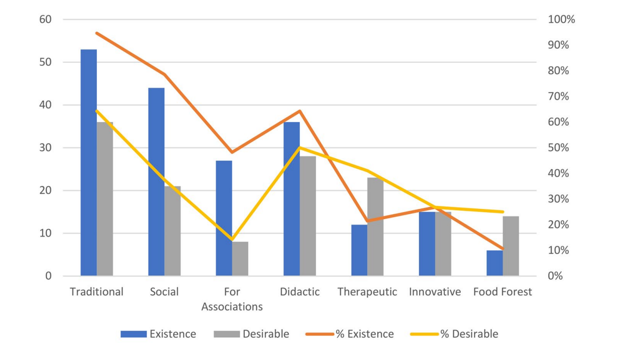


FIGURE 4
Graph showing the numbers (bars) and percentages (lines) of the answers to the questions (multiple choice) concerning the types of community gardens. The term "existence" relates to the question, "Which of these types of community gardens managed by Padua municipality exist in Padua?" The term "desirable" relates to the question, "Which of these types of community gardens should be promoted/increased in Padua?".

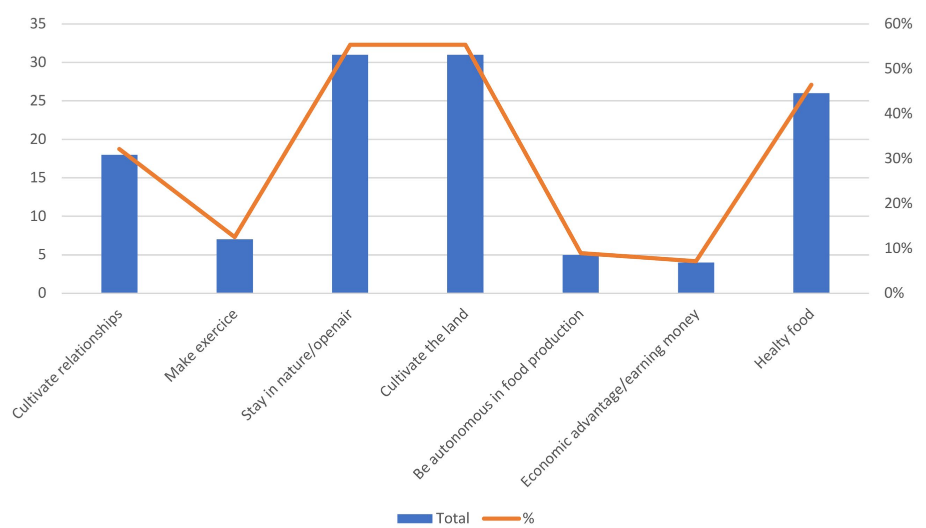


FIGURE 5
Graph showing the numbers (bars) and percentages (lines) of the answers to the question (multiple choice), "Why did you choose to cultivate a community garden?".

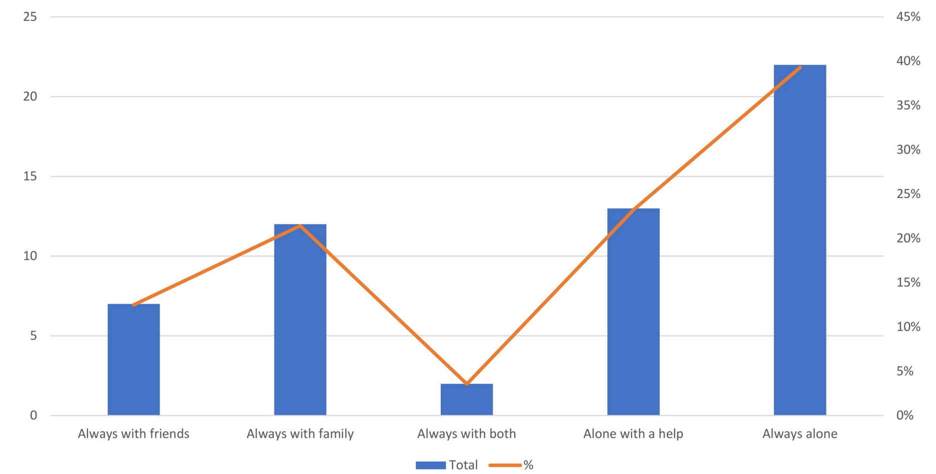


FIGURE 6
Graph showing the percentages of the answers to the question (multiple choice), "Who do you usually manage the plot with?".

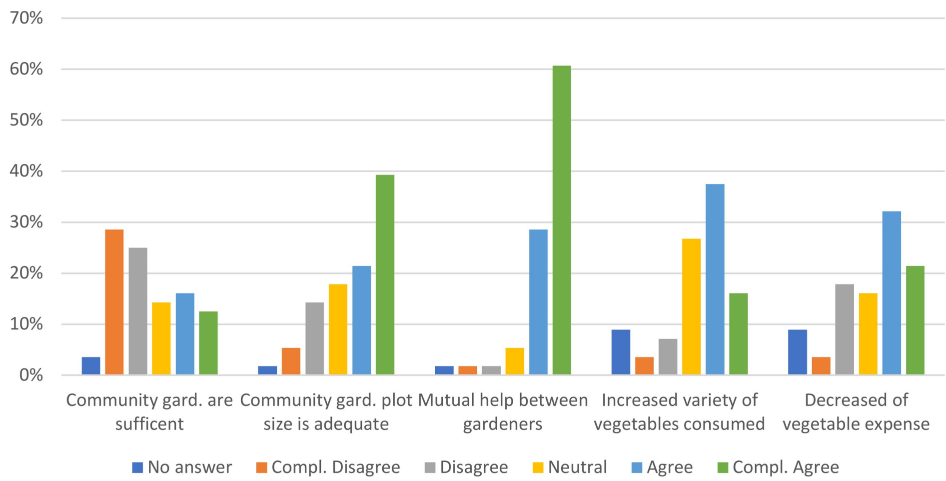


FIGURE 7
Graph of the answers (percentage) to different questions concerning the opinions of the gardeners about the key aspects regarding the use and management of community gardens.

users use scooters or motorcycles, but none of them report using busses or trams. In general, sustainable means of transport (bike and walking) were the favorite choices to reach the community gardens, accounting for 58% of the answers, of which the percentage for bikes was 35%.

Table 1 presents the ranking proposed by the interviewees regarding some key features and characteristics to consider in the selection of new areas where to create new community gardens. The ranking results are presented for all interviews and all respondents (all in Table 1), divided by those over 60 years old (>60 in Table 1) and those under 60 years old (<60 in Table 1). The interviewees strongly preferred community gardens located close to where the assignees live and, at the second place, the community gardens far from contaminated places. Closeness to cycle paths was at third place, and the presence of other public services near the community gardens was at fourth place. While the low rank of distance from bus/tram stops is not surprising, as none of the interviewees use these means of transport to reach the community gardens, the last rank of car parking is unexpected, considering the answers shown in Figure 8. Another group of features under the label *social characteristics* considers the social and economic features of possible assignees. The prioritization of areas with fewer opportunities of having private gardens is in the first place for all ages, followed by people with fewer economic opportunities. The presence of elderly people presents the main difference between those over 60 years old (at second place) and those under 60 (at fourth place). The population size of neighborhoods and social cohesion (i.e., the presence of associations that could manage the community gardens) had the lowest ranks.

## 3.3 Definitions of sMCDA criteria

The criteria and their weights used for the sMCDA simulations are presented in Table 2. The criteria types depend on the availability

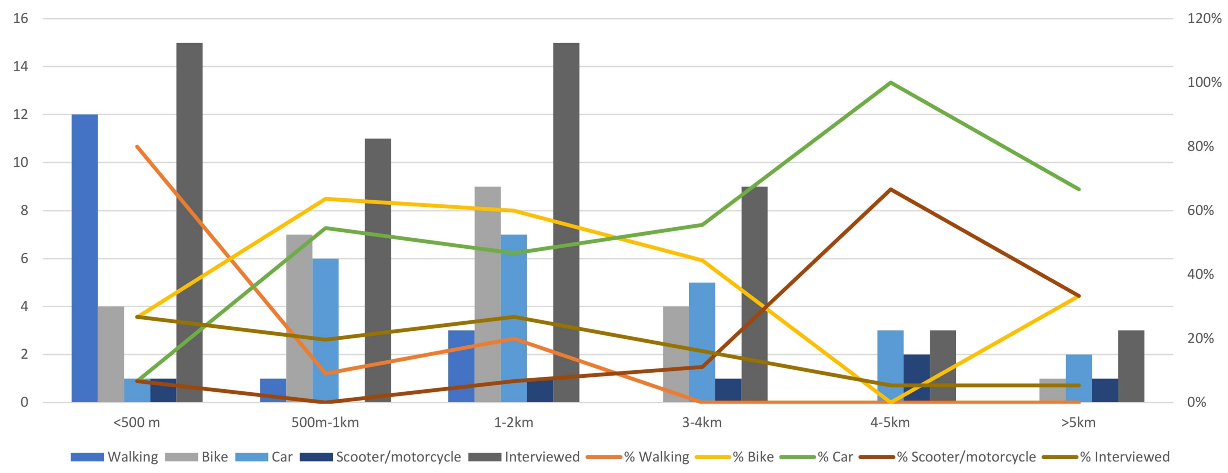


FIGURE 8
Graph showing the numbers (bars) and percentages (lines) of the answers to the question (multiple choice), "How do you usually reach the community gardens?" divided by the distances of the question, "How far is the community garden from your home?" (single choice). The bars and lines related to "interviewed" are the total respondents for each category.

of spatial and statistical data, and their usefulness has emerged based on meetings with key actors. We also included most of the criteria already considered by the municipality (see section 3.1). The criteria ranking and weights mainly followed those in Table 1, with some modifications because of adjustments related to the other results that emerged from the interviews with the gardeners, the evaluation of the interviews with key actors, and data availability. The criteria were divided between the two simulations carried out concerning the distance index (distance from features of interest) and the social index (socioeconomic aspects derived from statistics at the UU level). For all respondents, the types and weights of the criteria for each simulation mainly correspond to the ranking in Table 1 ($n = 56$), with some adjustments; for the distance index, we added the criterion of distance from existing community gardens at second place because of its importance for the key informants of the municipality. We also considered distance from pedestrian streets after cycle paths because of the high number of people who access the community gardens by walking; we preferred to put car parking before bus/tram stops because of the extensive use of cars to reach the community gardens. For the social index, we split the aspect of limited economic opportunities into three, assigning the same weight (i.e., densities of families with five or more members, the presence of migrants, and contributors with an income under 10,000 euros), because they resulted in the best available data that represented this characteristic on the basis of a discussion with the key informants. It is worth noting that the preferences for the distance index criteria (G/C column of Table 2, where G stands for gain and C stands for cost) indicate the distance from benefit features as a cost, such as cycle paths or residential buildings, because the farther the feature is, the worse it is for the community garden.

## 3.4 sMCDA simulations

The following maps and tables of the sMCDA simulations at the UU and municipality green area levels allow for the visualization of the areas to be prioritized in the planning of new community gardens, according to the selected criteria and weights. The values of each area in the maps range from 0 (less suitable for new community gardens) to 1 (most suitable) and are presented with a graduated palette of seven classes (using a natural Jenks classification that maximizes the differences between groups), in which lighter colors correspond to lower values, and darker colors indicate higher values.

Figure 9 and Table 3 present the final maps at the UU level for the distance index, the social index, and the final overall index that combines the two previous scenarios, assigning the same weights, which means the same level of importance.

According to the social index, the UUs to be prioritized for new community gardens are mainly those in the north–northeast sector of Padua, which corresponds to Arcella (25.1), San Bellino (25.2), San Carlo (24), Fiera (5.1), and Stanga (6)—the areas in Padua with the highest density of migrants, families, and elder people and with a low presence of private green areas. The distance index privileges central UUs, particularly Piazze (1.1), Santo-Portello (1.3), Prato Della Valle (1.4), San Giuseppe (3), Savonarola (1.2), and Ponte di Brenta (29) in the extreme northeast sector. These results are attributed to the high average distances of existing community gardens, the low average distance of residential buildings, and the average closeness of cycle paths and other important public services, such as playgrounds or areas for dogs. The combination of the two simulations in the overall index shows a sort of dark red corridor of suitable UUs from the north–northeast to central–west, in which the contribution of the distance index is prominent in the central areas (such as for the Piazze UU, 1.1), while the social index influences the northern and western areas more. A less suitable UU for all simulations is the industrial area (30.1) in the east sector of the city because of the lack of most criteria considered as benefits. Overall, peri-urban areas, particularly those in the northwest, east, southwest, and southeast parts of Padua, present the lowest values because of their lowest service and population densities and the highest presence of private green areas.

Table 4 shows the number of municipality green areas considered in this study, such as urban parks, generic green, and playground

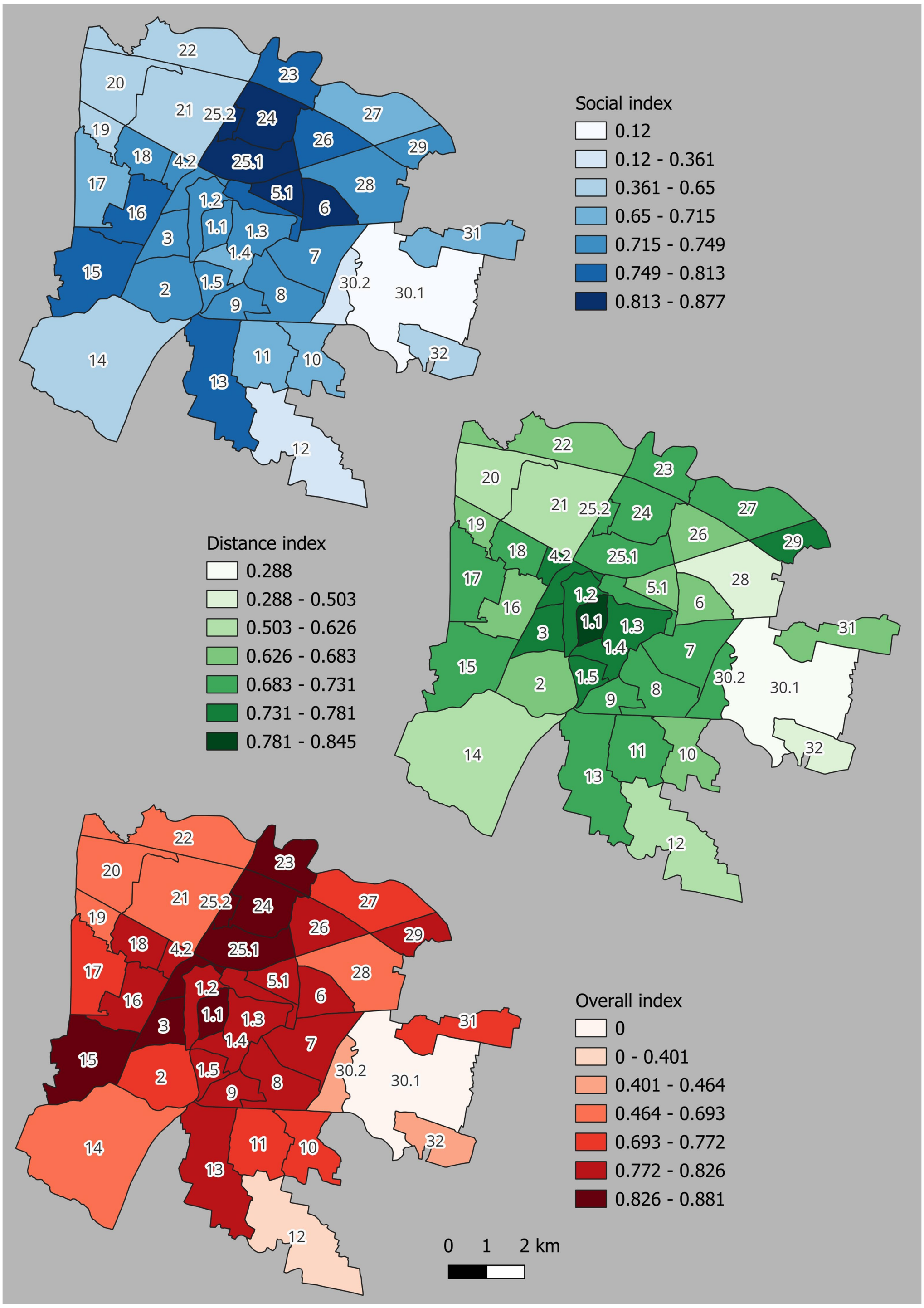


FIGURE 9
Maps of the results of the three sMCDA simulations carried out for the 40 UUs: the Social index, the distance index, and the combination of the two simulations (overall index).

areas, according to the categorization made by the green public office. For each category, the percentage of areas that fall under an index value, grouped by 0.x, is shown per simulation. As can be seen, most of the 476 areas are generic green (191), followed by urban parks (111) and school gardens (100), while there is a lower presence of playground areas (37) and other typologies. More than 60% of all categories score values from 0.8 to above for the overall index, while the areas are more distributed along the values for the social and distance indexes, even if, in general, most of them obtained scores over 0.7. For the social index, green areas show similar values for each UU because most criteria are derived from statistical data at the UU scale, while the green areas for the distance index present a sparser distribution because the values are influenced by distances from the features distributed all over the city, even if, in most cases, these

TABLE 3 Values of the 40 UUs according to the three MCDA simulations.

| UU | Overall | Social | Distance |
|---|---|---|---|
| 25.2 San Bellino | 0.8814 | 0.8767 | 0.7304 |
| 1.1 Piazze | 0.8526 | 0.7311 | 0.8450 |
| 24 San Carlo | 0.8479 | 0.8559 | 0.6995 |
| 25.1 Arcella | 0.8422 | 0.8686 | 0.6906 |
| 23 Pontevigodarzere | 0.8413 | 0.7927 | 0.7222 |
| 3 San Giuseppe | 0.8366 | 0.7372 | 0.7772 |
| 15 Brusegana | 0.8318 | 0.7808 | 0.7199 |
| 4.1 Porta Trento Sud | 0.8305 | 0.7492 | 0.7496 |
| 4.2 Porta Trento Nord | 0.8261 | 0.7441 | 0.7493 |
| 1.3 Santo - Portello | 0.8229 | 0.7201 | 0.7814 |
| 29 Ponte di Brenta | 0.8228 | 0.7314 | 0.7617 |
| 1.5 Città Giardino | 0.8199 | 0.7318 | 0.7562 |
| 13 Guizza | 0.8180 | 0.7747 | 0.7081 |
| 1.2 Savonarola | 0.8177 | 0.7260 | 0.7612 |
| 26 Mortise | 0.8176 | 0.8131 | 0.6833 |
| 1.4 Prato della Valle | 0.8171 | 0.7153 | 0.7786 |
| 5.2 Stazione Ferroviaria | 0.8154 | 0.7855 | 0.6970 |
| 9 Madonna Pellegrina | 0.8069 | 0.7392 | 0.7271 |
| 5.1 Fiera | 0.8067 | 0.8369 | 0.6611 |
| 8 Sant'Osvaldo | 0.8045 | 0.7327 | 0.7312 |
| 18 Sant'Ignazio | 0.8041 | 0.7382 | 0.7243 |
| 6 Stanga | 0.8016 | 0.8573 | 0.6489 |
| 7 Forcellini | 0.7927 | 0.7306 | 0.7167 |
| 16 Cave | 0.7885 | 0.7782 | 0.6706 |
| 2 Sacra Famiglia | 0.7723 | 0.7381 | 0.6822 |
| 17 Brentelle | 0.7547 | 0.7017 | 0.6955 |
| 11 SS. Crocefisso | 0.7544 | 0.6995 | 0.6976 |
| 27 Torre | 0.7506 | 0.6987 | 0.6931 |
| 31 Camin | 0.7416 | 0.7052 | 0.6737 |
| 10 Voltabarozzo | 0.7269 | 0.7023 | 0.6569 |
| 22 Altichiero | 0.6926 | 0.6488 | 0.6678 |
| 19 Montà | 0.6736 | 0.6282 | 0.6649 |
| 21 Sacro Cuore | 0.6468 | 0.6505 | 0.6009 |
| 28 San Lazzaro | 0.6353 | 0.7422 | 0.5035 |
| 14 Mandria | 0.6329 | 0.6192 | 0.6159 |
| 20 Ponterotto | 0.6192 | 0.5939 | 0.6261 |
| 32 Granze | 0.4642 | 0.5972 | 0.3769 |
| 30.2 Isola di Terranegra | 0.4484 | 0.2884 | 0.7283 |
| 12 Salboro | 0.4008 | 0.3613 | 0.5824 |
| 30.1 Zona Industriale | 0.0000 | 0.1198 | 0.2877 |

UUs are ordered according to the value of the overall index.

features present a higher concentration in certain UUs as can be seen in Figure 9.

The influence of the social index on the pattern of distribution of green areas on the overall index is visible in Figure 10, which shows the map of this final simulation, taking into consideration only urban parks (111 areas), which is the preferred category to implement community gardens according to the community garden municipality office. This figure also zooms in on two of the most suitable urban parks according to the simulation—one located in San Bellino and another located in San Carlo in the north sector of Padua.

It is interesting to note that one of the most suitable UUs, namely, Piazze (1.1), lacks urban parks, so possible public interventions should consider the closest areas in the Savonarola (1.2) and Santo-Portello (1.3) UUs, which have middle values.

## 3.5 Participation and sMCDA as tools for improving sustainable urban planning

Our study proposes a transparent and systematic methodology to map community garden siting at two scale levels: the sub-urban

TABLE 4 Number of the different typologies of municipality green areas and their percentages for each sMCDA simulation value, grouped by 0.x.

| Green area typologies | Overall | Social | Distance |
|---|---|---|---|
| 1—Playground areas | | 33 | |
| 0.5–0.6 | 0.00% | 0.00% | 3.03% |
| 0.6–0.7 | 3.03% | 27.27% | 15.15% |
| 0.7–0.8 | 30.30% | 42.42% | 81.82% |
| 0.8–0.9 | 57.58% | 30.30% | 0.00% |
| 0.9–1 | 9.09% | 23.32% | 0.00% |
| 2—Urban parks | | 111 | |
| 0–0.1 | 0.00% | 1.80% | 0.00% |
| 0.1–0.2 | 0.00% | 0.00% | 0.00% |
| 0.2–0.3 | 0.00% | 0.00% | 0.00% |
| 0.3–0.4 | 1.80% | 3.60% | 0.00% |
| 0.4–0.5 | 0.00% | 0.00% | 0.00% |
| 0.5–0.6 | 3.60% | 0.00% | 1.80% |
| 0.6–0.7 | 0.90% | 9.91% | 27.93% |
| 0.7–0.8 | 18.02% | 47.75% | 69.37% |
| 0.8–0.9 | 73.87% | 36.94% | 0.90% |
| 0.9–1 | 1.80% | 0.00% | 0.00% |
| 2a—Generic green areas | | 192 | |
| 0–0.1 | 0.00% | 1.05% | 0.00% |
| 0.1–0.2 | 0.00% | 0.00% | 0.00% |
| 0.2–0.3 | 0.00% | 0.00% | 0.00% |
| 0.3–0.4 | 1.05% | 3.14% | 0.00% |
| 0.4–0.5 | 0.52% | 0.00% | 1.57% |
| 0.5–0.6 | 3.14% | 0.00% | 2.62% |
| 0.6–0.7 | 4.19% | 15.18% | 34.03% |
| 0.7–0.8 | 21.99% | 49.21% | 61.26% |
| 0.8–0.9 | 65.97% | 31.41% | 0.52% |
| 0.9–1 | 3.14% | | |
| 4—River banks | | 13 | |
| 0.6–0.7 | 0.00% | 0.00% | 53.85% |
| 0.7–0.8 | 7.69% | 38.46% | 46.15% |
| 0.8–0.9 | 92.31% | 61.54% | 0.00% |
| 5a—School gardens | | 100 | |
| 0.3–0.4 | 0.00% | 2.00% | 0.00% |
| 0.4–0.5 | 0.00% | 0.00% | 0.00% |
| 0.5–0.6 | 2.00% | 0.00% | 0.00% |
| 0.6–0.7 | 0.00% | 14.00% | 25.00% |
| 0.7–0.8 | 18.00% | 40.00% | 74.00% |
| 0.8–0.9 | 76.00% | 44.00% | 1.00% |
| 0.9–1 | 4.00% | 0.00% | 0.00% |
| 5f—Public buildings green areas | | 27 | |
| 0.1–0.2 | 0.00% | 0.00% | 3.70% |
| 0.2–0.3 | 0.00% | 0.00% | 0.00% |
| 0.3–0.4 | 0.00% | 0.00% | 0.00% |
| 0.4–0.5 | 3.70% | 0.00% | 3.70% |
| 0.5–0.6 | 0.00% | 0.00% | 0.00% |
| 0.6–0.7 | 3.70% | 11.11% | 22.22% |
| 0.7–0.8 | 7.41% | 55.56% | 66.67% |
| 0.8–0.9 | 85.19% | 33.33% | 3.70% |
| All green areas total | | 476 | |

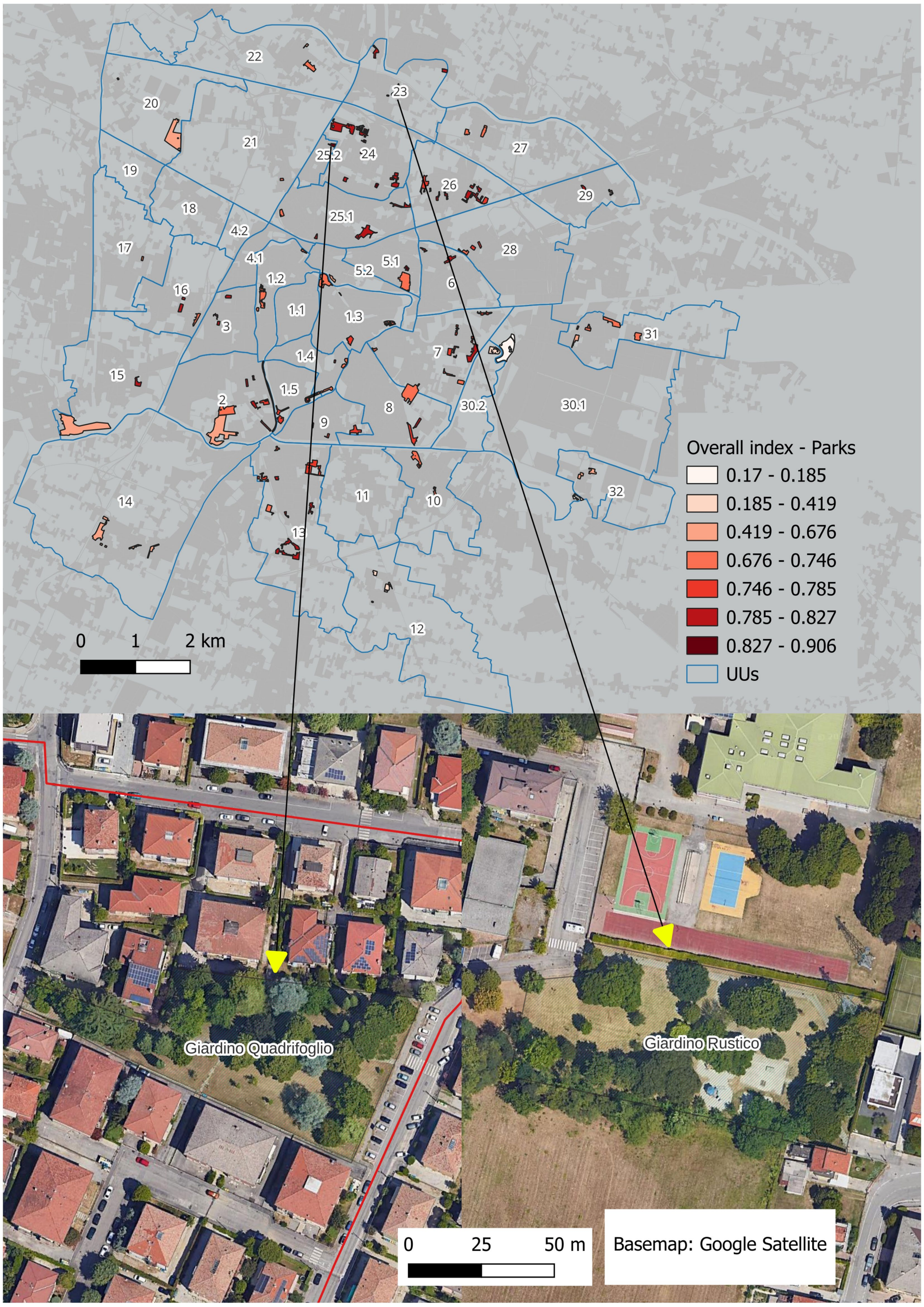


FIGURE 10
Map of the final sMCDA simulation (overall index) for the green municipality areas categorized as parks. Below is a zoomed image of two of the more ranked parks.

division (UUs) and municipality green area levels. In this way, we tried to support the prioritization of different kinds of management areas for the introduction of new community gardens in Padua. This objective is accomplished through the implementation of a participatory methodology to obtain the final outcomes as a result of multistakeholder participation. Moreover, this study partially fills the gap in knowledge about community garden siting by testing the introduction of a stakeholder interview in the sMCDA. As reported by Smith et al. (2021), the sMCDA participatory approach is rarely applied in the identification and location of community gardens. Therefore, the methodology adopted is useful for synthesizing the different criteria that should be considered when localizing potential sites.

It is also important to highlight that the interviews revealed how the practitioners mainly value, apart from food security, the cultural ES that community gardens provide, including being in contact with nature, facilitating community gatherings, and strengthening social relations (Cumbers et al., 2018). These results are similar to those of previous studies, such as those of Turner et al. (2011), highlighting the importance of community gardens for social cohesion and the cultivation of relationships. In more detail, community gardens help practitioners form a denser network than that in their everyday lives (Glover, 2003) as well as help reduce isolation through the sharing of seeds, tools, knowledge, and ideas (Joshi and Wende, 2022). Additionally, our respondents recognized the benefits of this activity in terms of physical health and wellbeing (Koay and Dillon, 2020; Lampert et al., 2021).

These findings are informative for local policymakers and municipal agencies interested in implementing other community gardens in Padua. As seen in the interviews with the local office, the criteria used by the municipality to allocate new community gardens are mainly focused on spatial issues or proximity to other services, without applying any MCDA or participatory methodology. Informed by the responses in the practitioners' interviews and the results of our analysis, this study could become an effective guide for future city policies regarding the siting of new community gardens.

Moreover, we believe that the methodology developed can be easily transferred to and applied in other cities to suggest community garden policy orientations and to integrate this topic into urban planning discourse. A coordinated planning process developed by the administration and strong community engagement could also involve more citizens, including younger ones, in the cultivation of community gardens.

Finally, as largely reported by the scientific literature, we also underline that the involvement of practitioners in surveys could foster the empowerment of citizens by increasing their awareness of specific issues, such as increasing urban agriculture in cities.

### 3.6 Limitations and future perspectives

The MCDA approach applied in this study enables the exploration of a quali-quantitative strategic methodology to inform the siting of community gardens in the city of Padua.

In this framework, additional research is needed, notably considering abandoned urban areas of the city as alternative and supplementary choices to the municipal green areas already investigated. According to Newell et al. (2022), localized community gardens on vacant or underutilized lands provide 2-fold benefits: (i) increasing the available areas for new community gardens in neighborhoods where the availability of municipal green areas is scarce and (ii) making productive use of abandoned spaces.

Future research could involve an increase in the size and diversification of the survey pool. More practitioners could be included in the survey by also involving the users of the 12 other community gardens already located in Padua. Furthermore, adding a pool of participants who are representative of migrants could obtain different results.

It is also important to highlight that future local regulations on community gardens should consider university students in the allocation of plots. Padua is considered a university city, hosting more than 70,000 students; however, most off-campus students do not change their residences, and they are not allowed to access community garden lists. The involvement of this category could be an important strategy to improve social cohesion among different categories of practitioners and could encourage social interactions across generations (Yotti Kingsley and Townsend, 2006).

Additional physical data and criteria could be implemented in subsequent steps of the MCDA process. Remote sensing data, such as high-resolution Digital Terrain and Surface Models coupled with vegetation indexes, could improve site selections by providing the real available green surface for each municipality area, so excluding buildings, trees, and paved elements. Other technical criteria, which should be directly evaluated by local policymakers, could include soil farming quality, soil contamination, slope steepness, and access to water. Moreover, soil testing should be highly considered if vacant or underused lands are included in order to avoid the presence of contaminants that, if ingested, could pose a health risk (McBride et al., 2014).

Finally, as reported by the scientific literature, the implementation of didactic and therapeutic community gardens can promote environmental education, in which both primary and secondary students are involved (Lloyd and Paige, 2022; Wood et al., 2022).

## 4 Conclusion

Community gardens are among the current and powerful strategies to re-introduce agriculture into urban contexts while also involving citizens and implementing green spaces in cities as well as improving quality of life of residents. In this study, we applied the sMCDA methodology to identify the neighborhoods to be prioritized when locating new community gardens in the city of Padua, Italy, through the direct involvement of practitioners in this choice. A survey was delivered to the users of 7 out of 19 community gardens located in the city.

The results identified neighborhoods to be prioritized in the planning of new community gardens according to three different scenarios: the distance index, the social index, and the combination of the two (overall index).

To conclude, this study highlighted the importance of adopting a decision-making methodology to support local policymakers and municipal agencies that are interested in implementing other community gardens in Padua. The case study and the methodology adopted could also be useful for other cities by providing step-by-step processes that can be directly applied.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

DC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft. DG: Formal analysis, Investigation, Methodology, Writing – original draft. FP: Conceptualization, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Scaling up: microbiome manipulation for climate change adaptation in large organic vineyards

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Regenerative agriculture offers important solutions to the enormous challenges that the climate crisis poses on food production. However, there are doubts about the possibility of implementing many of these solutions in a particularly important sector: the large scale. This paper addresses the issue, presenting examples of large-scale vineyard soil microbiome manipulation in Chile. The South American country has strongly faced the effects of climate change during the last decade and the organic viticulture sector is actively seeking strategies to adapt to the new climatic reality. Here the results of 4 experiments under real production conditions are shown. The experiments were designed to assess the effects of adding various microbial consortia to the soil on key agronomic parameters. Successful as well as unsuccessful cases are presented, allowing discussion of some conditions under which the microbiome manipulation can be expected to have positive effects. It was found that under good management conditions, incorporating effective microorganisms has positive effects on important production parameters (yield, root and vegetative growth). However, when fields yields are trending downward for prolonged periods, the incorporation of effective microbial consortia (e.g., antagonistic fungi, nutrient-fixing and nutrient-solubilizing bacteria) does not have a positive effect on the vineyard trend immediately. Similarly, even in favorable conditions the positive effects cannot be expected to be expressed in the short term (i.e., in just a few months). Therefore, its use should be conceived as a long-term strategy, not as an immediate solution to urgent management problems.

KEYWORDS

**regenerative agriculture, ecological soil management, large-scale agriculture, plant microbiome, efficient microorganisms**

## 1 Introduction

> *To see a world in a grain of sand and a heaven in a wild flower, hold infinity in the palm of your hand and eternity in an hour. Auguries of Innocence by* Blake W. (1988).

Extreme temperatures have become a daily occurrence, and it is not uncommon to see a new record set somewhere on the planet (Witze, 2022). Undoubtedly, we are living the beginning of a serious climate crisis at a planetary level and it is necessary to adapt to this context (Lovelock, 2007; Archer and Rahmstorf, 2010; Shen et al., 2018; Chakrabarty, 2021). For example, in Chile, a climate emergency was declared in 2021 due to the intense drought suffered in the last decade (Aparicio, 2021). This has meant significant challenges for its viticulture sector, especially for the large-scale and export-oriented subsector (Crowley, 2000; Hadarits et al., 2010; Mills-Novoa et al., 2016; Haddad et al., 2020). Climate change poses a major threat to grapevine cultivation (Coombe, 1987; Moutinho-Pereira et al., 2004; Greer et al., 2010, 2013; Fraga et al., 2020; Jones et al., 2022) and this may have mayor economic repercussions worldwide (FAO/OIV, 2021). In the emerging organic wine sector, the situation becomes even more complex, due to restrictions impose on crop management by the different certifications and the increase in manufacturing cost, especially in systems with high dependence on external inputs (Pino, 2013; Migliorini and Wezel, 2017; Pekdemir, 2018).

Climate forecasts anticipate a global decrease in water availability in most wine-producing regions (Santillán et al., 2019). This issue has sparked significant concern within the viticulture industry, prompting a considerable number of scientific papers to delve into the subject (Fraga et al., 2012; Xu et al., 2012; Mosedale et al., 2016; Storchmann, 2016; Ollat et al., 2017; van Leeuwen et al., 2019). For instance, it is expected that the increase in aridity in the future will result in a widespread loss of suitability for viticulture in the mediterranean climate zones of southern Europe (Droulia and Charalampopoulos, 2021), region responsible for 54% of the world's wine exports (and 61% in terms of value) (Šajn, 2023). It is also important to consider that the feasibility of wine production is based both on yield and the quality of the grapes, as the latter can have a significant impact on the quality of the resulting wine and the prices consumers are willing to pay. In fact, wine prices, depending on their quality, can vary by a factor of up to 1,000, while yields usually fluctuate by a factor close to 10 (van Leeuwen et al., 2019).

The increase in temperatures and the reduction in rainfall, linked to climate change, can greatly affect the quality of the fruit and the yield of the crops in the vineyard (van Leeuwen et al., 2019). Among other aspects, climate change can impact the composition of the grape, its physiology, its phenology, and the quality of the wine. For example, high temperatures between veraison and harvest can result in an unbalanced fruit composition (due to the desynchronization in the development of sugars, acids, and other berry components) (van Leeuwen et al., 2019; Morales-Castilla et al., 2020). This can generate excessively high sugar levels, too low acidity, and an aromatic expression dominated by cooked fruit aromas, resulting in wines that lack freshness and aromatic complexity (Mira de Orduna, 2010; van Leeuwen et al., 2019; Morales-Castilla et al., 2020; Santos et al., 2020).

Among the techniques that can be used in organic agriculture to adapt agroecosystems to the new climatic context, is the manipulation of the microorganism community associated with plants, especially those present in the soil (Toro and Andrade, 2020; Chouhan et al., 2021; Antoszewski et al., 2022; Sandrini et al., 2022). This strategy can be underappreciated when the complexity of this component is underestimated (Vandermeer and Perfecto, 2018). However, soil is home to 59% of the planet's biodiversity (Anthony et al., 2023) and is a complex web of ecological interactions (Wall and Moore, 1999; Reynolds et al., 2003).

In fact, the well-being and overall health of plants is highly dependent on these ecological interactions (Barrow et al., 2008, Chouhan et al., 2021; Antoszewski et al., 2022; Sandrini et al., 2022). Particularly important are those between the microorganisms associated with them, whether inside, outside or in the immediate vicinity of their bodies (Barrow et al., 2008; Qiao et al., 2023), which can help plants withstand important stress conditions (Barrow et al., 2008; Albornoz et al., 2022). The organisms involved in these interactions are known as the plant microbiome in the scientific literature (Whipps et al., 1988; Lederberg and McCray, 2001; Marchesi and Ravel, 2015; Berg et al., 2020) and are generally referred to as efficient microorganisms in the ecological agriculture milieu (Singh et al., 2011; de Araujo Avila et al., 2021). These microorganisms are related to health, well-being and tolerance to different forms of stress in plants (Mesa-Marín et al., 2019; Redondo-Gómez et al., 2022), for example, through the production of phytohormones, such as indole acetic acid, cytokinin, abscisic acid and ethylene reduction (Martínez-Viveros et al., 2010; Basu et al., 2021; Gupta et al., 2022; Notununu et al., 2022; Carreiras et al., 2023).

The microbiome can aid in the adaptation of crops to climate change through various mechanisms. For example, one expected impact of climate change is a significant reduction in rainfall and water availability for agriculture (Malek et al., 2018; Arora, 2019; Malhi et al., 2021), a situation already present in Chilean agriculture (del Pozo et al., 2019; Fernández et al., 2019; Vicuña et al., 2021). In such circumstances, introducing efficient microorganisms into the soil can promote root development (Lareen et al., 2016; Mhlongo et al., 2018; Pascale et al., 2020; Molefe et al., 2023), enabling more thorough soil exploration for water and enhancing plant vigor under harsh conditions (Agler et al., 2016; Tao et al., 2019; Arif et al., 2020; Singh et al., 2020; Trivedi et al., 2020; Gupta et al., 2021).

To some extent, plant health can be conceived as a possible state that emerges from interactions in its microbiome. Thus, the manipulation of this community offers important opportunities for the ecological management of agroecosystem in general (Chouhan et al., 2021) and to adapt these systems to the new climatic conditions in particular (Barrow et al., 2008; Albornoz et al., 2022). In fact, efficient microorganisms can be a valuable tool to adapt vineyards to new climatic conditions (Aguilera et al., 2022; Carreiras et al., 2023). However, agroecological practices are typically associated with small-scale farming, it is therefore necessary to demonstrate that they work at larger scales (Dalgaard et al., 2003; Nicol, 2020; Petit et al., 2020; Mayer et al., 2022), as is the case of Chilean export viticulture (Crowley, 2000).

The objective of this paper is to present a set of results on the manipulation of the microbiome in large-scale viticultural systems, in the context of the climate change that Chilean agriculture is currently facing. For this, we will present: 1—Results on the effect of incorporating or not, functional microorganisms in organic vineyards, 2—An experiment where the different treatments consist in adding (at consecutive times) different functional microorganisms in organic vineyards, 3—Results, at nursery level, on the short-term effect of inoculating grapevine plants with mycorrhiza-forming fungi, and 4—An experiment in which the effect of applying effective microorganisms in conjunction with a sugar source is evaluated in organic vineyards. In summary, this research aimed to evaluate the efficacy of various microbiome manipulation strategies in real-world field conditions, in an agricultural setting that is experiencing substantial impacts from climate change (Young et al., 2010; Roco et al., 2014, 2017). Consequently, the findings of this study offer practical value to farmers engaged in organic viticulture, as they search for feasible strategies to adapt to the challenging realities imposed by climate conditions.

## 2 Materials and methods

This article shows data obtained under real commercial field management conditions. All trials were conducted in commercially active fields, the harvests of which were taken to vinification. For this same reason, when the response variables involve destruction or damage to plants, the sample sizes conform to the minimum suggested for conducting efficacy trials (Kalamarakis and Markellou, 2007; EPPO, 2012a,b). The treatments used in the different experiments consist of bacterial and/or fungal plant growth-promoting consortia, based on evidence showing that this strategy is superior to the use of monospecific treatments (Carreiras et al., 2023). This is because the use of a single strain of microorganism does not allow benefiting from the synergistic effects offered by consortia, thanks to the activation of different growth-promoting mechanisms and the interaction between them (Mesa-Marín et al., 2019; Redondo-Gómez et al., 2022).

For the reasons set forth above, the following criteria were used in conducting the experiments: 1—The trials were carried out in actively producing crop fields, which have similar characteristics (in terms of soil, area, planting density, and varieties used) to the production units characteristic of the regions in which the experiments were conducted. 2—The microbial consortia used are readily available in commercial formulations, and the species included are of recognized utility in organic farming. 3—The response variables evaluated in the experiments are of easy agronomic interpretation and are routinely measured and used in commercial vineyards to make management decisions. These variables were measured using the techniques routinely used in the vineyards. This set of criteria aims to encourage the use of the results of this work by farmers.

The characteristics of four experiments are presented below. In all cases the microorganisms were used under the hypothesis that their incorporation into the system would improve the performance of plants under climatic stress conditions (Barrow et al., 2008; Aguilera et al., 2022; Carreiras et al., 2023), due to high solar radiation, high temperatures, low relative humidity and reduced rainfall levels. The microorganisms used in the experiments are part of commercial formulations available in Chile, approved for use in organic agriculture according to the USDA-NOP and EU-Chilean 20.089 standards. In all cases, the extra ingredients found in the treatments are either part of the commercial formulations used in the experiments (i.e., co-formulants, humic acid and seaweed extracts) or are incorporated to evaluate their effect in conjunction with the microorganisms (i.e., natural nanoparticles, composted hyacinth extract and sugar). In all cases, multiple modeling techniques were used to analyze the data (conventional analysis of variance, non-parametric analysis by ranks, generalized linear models, and permutation analysis of variance). The details of the analyses used in each case are presented after the description of the treatments for each experiment.

### 2.1 Experiment 1

This experiment was conducted during the 2020–2021 season in Santa María commune (Valparaiso Region, Chile) on a total area of 8 ha planted with Cabernet Sauvignon variety (established in 2012). The vineyard has a planting distance of 2.2 m between-rows by 1.2 m in-rows, using a simple trellis system, under a controlled drip irrigation system. The site has a loam soil, with 1.8% of organic matter and pH 7.5. Daily values of air temperature (average), accumulated precipitation, and solar radiation during the experiment are shown in the Supplementary Table S1. A completely randomized one-way classification design was used (Montgomery, 2004), to evaluate the effect of incorporating into the soil (via fertigation) efficient microorganisms, in contrast to a control. Treatments are identified as: T1—Control, T2—Incorporation of effective microorganisms. Fifteen replicates of each treatment were carried out. Each experimental unit consisted of 18.180 linear meters. In total, each treatment occupied an area of 4 ha. In treatment 2, microorganisms were applied on two dates (see details in Table 1).

The variables evaluated are associated with root development (root weight) and vigor expression (pruning weight). Both are important parameters in commercial wine production. To calculate the weight of the roots, trial pits were made using the modified monolith method (Böhm, 1979). For this purpose, a block of soil (60 cm wide x 60 cm deep x 240 cm long) was extracted from the west side of the plants and the roots were obtained from it. The roots were washed and weighed in the laboratory. To determine the pruning weight, the commercial pruning of a portion of the vineyard called "claro" or "entrepostе" (a 6-meter portion of a row with 5 vine plants) was carried out. In other words, after winter pruning of vineyard, the weight of plant material removed was quantified.

The following analyses were performed on the data obtained (Montgomery, 2004): 1—Kolmogorov–Smirnov normality test,

**TABLE 1** Timeline of applications and microorganisms used in experiment 1.

| Applications | First date (consortium 1) | Second date (consortium 2) |
|---|---|---|
| Treatment 1 | – | – |
| Treatment 2 | *Trichoderma rifai* (strain AMTtr02)[1]<br>*Trichoderma harzianum* (strain AMTtr03)[1]<br>*Trichoderma virens* (strain AMTtr12)[1]<br>*Bacillus amyloliquefaciens* (strain AMTba21)[2]<br>*Bacillus subtilis* (strain AMTbsR06)[2]<br>*Lysinebacillus* spp.[3]<br>*Bacillus* spp.[3] | *Trichoderma rifai* (strain AMTtr02)[1]<br>*Trichoderma harzianum* (strain AMTtr03)[1]<br>*Trichoderma virens* (strain AMTtr12)[1]<br>*Bacillus amyloliquefaciens* (strain AMTba21)[2]<br>*Bacillus subtilis* (strain AMTbsR06)[2]<br>*Penicillium smithii* (strain AMTps01)[4]<br>*Penicillium bilaie* (strain AMTpb01)[4]<br>*Penicillium cellulolyticus* (strain AMTpc01)[4]<br>*Bacillus megaterium* (strain AMTbm01)[2]<br>*Bacillus aryabhattai* (strain AMT bar01)[2] |

[1]Minimum concentration $3 \times 10^8$ cfu/g of *Trichoderma* spp. in total.
[2]Minimum concentration $5 \times 10^9$ cfu/g of *Bacillus* spp. in total.
[3]Minimum concentration $1 \times 10^{10}$ cfu/g of bacteria in total.
[4]Minimum concentration $1 \times 10^9$ cfu/g of *Penicillium* spp. in total.
Doses applied on the first and second date are 0.5 Kg/ha.
cfu, colony forming units.

2—Levene's test for homogeneity of variances. Where these assumptions were met, the variables were evaluated using T-tests. In cases where non-normality and/or heteroscedasticity deviations occurred, which could not be corrected using Box-Cox transformations (Dag and Ilk, 2017), variables were also evaluated using the nonparametric Mann–Whitney rank test (Montgomery, 2004). Generalized linear models and permutation analysis of variance (Permanova) were also performed for each response variable (Anderson, 2001; Bolker et al., 2009). All analyses were performed in the R programming environment (R Core Team, 2021), according to the protocols outlined in Bates et al. (2015), Lawson (2015) and Oksanen et al. (2020) for the indicated analyses.

## 2.2 Experiment 2

The experiment was conducted during the 2020–2021 season in Chimbarongo Commune (Libertador General Bernardo O'Higgins Region, Chile) on a total area of 10 ha planted with Cabernet Sauvignon variety (established in 2005). The vineyard has a planting distance of 1.8 m between-rows by 1 m in-rows, using a simple trellis system, under a controlled drip irrigation system. The site has a loam soil, with 2.4% of organic matter and pH 6.1. Daily values of air temperature (average), accumulated precipitation, and solar radiation during the experiment are shown in the Supplementary Table S2. A completely randomized one-way classification design was used (Montgomery, 2004), to evaluate the effect of incorporating into the soil (via fertigation) different combinations and application times of efficient microorganisms, plus a control. The different treatments were (see details in Table 2): T1—Control, T2—Application (at a single point in time) of a set of microorganisms, T3—Sequential application of different sets of microorganisms and T4—Sequential application of different sets of microorganisms (same as those used in T3) plus natural nanoparticles. Treatments 2, 3 and 4 were established by crop experts and bioinput suppliers' recommendations. There were 10 replicates of each treatment, each experimental unit consisted of 95 rows. The same variables already described in Experiment 1 were evaluated (using the same methodologies).

The following analyses were performed on the data obtained (Montgomery, 2004): 1—Kolmogorov–Smirnov normality test, 2—Levene's test for homogeneity of variances. Where these assumptions were met, the variables were evaluated using ANOVAs. In cases where non-normality and/or heteroscedasticity deviations occurred, which could not be corrected using Box-Cox transformations (Dag and Ilk, 2017), variables were also evaluated using the Kruskal–Wallis rank tests (Montgomery, 2004). Generalized linear models and permutation analysis of variance (Permanova) were also performed for each response variable (Anderson, 2001, Bolker et al., 2009). All analyses were performed in the R programming environment (R Core Team, 2021), according to the protocols outlined in Bates et al. (2015), Lawson (2015) and Oksanen et al. (2020) for the indicated analyses.

## 2.3 Experiment 3

The experiment was conducted during the 2021–2022 season in Chimbarongo Commune (Libertador General Bernardo O'Higgins Region, Chile), in a nursery (use to obtain plants for replanting). A completely randomized one-way classification design (Montgomery, 2004) was used to evaluate the effect, in Sauvignon Blanc grapevines planted in nursery, of different forms of mycorrhiza-forming fungi application, plus a control. Specifically, three treatments were evaluated (see details in Table 3): T1—Control, T2—Application via drenching of 2 g of mycorrhizae in a 250 mL solution with non-chlorinated water, applied with a pitcher on the substrate in which the vines were planted (i.e., post-planting) and T3—Immersion of roots for 10 min in a 200 lt solution containing mycorrhizae (1 g of mycorrhizae: 125 mL of non-chlorinated water) (i.e., prior to planting).

In all cases the plants were planted on standard substrate (see Table 4) of grapevine nursery, in plastic bags (5 L). Daily values of air temperature (average), accumulated precipitation, and solar radiation during the experiment are shown in the Supplementary Table S3. The effect of treatments on root weight was evaluated. For this purpose, the plants were extracted from the bags and the substrate adhered to the roots was removed with a pressure washer. The roots were cut and taken to the laboratory, where they were weighed. Measurements were made at two different times: 180 days after application and 240 days after application. The two measurements were made on different plants. At each measurement time, 20 plants per treatment were evaluated. The data were analyzed using the same methodology described in experiment 2.

## 2.4 Experiment 4

The experiment was conducted during the 2022–2023 season in the Santa María Commune (Valparaiso Region, Chile) on a total area of 6 ha planted with Cabernet Sauvignon variety (established in 2010). The vineyard has a planting distance of 2.2 m between-rows by 1.2 m in-rows, using a simple trellis system, under a drip irrigation system. The site has a loam soil, with 1.8% of organic matter and pH 7.5. Daily values of air temperature (average), accumulated precipitation, and solar radiation during the experiment are shown in the Supplementary Table S4. A completely randomized two-way classification design (Montgomery, 2004) was used to evaluate the effect of two factors (each with two levels). The factors evaluated were: Factor 1—incorporation or not of efficient microorganisms to the soil, and Factor 2—application or not of a sugar source to the crop (jointly to leaves and soil). A full factorial design (Montgomery, 2004) was used to evaluate the effect of the different combinations of factor levels in the bunch weight at harvest. A total of 810 bunch measurements were made in each of the combinations of the two factors (called treatments and named: T1, T2, T3 and T4).

The sugar source used in this trial was organic cane sugar (28% total sugars, 46% organic matter), in conjunction with a composted hyacinth plant extract (enriched with willow bark). The efficient microorganisms used were: consortium 3, consortium 4 and *Trichoderma harzianum* (i.e., the microorganisms used in the treatment 3 of experiment 2). The characteristics of the different combinations of inputs evaluated in each treatment are described below:

T1—Control. Neither sugars nor efficient microorganisms were applied.

TABLE 2 Timeline of applications and microorganisms used in experiment 2.

| Application dates (Phenology) | Treatment 1 | Treatment 2 | Treatment 3 | Treatment 4 |
|---|---|---|---|---|
| October 2nd<br>(Beginning of budburst) | – | – | Consortium 3<br>Dosage: 3 kg/ha | Consortium 3<br>Dosage: 3 kg/ha<br>+<br>Nano Particles[a]<br>Dosage: 3 kg/ha |
| October 16th<br>(2 weeks after budburst) | – | – | *Trichoderma harzianum*<br>Dosage: 2 kg/ha | *Trichoderma harzianum*<br>Dosage: 2 kg/ha<br>+<br>Nano Particles[a]<br>Dosage: 3 kg/ha |
| October 30<br>(Radical flash start) | – | Consortium 4<br>Dosage: 2 kg/ha | Consortium 4<br>Dosage: 2 kg/ha | Consortium 4<br>Dosis: 2 kg/ha<br>+<br>Nano Particles[a]<br>Dosage: 3 kg/ha |
| January 20<br>(Pre-veraison) | – | – | Consortium 5<br>Dosage: 1 L/ha | Consortium 5<br>Dosage: 1 L/ha<br>+<br>Nano Particles[a]<br>Dosage: 3 kg/ha |

Consortium 3: *Bacillus thuringiensis* strain Anemophila 8 g/kg; *Bacillus cereus* strain Bromelia 8 g/kg; *Bacillus cereus* strain Peumo 8 g/kg. In the concentration of strains 1 × 10 cfu/g.
Consortium 4: *Trichoderma virens* strain Luito, *Bacillus subtilis* strain N5 $7 \times 10^7$ cfu/g. Coformulants $3 \times 10^7$ cfu/g 96.4% w/w (964 g/kg).
Consortium 5: *Trichoderma* spp. 3,651% w/v, Concentrated Suspension $1 \times 10^9$ conidia/mL.
cfu: colony forming units. [a]Natural nano particles 98% w/w particle size 230 mesh.

TABLE 3 Treatments used in experiment 3.

| Treatments | Application mode |
|---|---|
| T1 | None |
| T2 | Consortium 6<br>Via drenching<br>(dosage: 250 mL/plant) |
| T3 | Consortium 6<br>Via immersion<br>(10 min in mycorrhizae solution) |

Consortium 6 (active ingredients at 0.1%): *Glomus intraradices* (225 viable propagules/gram), *Glomus aggregatum* (225 viable propagules/gram), *Glomus mosseae* (225 viable propagules/gram), *Glomus etunicatum* (225 viable propagules/gram), humic acid (powder) approx. 49.95%, seaweed extract (powder) approx. 49.95%.
Immersion was performed by immersing plants in a solution with consortium 6 in a bucket for 10 min. Drenching was performed by applying the solution with the consortium 6 with a back pump to the bagged plant substrate.

T2—A sugar source (plus hyacinth) was applied to the foliage and soil as described in Tables 5, 6.

T3—Different efficient microorganisms were applied to the soil as described in Table 7.

T4—A sugar source (plus hyacinth) and soil efficient microorganisms were applied as described in Tables 8, 9.

The following analyses were performed on the response variable (Montgomery, 2004): 1—Kolmogórov-Smirnov normality test, 2—Levene's test for homogeneity of variances. Since the response variable presented deviations from normality and heteroscedasticity, which could not be corrected using Box-Cox transformations (Dag and Ilk,

TABLE 4 Composition of the substrate used in experiment 3.

| | | | |
|---|---|---|---|
| **pH** | 6.1 | **Total magnesium (MgO)** | 0.5% |
| **Electrical conductivity** | 3.7 dS/m | **Total iron (Fe)** | 6,965 mg/kg |
| **Organic matter** | 54.5% | **Total manganese (Mn)** | 262 mg/kg |
| **Organic carbon** | 30.3% | **Total boron (B)** | 47 mg/kg |
| **Total nitrogen (N)** | 1.15 | **Total copper (Cu)** | 80 mg/kg |
| **Relation C/N** | 26.3 | **Total zinc (Zn)** | 91 mg/kg |
| **Total phosphorus (P2O5)** | 2.5% | **Humidity** | 35% |
| **Total potassium (K2O)** | 0.58% | **Dry matter** | 65% |
| **Total calcium (CaO)** | 3.5% | – | – |

TABLE 5 Foliar applications in treatment 2 of experiment 4.

| Date | Phenological stage | Sugar Lt/ha | Hyacinth Lt/ha | Spray Lt/ha |
|---|---|---|---|---|
| November 15 | Flowering | 0 | 10 | 500 |
| December 20 | Berry growth | 0 | 10 | 500 |
| January 15 | Veraison | 1.5 | 10 | 500 |
| February 10 | Pre-harvest | 1.5 | 10 | 500 |

TABLE 6 Soil applications made in treatment 2 of experiment 4.

| Date | Phenological stage | Sugar Lt/ha | Hyacinth Lt/ha |
|---|---|---|---|
| October 25 | Beginning of sprouting | 5 | 10 |

TABLE 7 Microorganisms used in treatment 3 of experiment 4.

| Date | Phenological stage | Consortium 3 kg/ha | *T. harzianum* kg/ha | Consortium 4 kg/ha |
|---|---|---|---|---|
| October 25 | Beginning of budburst | 3 | – | – |
| November 15 | Flowering | – | 2 | – |
| December 20 | Berry growth | – | – | 2 |
| January 15 | Veraison | – | – | 1 |

TABLE 8 Foliar applications made in treatment 4 of experiment 4.

| Date | Phenological stage | Sugar Lt/ha | Hyacinth Lt/ha | Spray Lt/ha |
|---|---|---|---|---|
| November 15 | Flowering | 0 | 10 | 500 |
| December 20 | Berry growth | 0 | 10 | 500 |
| January 15 | Veraison | 1.5 | 10 | 500 |
| February 10 | Pre-harvest | 1.5 | 10 | 500 |

2017), it was evaluated by means of an ANOVA performed on the data transformed using the Aligned Rank Transform (ART) procedure (Wobbrock et al., 2011; Elkin et al., 2021). It was also analyzed using a generalized linear model with a gamma-type error distribution (Bolker et al., 2009). Finally, permutation analysis of variance (Permanova) was also performed to the response variable (Anderson, 2001). All analyses were performed in the R programming environment (R Core Team, 2021), according to the protocols outlined in Bates et al. (2015), Lawson (2015) and de Mendiburu and Yaseen (2020), Oksanen et al. (2020) and Kay et al. (2021) for the indicated analyses.

# 3 Results

Levins (1966) rightly stated that "*all models leave out a lot and are in that sense false, incomplete, inadequate,*" and Box (1979) in the same vein said that "*all models are wrong, some are useful.*" For this reason, caution should be exercised in interpreting their results. One way to do this, without renouncing the clear advantages of their use in the interpretation of nature, is through the use of the concept of robustness proposed by Levins (1966). According to this, if multiple representations of reality (models), operating under different assumptions coincide, we are in the presence of a robust result.

In Levins' (1966) own words: "*our truth is the intersection of independent lies.*" It is for this reason that here are used multiple approaches to data modeling. In this regard, it is important to mention that the results obtained from these methodologies (conventional analysis of variance, nonparametric analysis of variance by ranks, generalized linear models and analysis of variance by permutations) in the majority of cases coincided, which is an indication of their robustness (in the sense mentioned above).

In all cases the results are summarized with boxplots. The mean value is indicated by a black cross. Multiple comparison results are shown using the compact letter display. In all cases, the multiple comparison tests were performed with an alpha value equal to 0.05 (with Bonferroni correction). In addition, the average value (for each treatment) is presented with numbers and the standard deviation in parentheses.

## 3.1 Results experiment 1

The root weight variable fits well to a normal distribution (Kolmogorov–Smirnov test statistic $D = 0.12939$, $p$-value $= 0.2251$) and has no significant heteroscedasticity issues (Levene test statistic $= 3.2433$, $p$-value $= 0.0825$). The variable pruning weight does not fit well to a normal distribution (Kolmogorov–Smirnov test statistic $D = 0.16511$, $p$-value $= 0.03605$) and has no significant heteroscedasticity issues (Levene test statistic $= 3.7787$, $p$-value $= 0.06202$). For the latter variable, normality issues could be solved by a Box-Cox transformation with a lambda hat value of $-0.32$ (Kolmogorov–Smirnov test values on the transformed data: $D = 0.08486$, $p$-value $= 0.8406$).

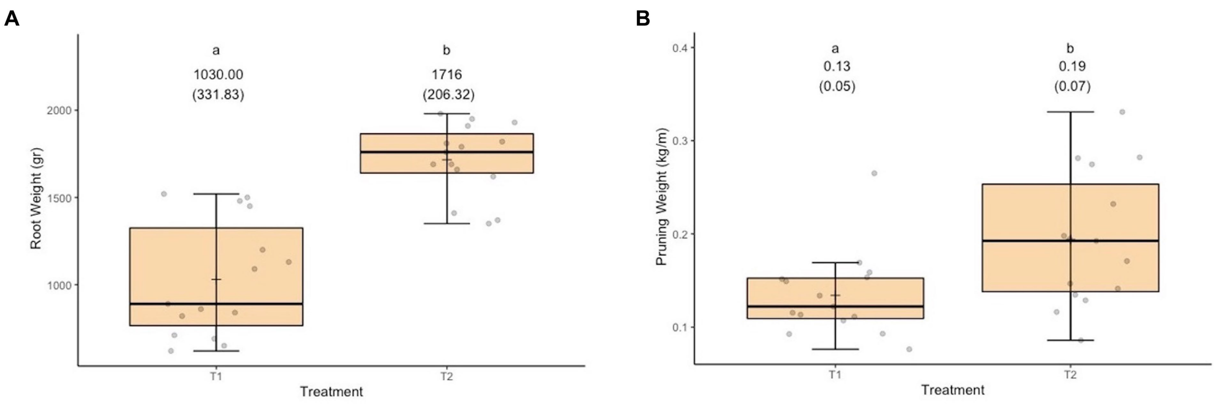
Incorporating efficient microorganisms was found to have effects (see Figure 1C) on both root growth and pruning weight. This is likely to be achieved through the interaction of microorganisms with roots, fixation atmospheric nitrogen and facilitation of phosphorus uptake, that may result in the stimulation of root and leaf growth (see Figures 1A,B). In both cases the effects are in the desired direction (considering that the plants are subjected to strong stress due to solar radiation and drought, which limits their productive potential and oenological quality). Specifically, in the treatment involving microorganisms is observed: 1—Roots have a higher development (see Figure 1A), which suggests a greater capacity of plants to take advantage of moisture and capture nutrients in the soil, as well as to increase root exploration. 2—In the case vegetative development, there is a higher pruning weight (see Figure 1B), which is associated with greater plant vigor, higher capacity to accumulate photoassimilates and therefore greater productive potential.

## 3.2 Results experiment 2

The variable root weight fits well to a normal distribution (Kolmogorov–Smirnov test statistic $D = 0.12202$, $p$-value $= 0.14$) and has no issues of heteroscedasticity (Levene test statistic $= 0.55928$, $p$-value $= 0.6453$). The variable pruning weight fits well to a normal distribution (Kolmogorov–Smirnov test statistic $D = 0.077778$, $p$-value $= 0.7851$) and has no heteroscedasticity issues (Levene test statistic $= 0.81566$, $p$-value $= 0.4937$). No effect of treatments was found on the response variables evaluated (see Figure 2C). In terms of the responses to the treatments, it is worth commenting that for root weight a less uniform response is observed, than what was observed for pruning weight (see Figures 2A,B). This possibly has to do with the fact that the roots are directly in the medium in which the microorganisms were incorporated, so their action could be manifested there first.

TABLE 9 Soil applications made in treatment 4 of experiment 4.

| Date | Phenological stage | Sugar Lt/ha | Hyacinth Lt/ha | Consortium 3 kg/ha | *T. harzianum* kg/ha | Consortium 4 kg/ha |
|---|---|---|---|---|---|---|
| October 25 | Beginning of budburst | 5 | 10 | 3 | – | – |
| November 15 | Flowering | – | – | – | 2 | – |
| December 20 | Berry growth | – | – | – | – | 2 |
| January 15 | Veraison | – | – | – | – | 2 |




C

| Roots | | | | Pruning | | |
|---|---|---|---|---|---|---|
| Test | Statistic | p-value | | Test | Statistic | p-value |
| t-test | t = -6.7995 | 2.192e-07 | | t-test | t = -2.7173 | 0.01116 |
| Wilcoxon rank | W = 12 | 3.35e-05 | | Wilcoxon rank | W = 52 | 0.01126 |
| PERMANOVA | F = 46.233 | 0.001 | | PERMANOVA | F = 7.3881 | 0.012 |
| GLM (gamma) | chi-sq. = 1.93 | > 0.01 | | GLM (gamma) | chi-sq. = 1.02 | > 0.01 |

FIGURE 1
Results of experiment 1. **(A)** Results of the root weight variable. **(B)** Results of the pruning weight variable. **(C)** Values obtained in the tests performed. T1, control; T2, application of microorganisms presents in consortia 1 and 2. GLM, generalized linear model (a gamma type error distribution was used in the GLMs).

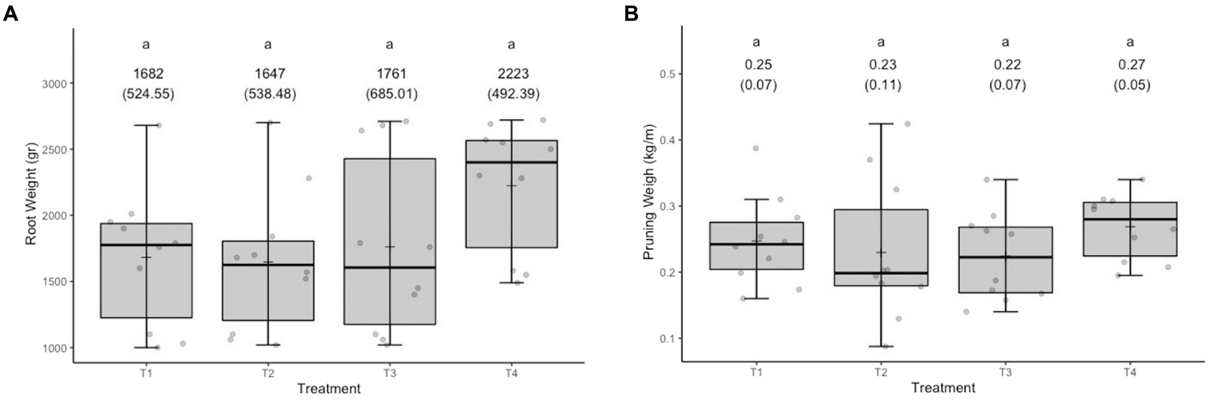
## 3.3 Results experiment 3

The variable root weight in the first measurement (Figure 3A) fits well to a normal distribution (Kolmogorov–Smirnov test statistic D = 0.10192, *p*-value = 0.126) and has no heteroscedasticity issues (Levene test statistic = 0.81789, *p*-value = 0.4465). The variable root weight in the second measurement (Figure 3B) fits well to a normal distribution (Kolmogorov–Smirnov test statistic D = 0.065306, *p*-value = 0.7577) and has no heteroscedasticity issues (Levene test statistic = 0.67022, *p*-value = 0.5156). The overall relationship between the different treatments is similar for the two measurement times (see Figures 3A,B). Figure 3C shows that, for both measurement moments, the *p*-values obtained are close to the historical significance threshold of 0.05. However, the *p*-values obtained on the second date are lower than those obtained on the first date. For the second date, according to the Tukey multiple comparisons test ($\alpha$ = 0.05 and Bonferroni adjustment), only the difference between T1 and T2 presents a 95% confidence interval that does not include 0 (see Figure 3D). It is worth mentioning (in term of effect sizes) that in the treatments that involve fungi, the roots weights (in average) at least 20 gr more than the control.

## 3.4 Results experiment 4

The response variable of the experiment does not fit well to a normal distribution (Kolmogorov–Smirnov test statistic D = 0.12437, *p*-value < 2.2e-16) and have significant heteroscedasticity issues (Levene test statistic = 28.848, *p*-value < 2.2e-1). The variable distribution is skewed to the right and the data fit better to a model with a gamma error distribution (AIC = 32293.04) than to one with a normal distribution (AIC = 33757.9). The issues of non-normality and heteroscedasticity could not be solved by Box-Cox transformation and the data do not meet the requirements of the aligned rank transform procedure (i.e., not all column of the aligned responses sum to zero). Therefore, in this case the best alternatives are a Pernanova and a GLM with a gamma error distribution.

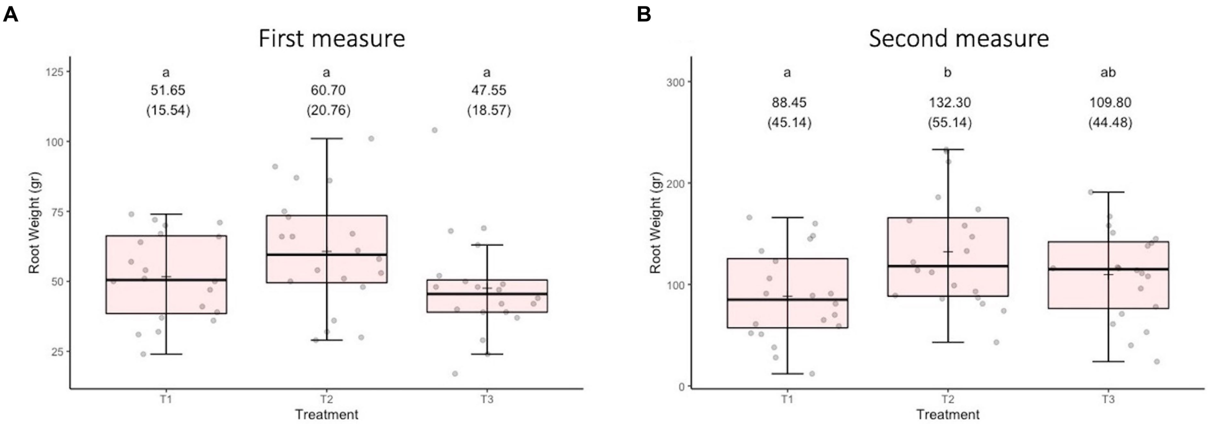
Figure 4 shows that there is a treatment effect, with the best result (higher bunch weight) obtained with treatment 4 (groups created using pairwise Permanovas, with $\alpha$ = 0.05 and a Bonferroni adjustment), which consists of the joint application of efficient microorganisms and a sugar source (plus hyacinth) (see Figure 4A). In fact, the joint application has a positive synergistic effect on bunch




C

| Roots | | | | Pruning | | |
|---|---|---|---|---|---|---|
| Test | Statistic | p-value | | Test | Statistic | p-value |
| ANOVA | F = 2.208 | 0.104 | | ANOVA | F = 0.7 | 0.558 |
| Kruskal-Wallis | chi-sq. = 4.7086 | 0.1944 | | Kruskal-Wallis | chi-sq. = 3.4627 | 0.3256 |
| PERMANOVA | F = 2.241 | 0.092 | | PERMANOVA | F = 0.69984 | 0.551 |
| GLM (gamma) | chi-sq. = 0.12 | 0.6 | | GLM (gamma) | chi-sq. = 0.20 | 0.59 |

FIGURE 2
Results of experiment 2. **(A)** Results of the root weight variable. **(B)** Results of the pruning weight variable. **(C)** Values obtained in the tests carried out. T1, Control; T2, Application (in a single moment) of the set of organisms present in consortium 4; T3, Application in sequence of the set of microorganisms present in consortia 3, 4 and 5 (plus *Trichoderma harzianum*); T4, Application in sequence of the set of microorganisms used in T3, plus natural nanoparticles. GLM: generalized linear model (a gamma type error distribution was used in the GLMs).




C

| Roots first measure | | | | Roots second measure | | |
|---|---|---|---|---|---|---|
| Test | Statistic | p-value | | Test | Statistic | p-value |
| ANOVA | F = 2.67 | 0.0779 | | ANOVA | F = 4.088 | 0.0219 |
| Kruskal-Wallis | chi-sq. = 5.1844 | 0.07486 | | Kruskal-Wallis | chi-sq. = 6.1369 | 0.04649 |
| PERMANOVA | F = 2.6697 | 0.084 | | PERMANOVA | F = 4.0879 | 0.019 |
| GLM (gamma) | chi-sq. = 0.62 | 0.07 | | GLM (gamma) | chi-sq. = 1.61 | 0.02 |

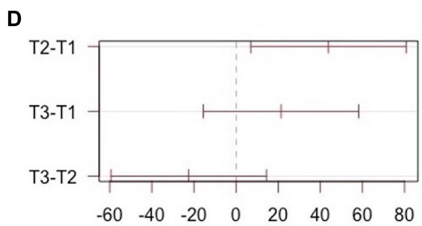
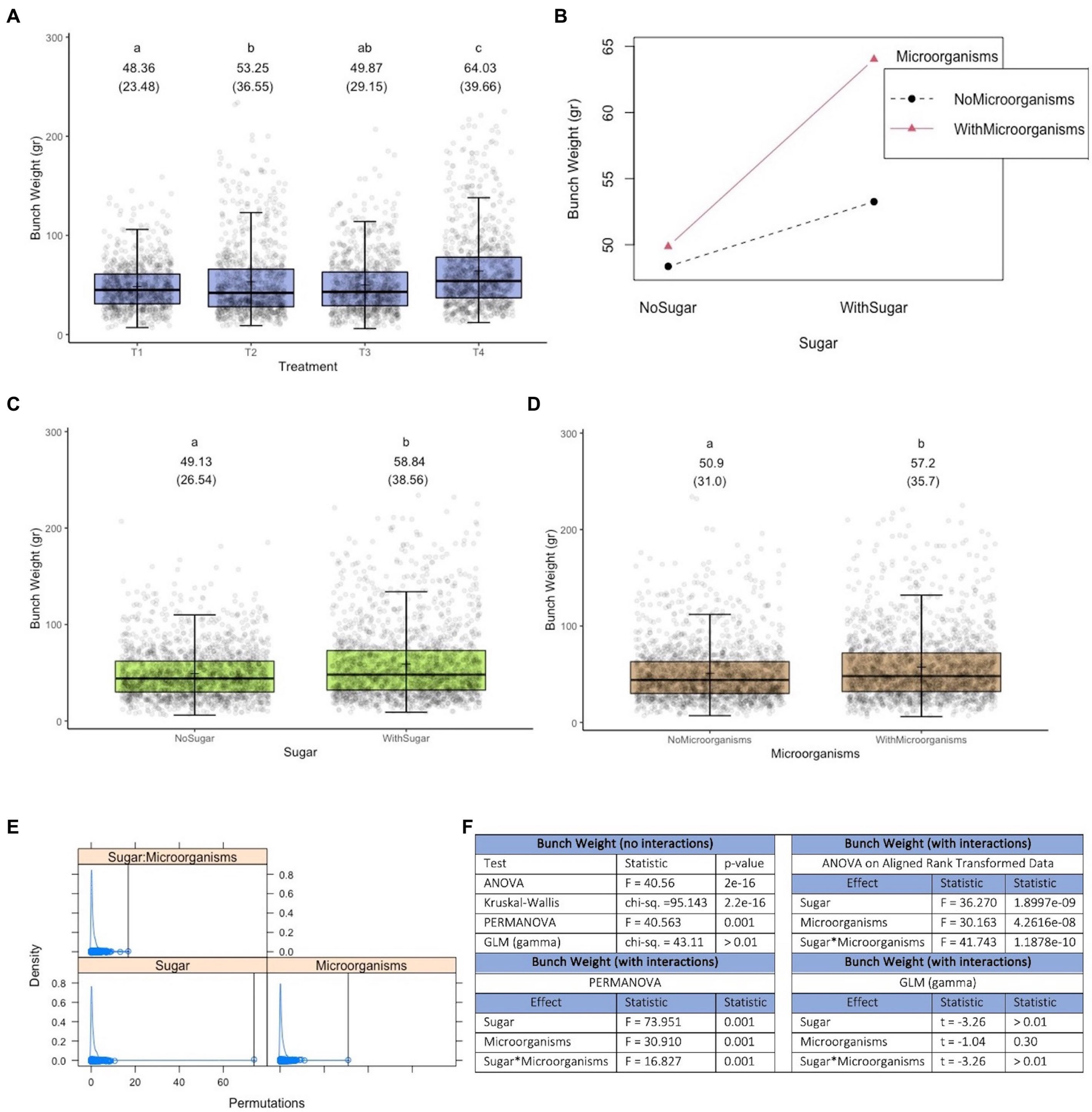



FIGURE 3
Results of experiment 3. **(A)** Results of the root weight variable in the first measurement. **(B)** Results of the root weight variable in the second measurement. **(C)** Values obtained in the tests performed. **(D)** 95% confidence interval of the Tukey multiple comparisons test for the second date. T1: Control, T2: Application of the set of organisms present in consortium 6 via drenching; T3, Application of the set of organisms present in consortium 6 via immersion; GLM, generalized linear model (a gamma type error distribution was used in the GLMs).

weight (see the different slopes in the lines of Figure 4B). It is worth noting that both, the application of microorganisms and sugar separately (i.e., main effects), have positive effects on the response variable. As can be seen in Figures 4E,F for Permanova, both the main effects and their interaction are significant at 0.05 threshold level.




| Bunch Weight (no interactions) | | |
|---|---|---|
| Test | Statistic | p-value |
| ANOVA | F = 40.56 | 2e-16 |
| Kruskal-Wallis | chi-sq. =95.143 | 2.2e-16 |
| PERMANOVA | F = 40.563 | 0.001 |
| GLM (gamma) | chi-sq. = 43.11 | > 0.01 |
| **Bunch Weight (with interactions)** | | |
| PERMANOVA | | |
| Effect | Statistic | Statistic |
| Sugar | F = 73.951 | 0.001 |
| Microorganisms | F = 30.910 | 0.001 |
| Sugar*Microorganisms | F = 16.827 | 0.001 |

| Bunch Weight (with interactions) | | |
|---|---|---|
| ANOVA on Aligned Rank Transformed Data | | |
| Effect | Statistic | Statistic |
| Sugar | F = 36.270 | 1.8997e-09 |
| Microorganisms | F = 30.163 | 4.2616e-08 |
| Sugar*Microorganisms | F = 41.743 | 1.1878e-10 |
| **Bunch Weight (with interactions)** | | |
| GLM (gamma) | | |
| Effect | Statistic | Statistic |
| Sugar | t = -3.26 | > 0.01 |
| Microorganisms | t = -1.04 | 0.30 |
| Sugar*Microorganisms | t = -3.26 | > 0.01 |

FIGURE 4
Results of experiment 4. **(A)** Results of the variable bunch weight. **(B)** Interaction diagram between the factors microorganisms and sugar. **(C)** Main effect of the sugar factor. **(D)** Main effect of the microorganisms factor. **(E)** Density plot of the results obtained in Permanova [the black vertical lines represent the values of the pseudo-F statistic; its specific values and the associated $p$-values are presented in **(F)**]. **(F)** Values obtained in the tests performed. T1, Control; T2, Application of a sugar source; T3, Application of the set of microorganisms presented in consortia 3, 4 and 5 (plus *Trichoderma harzianum*); T4, Application of the microorganisms used in T3 and sugar; GLM, generalized linear model (a gamma type error distribution was used in the GLMs).

# 4 Discussion

Results of experiments 1 and 4 support published evidence on the benefits of efficient microorganisms to agroecosystems (Martínez-Viveros et al., 2010; Schütz et al., 2018; Basu et al., 2021; Ferreira et al., 2021; Antoszewski et al., 2022; Gupta et al., 2022; Notununu et al., 2022). While experiments 2 and 3 results show some elements that should be taken into account when carrying out microbiome manipulations in ecological farming.

With respect to experiment 2, in order to make a fair assessment of its results, it is good to take into account the historical behavior of the vineyard area where it was carried out. Figure 5 shows that the vineyard sector in which it was implemented, has a clear downward trend in its harvests. This area has been under organic management for more than 12 years and shows clear signs of decline. This is a completely different situation from that found in the areas where experiments 1 and 4 were conducted (data not shown).

It should be noted that, for the vineyard where experiment 2 was conducted, a harvest below 10.000 kg/ha is considered deficient (good values are between: 12.000–14.000 kg/ha). This threshold was not achieved in the 2 years prior to the development of the experiment (see Figure 5), for this reason the different treatments were elaborated

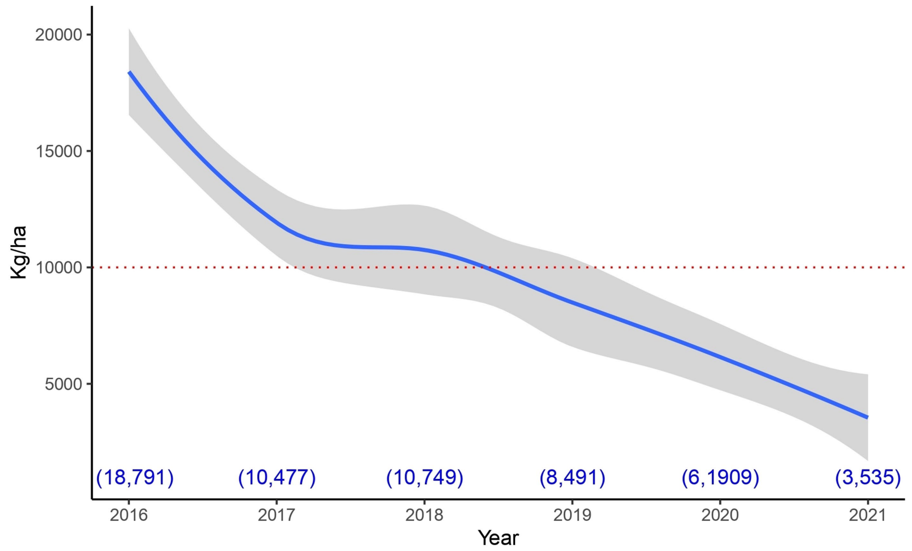



FIGURE 5
Historical production in the area where experiment 3 was carried out. The average production of the area is presented (with its 95% confidence interval). This was done using the smoothed conditional means procedure (Wickham, 2016). The red dotted line represents the minimum acceptable production according to the vineyard standards. The blue numbers in parentheses at the bottom of the graph represent the average production value per hectare for each year.

by a team of experts to try to address the production deficit. Even treatments inspired by the ecological succession process were tested, these involved the incorporation of different groups of microorganisms at different times (specifically treatments 3 and 4).

The low production associated with the sector where the experiment was carried out is possibly related to a number of causes: 1—adverse effect of weather, 2—excessive level of production before 2017 (well above the threshold of 14.000 kg/ha) and 3—mechanical damage caused (over the years) during weed control (because the distance between the rows is too short for the implement used for weeding). Thus, it is possible that the context in which efficient microorganisms were incorporated limited their effect. It should be noted that, given the historical performance of the sector, the vineyard manager decided to replant the vineyard after 2021 harvest (the year in which the experiment was completed).

It is fundamental to take into account that any manipulation of the microbiome is governed by ecological processes (at population and community levels) and that these take time. In a sense, microbiome interventions in agroecosystems are similar to augmentative approaches to biological control (Horn, 1988). In other words, the population density of certain organisms is artificially increased in order to make them perform an action desired by humans. However, changes in population densities are not immediately effective (Eisenhauer et al., 2010). In the case of soil microorganisms, it must be taken into account that in their action, important density dependent mechanisms intervene, for example, quorum sensing (Duddy and Bassler, 2021). While other mechanisms depend also on interactions between species (Qiao et al., 2023) and the nature of these interactions can change over time depending on various conditions such as, for example, the density of participating species (Bronstein, 1994; Griffon and Hernandez, 2019; Hernandez, 2021; Hanusch et al., 2023). Thus, important ecological phenomena in the soil influence the establishment and colonization of the environment by introduced microorganisms. Phenomena that, depending on different factors, may take different times, but certainly do not act immediately.

The times associated with the ecological phenomena possibly explain the results obtained in experiment 3 (particularly in the first measurement). Here it is worth commenting on the differences between the application modes of treatments 2 and 3 in experiment 3. In the case of treatment 3, the roots were in contact with the microorganism solution for 10 min, while in treatment 2 this solution was incorporated into the plant's growing substrate. Therefore, in treatment 2, a greater number of microorganisms are incorporated into the medium, which could lead to greater symbiosis with the roots. For this reason, it is likely that this method of application can achieve the population densities necessary to exert an effect on the plants in a shorter time.

The time required for the growth of microorganism populations may also be associated with the synergistic effect observed in experiment 4. Because the sugar addition to the medium can create a favorable context for the rapid growth of microorganism populations. In addition, on previous experiences we have found that sugar has a positive effect on plants under climatic stress conditions. In this sense, it is important to mention that, in experiments not presented here (not involving efficient microorganisms), only applications of sugar to soil and leaves (together) were found to have positive effects on bunch size. The physiological explanation of this result in terms of fine mechanisms is unknown to us. It is an adaptation strategy inspired by a similar practice used in the management of avocado trees under stress due to climate change in Peru. These results may indicate that the effects of sugar extend to the microbiome found in the plant shoots. It is important to note that the consortia used in this experiment are the same as those used in the treatment 3 of experiment 2, which points out the importance of incorporating efficient microorganisms in a favorable environment.

Recently, there has been renewed interest in the holobiont concept, originally proposed by Lynn Margulis (1991). It accounts for the combination of the host (in this case the plant) with its microbiome. In other words, a holobiont is a composite entity, consisting of a host together with its microbiome (Roughgarden, 2020). It is important to mention that this controversial proposal already has an eco-evolutionary biomathematical theory that supports it (Roughgarden, 2023). In the context of ecological farming, what is really important is that selection on the holobiont, causes evolutionary changes in the traits of the holobiont itself (Roughgarden, 2020; Mesny et al., 2023; Wolfgang et al., 2023). This is particularly important for evolutionary breeding, which is a breeding strategy that really makes sense for ecological farming (Ceccarelli and Grando, 2020).

Evolutionary breeding is based on Fisher's fundamental theorem of natural selection (Fisher, 1999), which states that the action of natural selection increases the average fitness of populations (as long as they present genetic variation). This theorem can be extended to a context of species interactions (León and Charlesworth, 1978). Thus, the objective of evolutionary breeding is that the forces of evolution act on the agroecosystem as a whole (Ceccarelli et al., 2022). In this context, the co-evolution of the microbiome with the rest of the system is fundamental. Now, for this to be possible, this component must be explicitly included in the breeding programs with an evolutionary approach. However, this promising research (and field management) program should not be taken as an invitation to introduce exotic microorganisms into agroecosystem soils, as there is a long history of failed introductions with disastrous consequences (Ladau et al., 2023). On the contrary, these programs should be based on the use of indigenous organisms.

It is also important to assess, albeit on a subjective note, the impression that this set of experiments left on the people who manage these agricultural systems. In this regard, in all cases efficient microorganisms were incorporated into the vineyard management schemes. This means an area of 450 ha under regenerative soil management. It is worth noting that the current trend in ecological soil management seems to be towards a regenerative type of management, which not only involves fixing atmospheric carbon in the soil and incorporating rhizobacteria and mycorrhizal fungi, but also seeks to incorporate microorganisms such as predatory nematodes, amoebae, protozoa and aerobic fungi, thus increasing the complexity of the system (Ingham, 2000; Pane et al., 2012; St. Martin, 2014; Johns, 2017; St. Martin et al., 2020; White, 2020; Lazarova et al., 2021; Curadelli et al., 2023; Eon et al., 2023; Mishra et al., 2023). Therefore, the characterization and understanding of the ecological interaction network of soils is a promising research program, that can provide valuable results for regenerative agriculture in the near future.

It is also important to highlight that the results presented here correspond to exploratory experiments. These motivate and suggest other questions to be addressed. For example, it is interesting to evaluate if there is a threshold density at which microorganisms begin to have a positive effect on plants. Hence, a subsequent step could involve conducting experiments in which different concentrations of microorganisms are evaluated. Similarly, it is worthwhile to study if there is an optimal concentration for the applications. This last question could be explored using the response surface methodology (Montgomery, 2004). Also, it is compelling to study if there is an optimal structure (e.g., in terms of species richness) for the applied microbial consortia, this question could be explored using treatments of increasing complexity.

Finally, it is useful to draw comparisons with other studies on the subject, to highlight the particularities of our study, specifically regarding our experimental setups. For instance, Carreiras et al. (2023) elegantly demonstrated the potential of marine plant growth-promoting rhizobacteria consortia as an eco-friendly solution for mitigating heatwave stress in vineyards. Their research was conducted under greenhouse conditions, with plants potted and treated with microorganism consortia prepared and applied under controlled conditions, with light and temperature also controlled and the experiment was relatively small-scale (treatments consisted of 5 replicate plants). Such experimental setups are crucial for advancing knowledge in the field. However, they significantly differ from the conditions experienced during fieldwork on commercial farms, which can hinder their adoption by farmers. For this reason, our study was specifically designed to mirror real field management conditions, making it more relatable for farmers.

Naturally, our approach comes with certain trade-offs in accuracy (particularly in controlling sources of variation). Factors such as temperature, rainfall, and sunlight (which are beyond our control in the experiments) influence grape growth. Nevertheless, our study was conceived with the understanding that these factors represent the real-world variability that agriculture must adapt to. We believe that developing viable adaptation strategies requires both types of research (those conducted under clear-cut controlled conditions and those under real field conditions), because these approaches are complementary.

From a long-term perspective, soil microbiome manipulation can be used as an adaptation strategy to the new climatic conditions facing agriculture. Through an adequate configuration of stimuli, which could be partially incentivized by public policies, these microorganisms could be multiplied in the farms themselves. This can be achieved through simple techniques, such as the production of compost tea (Ingham, 2003), and thus help reduce the costs that affect the economic viability of the sector (Reganold and Wachter, 2016; Meemken and Qaim, 2018; Łuczka and Kalinowski, 2020).

## 5 Conclusion

Manipulation of the microbiome in large-scale organic farming as a climate change adaptation strategy is feasible. But in its execution, it must be taken into account that this promising management strategy is governed by ecological processes that take time. This is why these manipulations cannot be expected to have effect automatically. Similarly, in agroecosystems subjected to different forms of stress associated with poor overall condition, it is possible that the microorganisms fail to establish themselves and thus exert positive effects on the system. In short, manipulation of the microbiome is a regenerative soil management strategy that has great potential, but is by no means a panacea.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

CP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1285981/full#supplementary-material

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# Medicinal plants, biodiversity, and local communities. A study of a peasant community in Venezuela

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**Objective:** The main objective of this research was to record ethnobotanical data on the use and exploitation of medicinal plants, highlighting their importance for the biodiversity, culture, and tradition of a peasant community in Venezuela.

**Sample/method:** The study involved a population of 120 individuals, from which a sample size of 34 people was calculated using the formula for finite populations. A simple random sampling technique was employed, and all the participants were administered the TRAMIL (Traditions Medicine in Island) survey.

**Statistical analysis:** The ethnopharmacological table was constructed, and descriptive statistics were used for analysis.

**Results:** A total of 116 species of medicinal plants were documented to treat various health conditions. The informants reflected through their responses that they used medicinal plants in the first instance to address a health condition, employing varied forms of plant preparation, which include decoction (65.16%), raw consumption (16.77%), maceration (8.38%), and infusion (7.09%). The most commonly used plant parts are leaves, flowers, fruits, bark, peels, roots, and bulbs, while the most commonly used botanical families are Lamiaceae, Fabaceae, Rutaceae, Malvaceae, Verbenaceae, Acanthaceae, Asteraceae, and Euphorbaceae. On the other hand, the species with the highest TRAMIL Significant Use Level were Oregano orejón (*Coleus amboinicus* Lour.) (68.29), Malojillo [*Cymbopogon citratus* (D.C.) Stapf.] (60.97), Tua (*Jatropha gossypiifolia* L.) (34.15), Colombiana [*Kalanchoe pinnata* (Lam.) Pers.] (34.15), Poleo [*Micromeria brownei* (Sw.) Benth.] (29.27), Pasote (*Chenopodium ambrosioides* L.) (29.27), Llantén (*Plantago major* L.) (26.83), Te negro [*Phyla stoechadifolia* (L.) Small] (26.83), Yerbabuena (*Mentha* sp.) (21.85), and Curia (*Justicia pectoralis* Jacq.) (21.95).

**Conclusion:** The community of El Onoto de El Valle de Tucutunemo, Aragua State, Venezuela has a notable utilization of medicinal plant species in their instance to treat different health conditions, with the predominant focus on treating flu and stomach ailments. It is important to emphasize that all individuals approached through various data collection instruments reported using medicinal plants, both individually and within their families, spanning a wide range of ages from children to the elderly. This reflects that the use of medicinal plants is part of their cultural heritage and ancestral roots.

KEYWORDS

ethnobotany, medicinal plants, TRAMIL, local communities, resources of biodiversity

## Introduction

Plant resources are integral part of biodiversity, and throughout history, the relationship that humans establish with these resources has been evident. It is from this interaction that the need to study this linkage emerges, leading to the establishment of ethnobotany as a discipline. According to Barrera (1979), ethnobotany is defined as the study of traditional botanical knowledge, which must take into account the process of knowledge acquisition, its evolution over time, and its validation within the world of experimental science. On the other hand, Hernández (2012) defines ethnobotany as the field of science that investigates the interrelationships established between humans and plants, through time and in different environmental spaces. Both authors highlight the importance of the relationship between humans and plants, which can be analyzed through various aspects. One notable example is the medicinal use of some plant species, which creates a very close relationship that lasts over time.

It is known that many cultures take advantage of plants for their medicinal properties, incorporating them into their strategies for treating various health conditions. Particularly, in Venezuela, the use of medicinal plants holds considerable for rural families.

The study was carried out in the Valle de Tucutunemo community, a non-urban parish of the Zamora Municipality, Aragua State, specifically in the El Onoto sector. This is a community where families demonstrate an important attachment toward using plants to treat different health conditions. Despite the evident reliance on plant-based remedies, there was no documented information on this practice. Therefore, it was necessary to conduct a study with scientific rigor that would allow recording ethnobotanical data on medicinal species and their uses within this community.

This study was conducted using the methodology of the Traditions Medicine in Island Program (TRAMIL), which aims to provide scientifically proven alternatives to synthetic drugs by improving and rationalizing popular therapeutics based on the use of medicinal plants. Without denying the importance of institutional medicine, which is indispensable for treating severe cases, the scientists of the program try to learn more about traditional practices to differentiate what is mere belief from what is useful and effective, thereby enabling the people of the village to solve most of their health problems effectively and affordably (Piojan, 2004).

Durán et al. (2018) conducted a study of great value, highlighting the extensive use of the TRAMIL methodology over 35 years in Primary Health Care (PHC), particularly in Caribbean Basin's medicinal flora. The authors point out that primary health care, strategies for the promotion of well-being and integral health, equity and the social, cultural and economic development of communities, require practical and socially acceptable methods, one of these methods being the use of scientifically validated plant remedies for preventive or curative purposes for various common ailments. It is also important to note that studies of this nature have also benefited institutions such as health ministries in tropical regions. They have incorporated validated popular knowledge into the education and training of health professionals as well as program development.

## Area of research

The Tucutunemo Valley, com coordenadas 10°4′9″ N and 67° 27′ 35″, is an area inhabited by Carib Indians who, according to Botello (1982), practiced agriculture collectively. The El Onoto community is located in this agriculturally oriented valley, evolving from activities related to coffee cultivation in the mountainous area near the town, where they initially settled in an improvised manner at the foot of the hill. With the implementation of the Agrarian Reform in Venezuela in 1960, they were able to settle as a more organized community (Consejo Comunal de El Onoto, 2013). However, it is important to note that there is no health center in this community, and the families who live in this community must seek medical care atx'x the nearest clinics and hospitals.

## Sample and method

Within the quantitative approach, the sample constitutes a subgroup of the population from which data are collected and should be representative of that population (Hernández et al., 2003).

A simple random sampling method, which ensures all elements of the population have the same probability of being selected, was employed.

The sample size was calculated using the formula for finite populations (Balestrini, 2006), assuming that the population for the study was 120 people.

$$n = \frac{4pq}{4qp + (N - 1)\,E2}$$

Where:
n = sample size
N = population size = 120 people (2013 Census)
4 = test statistic at 95% confidence level
E2 = maximum permissible error (15%)
p = probability of success (0.5)
q = probability of failure (0.5)

In this case $n = 33.62$, which is approximately 34 people; however, the instrument was applied to a larger number, exactly 41 people.

At the beginning of the research, informed consent was obtained from this community and its inhabitants, through its organizational structure called the Communal Council. A data collection instrument based on the TRAMIL methodology (TRAMIL, 2014) was applied to the extracted sample. This instrument comprehensively captured information including the origin of information data on health problems, identification of plants used for treatment of health problems, traditional uses of these plants, and ways of obtaining knowledge. In this research, the person of legal age in each family who was at home when the instrument was applied was surveyed, and he/she had to provide information about the family group.

Concerning the plants reported by the respondents, it was essential to ensure their reliable identification. For this purpose, plant specimens were collected at the same time as the survey was carried out, in addition to pressing and identification of the samples collected. It is important to note that we revisited the survey site to make a new collection, if the initial sample taken did not allow for safe identification.

This survey established in the Caribbean Folk Medicine Applied Research Program (TRAMIL), which supports the established methodologies for ethnobotanical studies, is of utmost importance, since it allows to make viable the guidelines of the OMS (2000), which urged the member states to carry out a complete evaluation of their traditional medicine systems; to systematically make an inventory and a preclinical and clinical study of the medicinal plants used by the practitioners of traditional medicine and the population.

The TRAMIL survey adopts an approach that extends beyond the mere popular use of medicinal plants. Instead, it begins with the symptoms or health conditions as perceived by the human groups collaborating with the surveys, which results in the creation of a list of health conditions along with their respective plant species utilized by the communities to address them, thereby being the beginning of more specific studies of these species.

The Strategy on Traditional Medicine 2014–2023 (OMS, 2014) states that the lack of research data is the first difficulty faced by Member States regarding regulatory issues related to the practice of traditional and complementary medicine. Therefore, it is important to incorporate methodological tools that contribute to solving this problem.

The variables handled in the research were the following: information on botanical species used and uses of medicinal plants in the community (see Table 1).

## Instrument

The instrument used in this research was the Traditions Medicine in Island (TRAMIL) survey, which included the origin of the information, data on the health problem, data on the identification of the plants used to treat the health problem, data on the traditional uses of the plants, and ways of obtaining the knowledge. Similarly, only those uses of plant parts cited with a frequency ≥20% among all respondents who indicated using plants as their first resource for health condition, were taken into account, considering these as "Significant Uses," (TRAMIL, 2014).

## Structure of the instrument

The following is a description of each of the parts that make up the instrument:

**1. Origin of the information.**

This first part contains the informant's name, age, address, place of birth, and time of residence in the community.

**2. Health problems.**

The local name of the health problem, a description of the symptoms experienced, and the first resource used the last time the problem occurred.

**3. Identification of the plants used to treat the health problem.**

The names of the plants, origin of the plants used (whether wild or cultivated), and the location where the plant is found (backyard, shopping, or outside the house) are included, and the permission to collect the plant must be requested.

**4. Traditional uses of plants.**

The variables recorded include the part of the plant used to prepare the traditional remedy, amount needed to prepare the remedy, mode of preparation, amount of remedy administered each time, number of times the remedy is administered per day, indications for administering the remedy if the patient is a child, results obtained when using this remedy (excellent, good, fair, poor, or bad). Observations on whether this remedy can be dangerous, highlighting the most vulnerable population, and the reason for this possible danger were also recorded.

**5 Ways of obtaining knowledge.**

The ways of obtaining knowledge include the sources of ancestral knowledge.

## Analysis

A table of ethnopharmacological information of the medicinal plants used in the community of El Onoto de El Valle de Tucutunemo was constructed, which contains relevant information such as the botanical family and species, popular names, parts used, popular uses, preparation methods, number of citations in the research, and the TRAMIL Meaningful Use level.

Herbarium specimens were prepared and taxonomically identified through the use of reference literature and were given to the community for safekeeping.

The TRAMIL Significant Use Level (NUST) for each of the species recorded expresses those medicinal uses that are cited with a frequency ≥20% by the people surveyed. They can be considered significant from the point of view of their cultural acceptance and, therefore, deserve their evaluation and scientific validation (TRAMIL, 2014). This index is calculated by dividing the number of citations for the species by the number of informants surveyed.

$$\text{NUST} = \frac{\text{Use of the species(s)}}{\text{No of informants surveyed}} \text{x100}$$

TABLE 1 Research variables.

| Objective | Variables/categories | Indicators | Techniques/ instruments |
|---|---|---|---|
| Record ethnobotanical data on medicinal plants from the El Onoto community, through the TRAMIL methodology. | Information on species and uses of medicinal plants used in El Onoto. | Local name of species of medicinal plants, parts of the plant used, traditional use, method of preparation, amount used, dosage, health conditions addressed with medicinal plants, most used species and families. | TRAMIL questionnaire. |

Descriptive statistics were used to present information on the age of the informants, the methods of preparation and administration used, the parts of the medicinal plants most used by the informants, and the botanical families with the greatest number of species present in the community.

## Results

The selected instrument was applied to 41 people, of which 29 were women and 12 men, with an age ranging from 24 to 73 years. All the informants use medicinal plants for individual consumption and for the whole family, using various forms of preparation and administration.

The study made it possible to determine that in the community, they use various parts of the plants, highlighting 10 plant species with a significant level of use >20%.

### Recording of ethnobotanical data on medicinal plants

First, with all the information collected through the TRAMIL instrument, an ethnopharmacological information table, which contains data provided by the informants, was constructed (Table 2). These data were organized in a database using Microsoft Excel.

In the community studied, 116 species of medicinal plants were recorded to treat different health conditions, where each species was identified with its local name, part(s) of the plant used, its traditional use, botanical family, scientific name, and the number of citations provided by the people surveyed about each species.

### Most used forms of preparation and administration

It can be evidenced that, in the great majority, the form of preparation is decoction, with approximately 65.16%; however, there are other forms of preparation, such as raw extract (16.77%), maceration (8.38%), infusion (7.09%), and some less conventional forms such as roasting and frying, although these are less frequently reported.

As for the administration of these preparations, they are mostly administered orally (69.02%), topically (19.42%), through baths (8.63%), or gargles (2.87%).

The way of combining these preparations is varied, where they can use the decoction method to administer it orally or topically, and the latter consists of placing the plant together with water and let it boil and place it on the area to be healed. The raw extract form is used in the form of juice, which consists of extracting the substance from plants with pressure, either to be consumed orally or through topical use. In maceration, the shredded, crushed or crushed plant is soaked in water or any other liquid; however, in the community they make it with water and use it for baths and with liquor to bottle it and use it for specific conditions, such as "blood cleansing," "to remove phlegm," "fertility in women." Another raw form is the poultice, which involves placing the fresh plant directly on the skin. Additionally, poultices are made by crushing the plant

TABLE 2 Table of ethnopharmacological information.

| | Family | Species | Local name | Used portion | Uses | Preparation and administration | N° C | NUS |
|---|---|---|---|---|---|---|---|---|
| 1 | Lamiaceae | *Micromeria brownei* (Sw.) Benth | Poleo | Leaves | Flu, fever, phlegm | Decoction/oral | 12 | 29.27 |
| 2 | Lamiaceae | *Coleus amboinicus* Lour. | Orégano orejón | Leaves | Flu, asthma kidney stone, kidney infection, ovarian cysts. | Decoction/oral | 28 | 68.29 |
| | | | | | Earache | Raw juice/oral | | |
| 3 | Verbenaceae | *Lippia origanoides* Kunth. | Oreganito | Leaves | Flu | Decoction/oral | 6 | 14.63 |
| 4 | Burseraceae | *Bursera simaruba* (L.) Sarg. | Indio esnuo | Cortex | Flu, cough | Decoction/oral | 4 | 9.76 |
| 5 | Apiaceae | *Eryngium foetidum* L. | Cilantro e' monte | Root and leaves | Flu, stomach pain, asthma | Decoction/oral | 5 | 12.19 |
| 6 | Myrtaceae | *Psidium guajava* L. | Guava | Leaves, fruit peel and root | Diarrhea, vomiting, stomach pain | Decoction/oral | 8 | 19.51 |
| 7 | Poaceae | *Cymbopogon Citratus* (DC.) Stapf | Malojillo | Root | Diarrhea, vomiting, stomach pain | Decoction, infusion/oral | 25 | 60.97 |
| | | | | Leaves | Flu, chiquinguya, cold, fevers | | | |
| 8 | Rutaceae | *Citrus aurantiifolia* (Christm.) Swingle | Lemon | Fruits | Diarrhea, vomiting, stomach pain, | Raw juice/oral | 8 | 19.51 |

into a pulp and applying it in the form of dressings. The oral infusion, which is rarely used, is when the water is placed to boil and then poured onto the plant. The mixture is then covered and left to steep before being consumed.

## Parts of the most used medicinal plants

The parts of the plants indicated as the most used in the popular preparations were leaves, bark, fruit shells, flowers, unripe flowers, fruits, and acorns in some species, such as the banana. In addition, roots and bulbs are used, with leaves being predominantly the most used with 57%, followed by the root with 11%, bark and flowers with 7% each, and the other parts of the plants are used with <4%.

In this community, just as they use mixtures of plant species, they also use mixtures of different plant structures, that is, they can combine leaves and roots, bark and fruits, among others, and of different species, to treat a health condition. An example of this is the following mixture: "A sprig of pennyroyal, a leaf of oregano, a sprig of oreganito, conchita de indio esnuo, cilantro root and a small piece of onion," with which a decoction is made and taken to cure the flu. In this combination, five botanical families are mixed, which are Verbenaceae, Lamiaceae, Burseraceae, Apiaceae, and Maryllidaceae.

## Botanical families with the highest number of species present in the community

The botanical families with the highest number of medicinal plants used are Lamiaceae, Fabaceae, Rutaceae, Malvaceae, Verbenaceae, Acanthaceae, Asteraceae, and Euphorbaceae. This result coincides with those obtained in a research carried out in Cuba by Beyra et al. (2004), where these eight botanical families, among others, present the highest number of medicinal species used by the families of seven communities in the province of Camagüey. Similarly, in the research of Lastres et al. (2015) in the community Valle de la Cruz in southern Aragua, four of the botanical families were recorded with the highest number of medicinal plant species, which include Fabaceae, Lamiaceae, Asteraceae, and Acanthaceae.

The Lamiaceae family is important as a medicinal species, as reflected in several research studies carried out in this area. According to Castello Branco Rangel de Almeida and Albuquerque (2002), this may be due to the fact that its species are rich in essential oils, which give them medicinal properties widely recognized by the population; this is also expressed by Carbonó-Delahoz and Dib-Diazgranados (2013), who point out that, in general, the essential oils present in the plants of this family are rich in terpenes, and these compounds are attributed to various activities in traditional medicine applications.

## Medicinal plant species and the TRAMIL meaningful use level

The level of significant use TRAMIL expresses those medicinal uses that are cited with a frequency ≥20% by the people surveyed who use medicinal plants as a first resource for a specific health problem. In this case, the species with a frequency ≥20% are as follows: Oregano orejón (*Coleus amboinicus* Lour.) (68.29%), Malojillo [*Cymbopogon citratus* (D. C.) Stapf.] (60.97%), Tua (*Jatropha gossypiifolia* L.) (34.15%), Colombiana [*Kalanchoe pinnata* (Lam.) Pers.] (34.15%), Poleo [*Micromeria brownei* (Sw.) Benth.] (29.27%), Pasote (*Chenopodium ambrosioides* L.) (29.27%), Llantén (*Plantago major* L.) (26.83%), Tè negro [*Phyla stoechadifolia* (L.) Small] (26.83%), Hierbabuena (*Mentha* sp.) (21.85%), and Curia (*Justicia pectoralis* Jacq) (21.95%).

## Health conditions recorded in the community treated with medicinal plants

The 41 people participating in this research reported that both themselves and their family members have treated health conditions with medicinal plants exclusively or in a combination with medicines prescribed by a health entity. Among the most common ailments, some of them are follows: flu, fever, kidney stones, ear pain, ovarian cysts, asthma, stomach pain, cough, diarrhea, vomiting, common cold, chikungunya, skin fungus, boils, skin infections and wounds, ovarian inflammation, tonsillitis, insect bites, sores, shingles, toothache, parasitic infections, bone fractures, inflamed colon, stomach gas, strokes diabetes, cancer, arthritis, hypertension, scabies, hemorrhoids, abundant gynecological hemorrhages, insomnia, hair loss, headaches, rashes, triglyceride and cholesterol issues, circulation problems, hepatitis, facial paralysis, measles, rubella, belly pain, lechina, rhinitis, infertility, headache, sinusitis, mumps, swollen glands, and conjunctivitis. Notably, the most common ailments reported are colds and gastrointestinal conditions.

# Discussion

Through this study, the use of 116 species of medicinal plants, with many belonging to the Lamiacea family, to treat more than 50 health conditions was reported. The plant species with the highest frequency of TRAMIL Meaningful Use were oregano orejón (*Coleus amboinicus* Lour.) (68.29%) and malojillo [*Cymbopogon citratus* (D.C.) Stapf.] (60.97%).

Similar studies, such as that conducted by Soria et al. (2020), which involved an ethnobotanical study in family health units in Caaguazú, Paraguay, using the Meaningful Use TRAMIL (UST) method, identified 54 botanical families, corresponding to 93 genera and 116 species, being Asteraceae the best represented with 17 genera and 21 species. The native species with the highest consensus index was *Lippia alba*, highlighting that the conditions treated with medicinal species were mainly stomach pains and non-communicable diseases such as high cholesterol, uric acid, and anxiety states.

Ibarguen (2021), in his work in Chocó, Istmina municipality, Colombia, applying the TRAMIL survey, also found Asteraceae and Lamiaceae among the botanical families with the highest number of species used.

Aguaiza Quizhpilema and Simbaina Solano (2021) mapped various plants of therapeutic use of great importance in public health by conducting a study on medicinal plants and ancestral knowledge in rural communities in the province of Cañar, Ecuador, describing 87 plants with promising therapeutic potential. These plants are considered useful in the traditional medicine of Cañar, for which they suggest conserving, preserving, propagating, and researching prophylactic doses for these plants.

Similarly, Coronado-Peña and Román (2022) carried out a study applying a TRAML survey in Arauca, Colombia and found that the most used botanical families are Lamiaceae, Asteraceae, Rutaceae, Euphorbaceae, and Fabaceae, which coincides with the five most used botanical families in this study.

Gutiérrez Nava et al. (2023) conducted an ethnobotanical study based on 73 ethnobotanical surveys conducted randomly on pilgrims (key informants) who arrived at the Basilica of Guadalupe on December 12, 2022. The analysis of the results was performed based on the states of precedence of the key informants who attended, where the information was obtained from 10 states throughout the Mexican Republic, registering 24 plant species in the ethnobotanical analysis. It was agreed that the medicinal plant with the highest rate of consensus to treat disorders of the digestive system was Chamomile (*Matricaria recutita*), due to its anti-inflammatory, sedative, antispasmodic, and antimicrobial activities.

In general, this study shows that most of the medicinal plants in this community are prepared in the form of decoction; however, there are other forms of preparation, such as raw extraction, maceration, and infusion. While the administration of these preparations is mostly done orally or topically, although the forms of combining these preparations vary.

In relation to the parts of the plants indicated as the most used in the popular preparations, leaves were predominantly the most used, followed by the use of the root.

Gutiérrez Nava et al. (2023), in a study carried out with data obtained from several Mexican states, indicated that leaves were the most used part of the plant therapeutically with 71%, together with inflorescences which represent 11%.

When comparing the report of health conditions or uses, collected in this sample, with other research, it can be noted that, in the community of El Onoto, they treat more than 50 conditions with medicinal plants, while in other areas of the country, they report less health conditions treated with medicinal plants. An example of this is the research conducted in the Macoyal peasant community in Trujillo, where 99 people were interviewed and 20 uses were reported (Bermúdez and Velásquez, 2002). The result obtained could be related to the absence in the community of a health center, having to solve in a practical and timely manner with medicinal plants. This same idea is also developed in the research conducted by Gallegos (2016), where he expresses that, in the case of rural populations, the people face more restrictions in accessing medicines for several reasons, including difficulty in accessing a pharmacy and/or a health center, as is the case of the study community.

The informants expressed that they use mixtures of plants to treat a health condition and emphasize that they have the perception that several plants maximize their medicinal properties and combine them with the use of drugs prescribed by physicians. Morales Pérez et al. (2022) state that the active ingredients of medicinal plants can interact with the components of any other synthetic drug used at the same time and cause adverse reactions, aggravating the health situation of the consumer.

The mixture of drugs and medicinal plants, as is the case referred to by some of the participants in the study, seeking to reinforce the healing capacity of these remedies on the health condition, can generate the appearance of antagonistic actions between them or, worse, trigger a negative reaction in the person who consumes them. Definitely, this is an issue that must be addressed to ensure that families have a reliable tool at hand to take care of their health, in the event that they require it or that they so desire, but that it is efficient and safe.

According to the World Health Organization (OMS, 2014), the primary healthcare of up to 80% of the population in developing countries is based on traditional medicine, due to cultural tradition or because there are no other options, and in the case of rich countries, many people resort to various types of natural remedies because they consider natural to be synonymous with harmless. However, there are studies that point out the importance of making an effort to know and correctly handle the scientific name of plants of popular use, showing valid identifications of species and botanical families cultivated globally for their ornamental and medicinal value, in order to have greater safety and efficacy when using them (Orsini, 2021).

The gender of the people surveyed in this research was distributed among 29 women and 12 men, in which all of them presented a strong attachment to their community, where most of them were born there, or have been living in the area for more than 28 years and also come from nearby rural areas. As in this study, Díaz Mariñas (2019) conducted an ethnobotanical study in the village of La Manzanilla, San Marcos—Cajamarca in Peru, traditional knowledge resides in greater proportion in the female sex, since in this study of 15 people interviewed, 10 were women, suggesting the importance of women in the transmission of traditional knowledge.

The results obtained in this study can be analyzed in two ways. First, it may be that culturally, there is a great interest in medicinal plant species and their uses. On the other hand, the socioeconomic conditions of this community and the non-existence of a health center force the population to use them, and it may happen that this reality is not based on the traditional knowledge of the local resources of the community, but rather distorted with information from various sources on the use of medicinal plants for the care of different health conditions, thus favoring the dispersion of this knowledge about them. In relation to the importance of preserving traditional knowledge, a relevant strategy to achieve this objective is to involve the new generations in the knowledge about medicinal plants. In this regard, Guarnizo-Losada et al. (2022) point out that ethnobotanical studies in school environments are still scarce for many countries and regions; however, they emphasize that it is of great importance to continue recognizing ancestral knowledge and the valuable contributions made by the children from indigenous communities in schools regarding the use and management of plants. This is also valid for rural communities, making it possible to work from the link between the elders of the community with parents and the community in general, as a way of safeguarding the historical memory of the regions.

Knowing and documenting where medicinal plants are obtained, that is, their origin and distribution, provide tools that allow researchers and the community in general, to design short, medium, and long term conservation strategies, integrating the local knowledge of ethnic groups, which has been transmitted from generation to generation, thereby contributing to the permanence of medicinal plant species so that future generations can make use of local knowledge (Ruiz-Rosado et al., 2023).

The people participating in the research expressed that they received knowledge about medicinal plants from a family member or neighbor who knows about them, so they say they have confidence in medicinal plants and in the care of their health through this channel.

In this regard, it is essential to reflect on the role of biodiversity and the use of medicinal plants by communities. While it is true that a large proportion of the species used as medicinal plants are cultivated plants, many of them, in a considerable percentage, are wild plants that have proven medicinal properties or have been pointed out by popular knowledge (Fuentes, 2004). Jaime Muñoz (2019) points out that the geography of health acquires a relevant role in the compression of geographic space as a point of analysis for a better knowledge, compression, and analysis of the interaction of people's health with the location, and the spatial distribution of elements in the territory.

Several investigations have highlighted the use of medicinal plants as a primary option for health in rural communities, in addition to highlighting the need for the conservation of knowledge about the use of these plants and in many cases proposing how their use serves as a basis for their continued use as a therapeutic alternative (Soria et al., 2020; Lorenzo-Barrera et al., 2023; Trigueros-Vázquez et al., 2023).

Trigueros-Vázquez et al. (2023) point out that, even with official medical services, members of the Mochó and Kakchikel ethnic groups of the Sierra Mariscal, Chiapas, Mexico use and conserve plants for their medicinal properties. The study conducted by these researchers used ethnographic and ethnobotanical methodology to conclude that 97% of both ethnic groups use medicinal plants and obtain them mostly from their agroecosystems.

In the households surveyed, there is a high percentage of use of medicinal plants, which may express their strong attachment to their local traditional medicine, but, on the other hand, also suggests the absence in the community of a conditioned health center to which they can go. As a result, in many cases, the reality leads to an accelerated loss of species, which are part of the biodiversity of various areas and countries, affecting the conservation of various ecosystems, the preservation of their ancestral knowledge, and, therefore, the direct benefit to its inhabitants for the primary healthcare needs.

Carballo et al. (2005) point out that, sometimes, the increase in the use of manufactured products has resulted in a decrease in the consumption of traditional preparations with medicinal plants, but in most rural areas, traditional folk medicine is still used to the same or greater extent than pharmaceutical formulations. In some cases, traditional treatments replace academic medicine. In this regard, Jaime Muñoz (2019) reports that, in research conducted in rural communities in Chile, the people interviewed claim to prioritize the use of medicinal plants for treating health conditions, before seeking care at health centers. This is reflected in the fact that, in most cases, they maintain orchards or gardens containing medicinal plants.

The rural community where the research was carried out has stated through interviews that they use plants with medicinal use to alleviate diseases, so, in most of the houses, there is a garden or an orchard where people grow these plants.

## Conclusion

The community of El Onoto de El Valle de Tucutunemo, Aragua State, Venezuela exhibits a notable utilization of medicinal plant species in their instance to treat different health conditions, with the predominant focus on treating flu and stomach ailments. It is important to highlight that all individuals approached through various information collection instruments reported using medicinal plants, both individually and within their families, spanning a wide range of ages from children to the elderly. This reflects that the use of medicinal plants is part of their cultural heritage and ancestral roots.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Ethics statement

The studies involving humans were approved by Bioethics Committee of the Instituto de Estudios Cientificos y Tecnologicos (IDECYT)-UNESR. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

OM: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Data curation, Validation, Writing – review & editing. IT: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Supervision.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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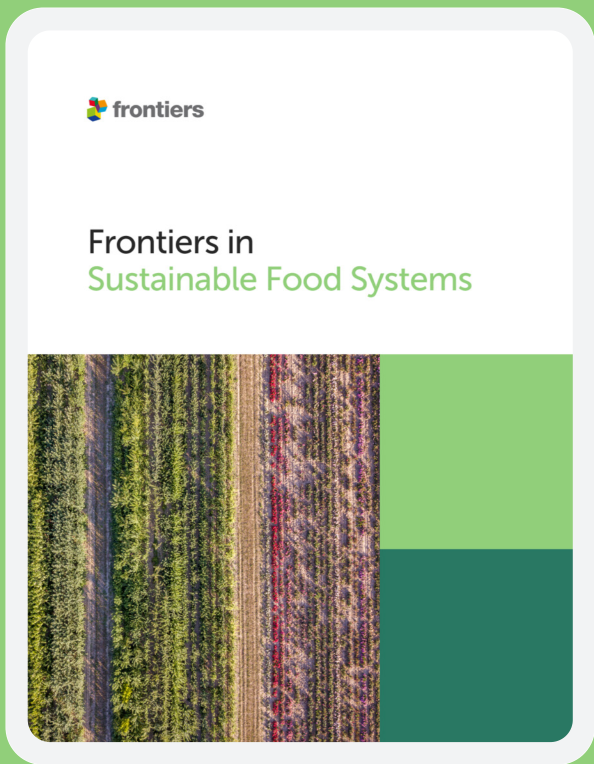


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