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Sustainability of dairy farming in Colombia's High Andean region

Claudia Durana[1]*, Enrique Murgueitio[2]* and Bernardo Murgueitio[3]*

[1]Facultad Estudios Ambientales y Rurales. Universidad Javeriana, Bogotá, Colombia, [2]Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria – CIPAV, Cali, Colombia, [3]Department of Geography, Universidad Nacional de Colombia, Bogotá, Colombia

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*CORRESPONDENCE
Claudia Durana
✉ durana.claudia@javeriana.edu.co
Bernardo Murgueitio
✉ bernardomurgueitiocalle@gmail.com
Enrique Murgueitio
✉ enriquem@fun.cipav.org.co

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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.

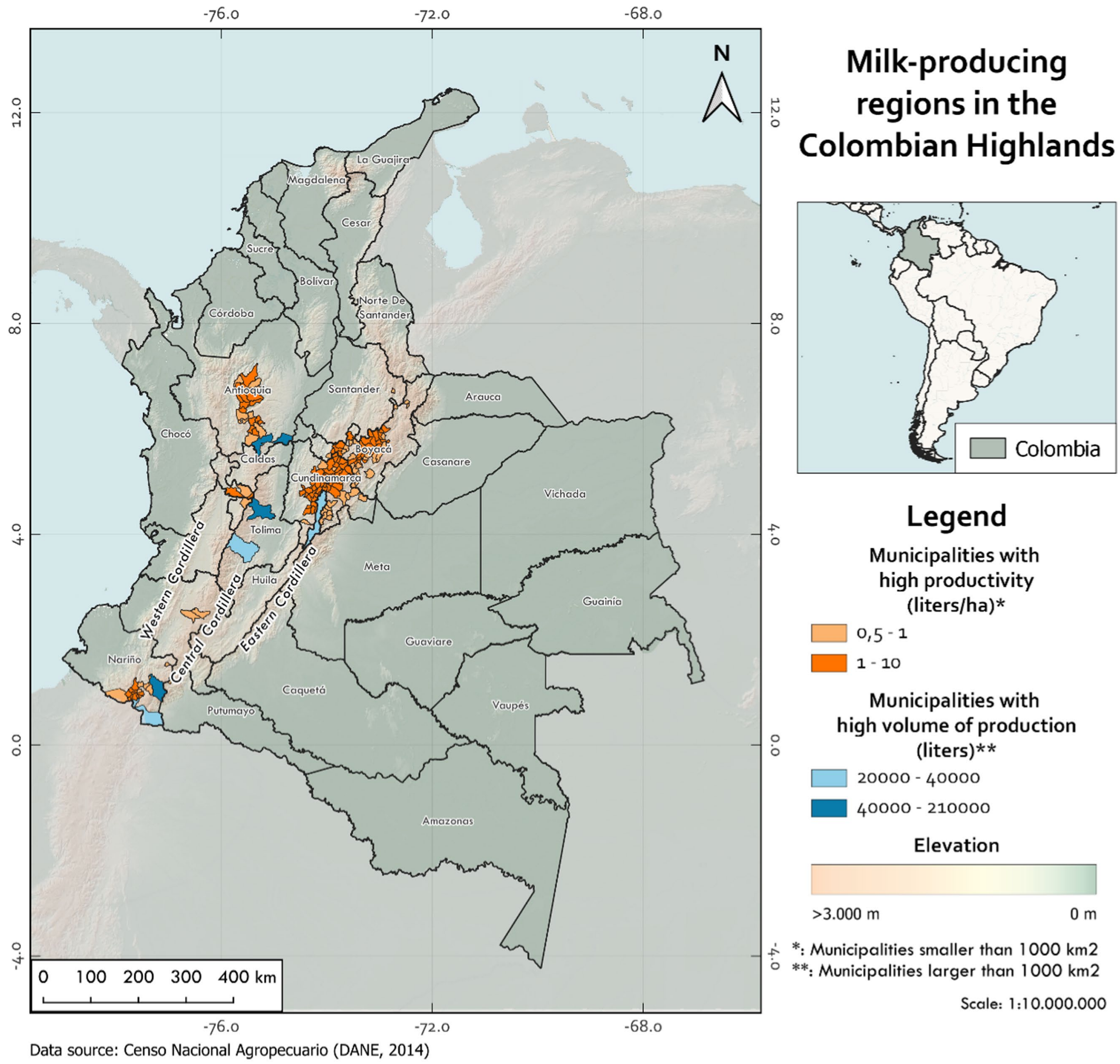
The definition of the High Andean region ecosystem varies according to the mountain range and authors' classification, with altitudes between 2,000 and 3,700 meters above sea level (Rodríguez et al., 2006). Here, references made to the High Andean region correspond to the mountainous areas of the Andes 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).

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 Overgrazing Permanent grazing in areas with moderate to high slopes No tillage or rotation with monocultures Use of fire to control shrubbery and plant life	Deforestation (when new areas are opened for production) Soil erosion and compaction Genetic uniformity due to gramineous monoculture Pressure on forest ecosystems due to the demand for wood and the entry of livestock into micro-watersheds 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 Mechanized tillage with inadequate tools/machinery (disc plows and others) Improved pastures Use of silos and hay Specialized animal genetics Livestock supplementation with concentrates (imported raw materials) Chemical fertilization in high doses Use of pesticides (herbicides and pesticides) Sprinkler or gravity irrigation.	Soil compaction Emission of enteric gases (CH_4) Higher GHG emissions due to fertilization and excess excreta in milking areas (N_2O) Loss of biodiversity due to the use of pesticides and antiparasitic products Contamination due to the use of antibiotics and hormones Ecological footprint of grain supplementation Water and soil contamination due to the use of synthetic fertilizers and pesticides 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).

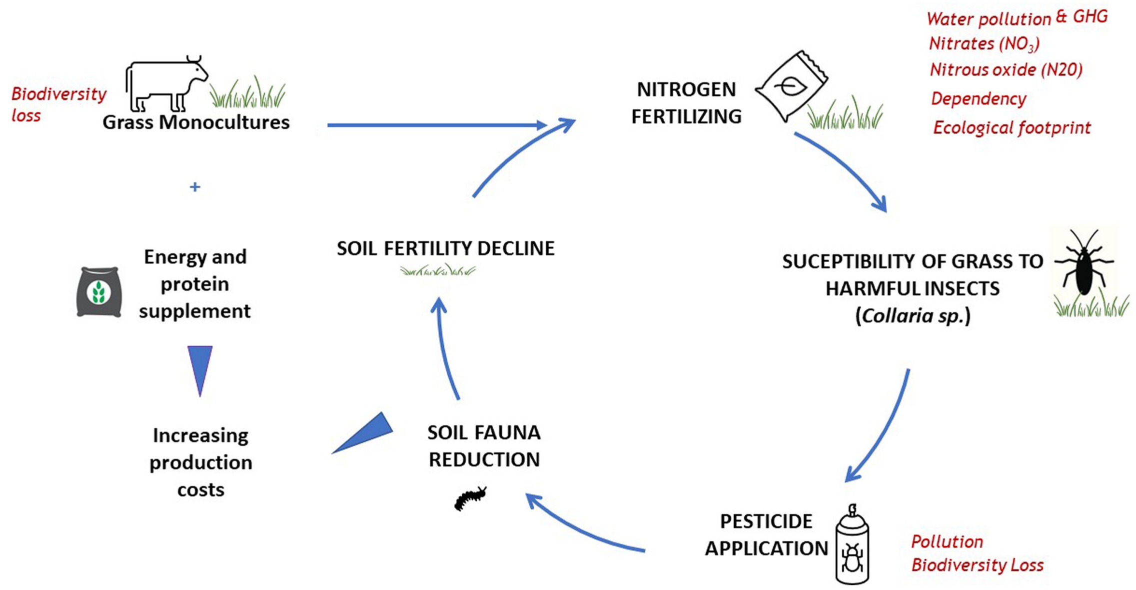


FIGURE 1
Vicious cost cycle of conventional intensification and environmental effects of milk production. Source: Author's elaboration from Lopera-Marín et al. (2020), Rodríguez et al. (2019), and Lopera et al. (2015).

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

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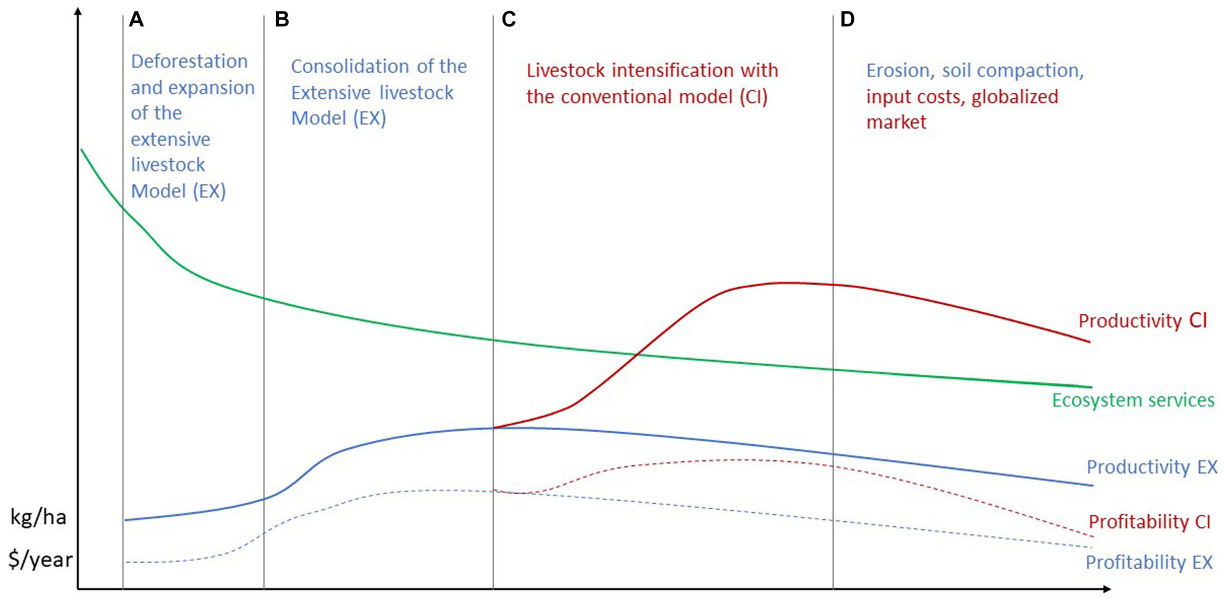

FIGURE 2
Diagram of temporal trends in productivity, profitability, and ecosystem services with extensive (EX) and conventional intensification (CI) models of cattle ranching in the High Andean regions. Author's elaboration from Cadena et al. (2019), Carulla and Ortega (2016), Holmann et al. (2003),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

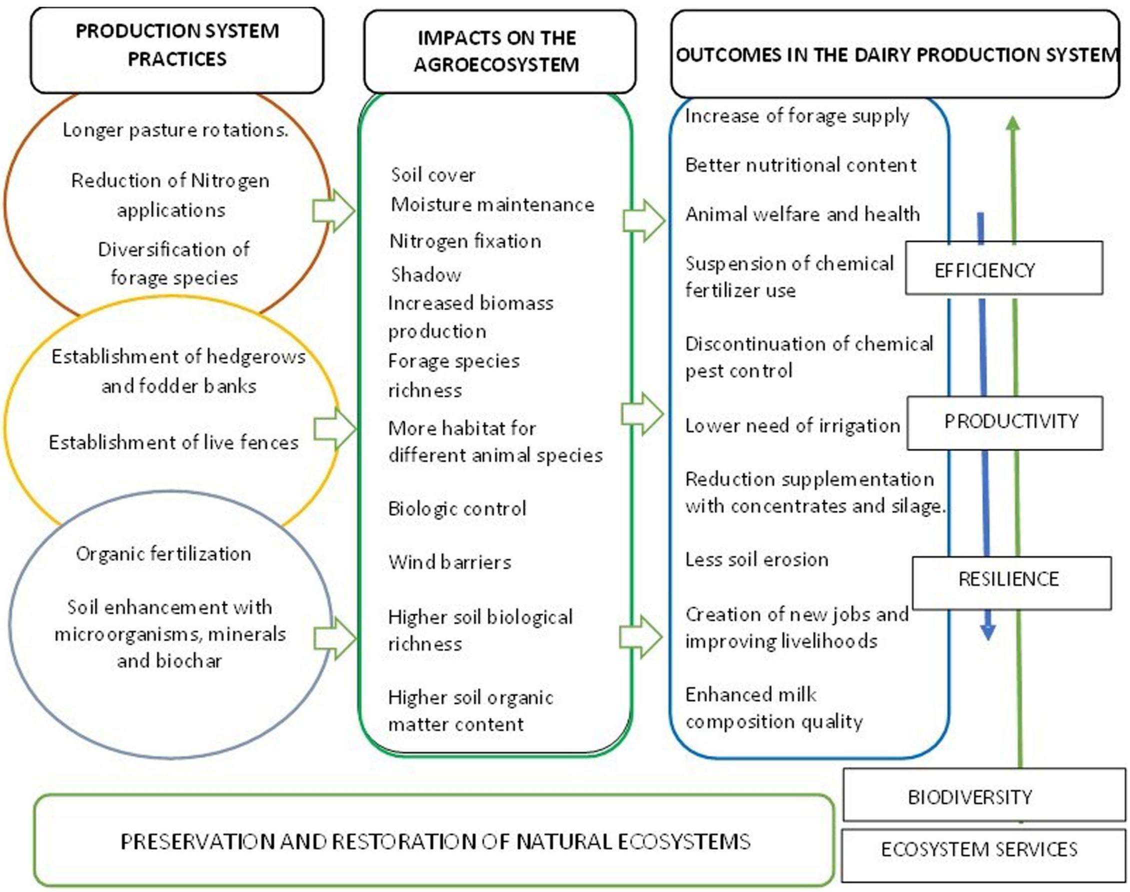

FIGURE 3
Production practices, impacts on the agrecosystem, and outcomes of agroecological and conservation management in high-altitude dairy silvopastoral systems. Source: Author's elaboration from Durana et al. (2022), Lopera et al. (2015), and Pezo and Ibrahim (1998).

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

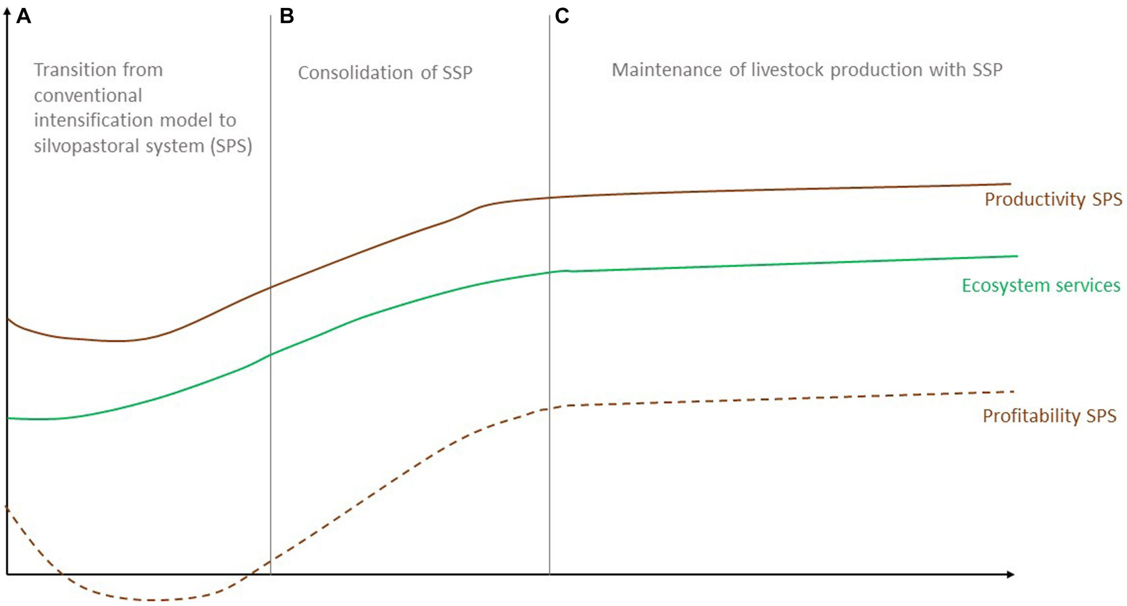

FIGURE 4
Behavior over time of the agroecological shift from a conventional model to a silvopastoral system. Source: Author's elaboration from Reyes et al. (2017), Lopera et al. (2015), and Pezo (2019).

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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References

Altieri, M. A. (2005). The myth of coexistence: why transgenic crops are not compatible with agroecologically based systems of production. *Bull. Sci. Technol. Soc.* 25, 361–371. doi: 10.1177/0270467605277291

Altieri, MA (2013). Construyendo resiliencia socio-ecológica en agroecosistemas: algunas consideraciones conceptuales y metodológicas. En: *Agroecología y Resiliencia Socioecológica: adaptándose al cambio climático*. Ed: Clara Inés Nicholls and Leonardo Alberto Ríos y Miguel Ángel Altieri. Red Iberoamericana de Agroecología para el Desarrollo de Sistemas Agrícolas Resilientes al Cambio Climático (REDAGRES), Red Adscrita al Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), Sociedad Científica Latinoamericana de Agroecología (SOCLA): Medellín–Colombia. pp. 94–104.

Altieri, MA, and Nicholls, CI (2022). *Agroecología, policrisis global y la transformación de los sistemas alimentarios*. Centro Latinoamericano de Investigaciones Agroecológicas (CELIA): Medellín, Colombia.

Altieri, MA, Nicholls, C, and Funes, F (2012). Agroecología: única esperanza para la soberanía alimentaria y la resiliencia socioecológica. Sociedad Científica Latinoamericana de Agroecología (SOCLA) Rio+20 Position paper presented at the Rio+20 United Nations Conference on Sustainable Development, Rio de Janeiro

Angulo-Arizala, J., Nemocón-Cobos, A. M., Posada-Ochoa, S. L., and Mahecha-Ledesma, L. (2021). Producción, calidad de leche y análisis económico de vacas Holstein suplementadas con ensilaje de botón de oro (*Tithonia diversifolia*) o ensilaje de maíz. *Biotecnología En El Sector Agropecuario Y Agroindustrial*. 20, 1–13. doi: 10.18684/bsaa.v.n.1535

Aynekulu, E., Suber, M., van Noordwijk, M., Arango, J., Roshetko, M., and Rosenstock, T. S. (2020). Carbon storage potential of silvopastoral systems of Colombia. *Land* 9:309. doi: 10.3390/land9090309

Balvanera, P, Hall, J, Raudsepp-Hearne, C, Van Bael, S, Murgueitio, E, and Calle, Z (2015). "La importancia de los servicios ecosistemicos para la sociedad." in *La gestion de las cuencas hidrograficas para asegurar los servicios ecosistemicos en las laderas del Neotropico*. eds. J. S. Hall, V. Kirn and E. Yanguas-Fernandez. Balboa, Panama: Instituto Smithsonian de Investigaciones Tropicales. 53–64.

Benavides, LM (2016). Análisis energético y balance de nitrógeno a escala predial en sistemas ganaderos de lechería especializada en el norte de Antioquia con diferentes niveles de intensificación (Doctoral dissertation). Available at: https://repositorio.unal.edu.co/handle/unal/58883

Broom, D. M., Galindo, F. A., and Murgueitio, E. (2013). Sustainable, efficient livestock production with high biodiversity and good welfare for animals. *Proc. Biol. Sci.* 280:20132025. doi: 10.1098/rspb.2013.2025

Buytaert, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J., et al. (2006). Human impact on the hydrology of the Andean páramos. *Earth Sci. Rev.* 79, 53–72. doi: 10.1016/j.earscirev.2006.06.002

Cadena, X, Reina, M, and Rivera, A (2019). *Precio regulado de la leche: ineficiencias, costos y alternativas*. Bogotá: Fedesarrollo, 91 p.

Calle, A. (2020). Can short-term payments for ecosystem services deliver long-term tree cover change? *Ecosyst. Serv.* 42:101084. doi: 10.1016/j.ecoser.2020.101084

Calle, A., and Holl, K. (2019). Riparian Forest recovery following a decade of cattle exclusion in the Colombian Andes. *For. Ecol. Manag.* 452. doi: 10.1016/j.foreco.2019.117563

Calle, Z., Murgueitio, E., and Chará, J. (2012). Integrating forestry, sustainable cattle-ranching and landscape restoration. *Unasylva* 63, 31–40.

Calle, Z., Murgueitio, E., Chará, J., Molina, C. H., Zuluaga, A. F., and Calle, A. (2013). A strategy for scaling-up intensive silvopastoral systems in Colombia. *J. Sustain. For.* 32, 677–693. doi: 10.1080/10549811.2013.817338

CAR (2009). *Plan de ordenación y manejo de la cuenca del Rio Negro Departamento de Cundinamarca. Documento Diagnóstico Prospectiva y Formulación*. Bogotá: Corporación Autónoma Regional de Cundinamarca.

Cárdenas, E. (2003). Estrategias de la investigación en forrajes de tierra fría en Colombia y avances en la Universidad Nacional de Colombia-Bogotá. *Rev. Med. Vet. Zoot.* 50, 20–24. doi: 10.15446/rfmvz

Cárdenas, E. (2011). *Lotus; nueva leguminosa forrajera para los sistemas lecheros de clima frío y zonas templadas*. Bogotá: Universidad Nacional de Colombia, Editorial Produmedios. (2011)

Carulla, J. E., and Ortega, E. (2016). Sistemas de producción lechera en Colombia: retos y oportunidades. Arch Latinoam. *Prod. Anim.* 24, 83–87.

Castro, E., Carulla, J., and Cárdenas, E. (2021). Productive potential of *Lotus uliginosus* in specialized dairy systems at the high altitudes of Colombian Andes. *Irish J. Agric. Food Res.* 48, 277–287.

Céspedes, C, Infante, A, and Espinoza, S. (2021). Principios y prácticas de sistemas productivos con criterios agroecológicos. En: CL Cecilia and VS Sigrid (Eds.). *Agroecología. Fundamentos y técnicas de producción, y experiencia en la Región de los Ríos. Chile. Libro INIA N° 45, 370 p*. Instituto de Investigaciones Agropecuarias: Osorno, Chile.

Chará, J, and Giraldo, C (2011). *Servicios Ambientales de la Biodiversidad en Paisajes Agropecuarios*. Fundación CIPAV, Cali. 76:46.

Chará, J., and Murgueitio, E. (2005). The role of silvopastoral systems in the rehabilitation of andean stream habitats. *Livest. Res. Rural. Dev.* 17.

Chará, J., Reyes, E., Peri, P., Otte, J., Arce, E., and Schneider, F. (2019). Silvopastoral systems and their contribution to improved resource use and sustainable development goals: evidence from Latin America. *FAO, CIPAV and Agri Benchmark Cali* 60:46. Licence: CC BY-NC-SA 3.0 IGO

Chará, J., Rivera, J. E., Barahona, R., Murgueitio, E., Deblitz, C., Reyes, E., et al. (2017). "Intensive silvopastoral systems: economics and contribution to climate change mitigation and public policies" in *Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty. Advances in agroforestry*. ed. F. Montagnini (Dordrecht: Springer), 395–416.

Chaves, M. E., Santamaría, M., and Sánchez, E. (2007). *Alternativas para la conservación y uso sostenible de la biodiversidad en los Andes de Colombia. Resultados 2001-2007*. Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Correal Urrego, G, and Van der Hammen, T (1977). *Investigaciones arqueológicas en los abrigos rocosos del Tequendama*. Bogotá: Banco Popular.

DANE (2014). Censo Nacional Agropecuario. Available at: https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/censo-nacional-agropecuario-2014

De Haan, C., Steinfeld, H., and Blackburn, H. (1977). *Livestock and the environment: finding a balance*. Rome, Italy: Food and Agriculture Organization of the United Nations, the United States Agency for International Development, and the World Bank.

Dietl, W, Fernández, F, and Venegas, C (2009). *Manejo Sostenible de Praderas. Su flora y vegetación. Boletín INIA 187*. Santiago: ODEPA.

Durana, C (2011). *Ganadería sostenible en fincas lecheras. Revista Colanta Pecuaria*. Medellín, Colombia: Colanta. 34, 76–88.

Durana, C, Egolf, P, Murgueitio, E, and Colcombet, L (2019). Factores socioculturales e institucionales para el escalamiento de Sistemas silvopastoriles: experiencias en el Nordeste Argentino (NEA) y Colombia. En: J. Rivera, P. Peri, J. Chará, M. Díaz, L. Colcombet and E Murgueitio. *X Congreso internacional sobre sistemas silvopastoriles: por una producción sostenible*. Libro de Actas. Editorial CIPAV, Cali. 556–566.

Durana, C., Lopera-Marín, J. J., Coronado, A., Murgueitio, E., and Galindo, A. (2022). Partial replacement of balanced feed by Sambucus peruviana forage in cows' dairy farms: case study in the high Andean zone in Colombia. *Livest. Res. Rural. Dev.* 34

Escobar, M I, Navas Panadero, A, Medina, C A, Corrales Álvarez, J D, and Tenjo, A I y Borrás Sandoval, LM. (2020). Efecto de prácticas agroecológicas sobre características del suelo en un sistema de lechería especializada del trópico alto colombiano. *Livest. Res. Rural. Dev.* 32:58.

Etter, A., and Van Wyngaarden, W. (2000). Patterns of landscape transformation in Colombia with emphasis in the Andean Region. *AMBIO A J Hum Environ* 29:432. doi: 10.1579/0044-7447-29.7.432

FAO (2018). Modelo de Evaluación Ambiental de ganadería Mundial. Resultados versión 2.0. Organización de las Naciones Unidas para la Alimentación y la Agricultura. Available at: http://www.fao.org/gleam/results/es/

FEDEGAN (2006). *Plan Estratégico de la Ganadería Colombiana 2019*. Bogotá, Colombia: Federación Colombiana de Ganaderos

FEDEGAN (2015) *Foro Internacional de Leche, Bogotá*. Alpina-Cámara de Comercio de Bogotá. Mayo.

FEDEGAN (2019). Cifras de referencia en. Available at: www.fedegan.org.co

FEDEGAN–Fondo Nacional del Ganado (2021). Cifras de referencia del sector ganadero colombiano. Available at: www.fedegan.org.co.

FEDEGAN–Fondo Nacional del Ganado (2022). Cifras de referencia del sector ganadero colombiano, Bogotá, Colombia. 134. Available at: www.fedegan.org.co.

Frossasco, G, Garcia, F, and Odorizzi, A., Ferrer Martinez, J, and Brunetti, M y Echeverría, A, (2015). *Evaluación de distintos sistemas lecheros intensivos*. Ediciones INTA, EEA Manfredi, Córdoba.

Funes-Monzote, F (2008). *Farming like we're here to stay the mixed farming alternative for Cuba*. PhD thesis. Wageningen: Wageningen University.

Gachetá, J C, Castillo, J L, and Ramírez, J (2018). *Prácticas de producción limpia para mejorar la calidad de pastos y leche en pequeños productores ganaderos de Sesquilé*, Cundinamarca. - Primera edición. Universidad Nacional de Colombia. Facultad de Ciencias Agrarias. 102 p.

Galindo, V. M., Calle, Z., Chará, J., and Ambrecht, I. (2017). Facilitation by pioneer shrubs for the ecological restoration of riparian forests in the Central Andes of Colombia. *Restor. Ecol.* 25, 731–737. doi: 10.1111/rec.12490.ISSN:1526-100X

Galindo, A., and Murgueitio, E. (2007). Reducción ganadera en los páramos, una contribución a la adaptación de la alta montaña al cambio climático. En: *IDEAM Memorias de la Primera Conferencia Internacional de Cambio Climático: Impacto en los sistemas de alta montaña*. IDEAM, Embajada de Suiza en Colombia y Universidad de Zurich. Imprenta Nacional. Bogotá, DC: IDEAM. pp. 189–206.

Galindo, A, Uribe, F, and Murgueitio, E (2019). *Fincas demostrativas Proyecto Ganadería Colombiana Sostenible. ©Editorial CIPAV*. Cali, Colombia: Editorial CIPAV. 104

Gallego, L., Mahecha, L., and Angulo, J. (2017). Producción, calidad de leche y beneficio: costo de suplementar vacas holstein con *Tithonia diversifolia*. *Agronomía Mesoamericana* 28:357. doi: 10.15517/ma.v28i2.25945

Garzón, J. E., and Cárdenas, E. A. (2013). Emisiones antropogénicas de amoniaco, nitratos y óxido nitroso: compuestos nitrogenados que afectan el medio ambiente en el sector agropecuario colombiano. *Revista de la Facultad de Medicina Veterinaria y de Zootecnia* 60, 121–138.

Gerber, PJ, Steinfeld, H, Henderson, B, Mottet, A, Opio, C, Dijkman, J, et al. (2013). *Hacer frente al cambio climático a través de la ganadería – Evaluación global de las emisiones y las oportunidades de mitigación*. FAO, Roma.

Giampietro, M (2015). *Multi-Scale Integrated Analysis of Agroecosystems*. Boca Raton: CRC Press.

Giampietro, M., and Mayumi, K. (2000). Multiple-scale integrated assessment of societal metabolism: introducing the approach. *Popul. Environ.* 22, 109–153. doi: 10.1023/A:1026691623300

Giraldo, N. V., and Chará, J. (2022). Efecto de los sistemas silvopastoriles intensivos en la reducción de la degradación física y biológica del suelo. *Livest. Res. Rural. Dev.* 34:17

Giraldo, C, Chará, J, Uribe, F, Gómez, JC, Gómez, M, Calle, Z, et al. (2018) Ganadería Colombiana Sostenible: entre la productividad y la conservación de la biodiversidad. G. Halffter and M. Cruz y C. Huerta (eds). *Ganadería sustentable en el Golfo de México*. Instituto de Ecología, A.C.: México, Pp. 35–64

Gliessman, S (2002) *Agroecology: Ecological Processes in Sustainable Agriculture*. Turrialba-Costa Rica: CATIE.

Global Agenda for Sustainable Livestock [GASL] (2014). Towards sustainable livestock. Available at: http://www.livestockdialogue.org/fileadmin/templates/res_livestock/docs/2014_Colombia/2014_Towards_Sustainable_Livestock-dec.pdf

Gómez, D (2014). *Caracterización, pronóstico y alternativas de manejo de las heladas en el sistema de producción lechero del valle de Ubaté y Chiquinquirá (Colombia. Tesis de Grado de Magister en Ciencias-Metereología)*. Universidad Nacional de Colombia Facultad de Ciencias, Departamento de Geociencias: Bogotá DC., Colombia.

Guatusmal-Gelpud, C., Escobar-Pachajoa, L., Meneses-Buitrago, D., Cardona-Iglesias, J., and Castro-Rincón, E. (2020). Producción y calidad de Tithonia diversifolia y *Sambucus nigra* en trópico altoandino colombiano. *Agronomía Mesoamericana* 31, 193–208. doi: 10.15517/am.v31i1.36677

Guhl, E (1959). *Distribución geográfica de la vegetación. Atlas de Economía Colombiana (Primera entrega)*. Bogotá: Banco de la República.

Hall, J, Kirn, V, and Yanguaz Fernández, E (2015). La Gestión de Cuencas Hidrográficas Para Servicios Ecosistémicos En Las Laderas de Los Neotrópicos. Instituto Smithsonian de Investigaciones Tropicales.

Herrero, M., Thornton, P., Gerber, P., and Reid, R. (2009). Livestock, livelihoods, and the environment: understanding the trade-offs. *Curr. Opin. Environ. Sustain.* 1, 111–120. doi: 10.1016/j.cosust.2009.10.003

Holmann, F., Rivas, L., Carulla, J., Rivera, B., Giraldo, L. A., Guzmán, S., et al. (2003). Evolution of milk production systems in tropical Latin America and its interrelationship with markets: an analysis of the colombian case (en línea). *Livest. Res. Rural. Dev.* 15

Hurtado, G, and Gonzalez, O. (2011). *Evaluación de la afectación territorial de los fenómenos El Niño/La Niña y análisis de la confiabilidad de la predicción climática basada en la presencia de un evento*. Bogotá: Intituto de hidrología, meteorología y estudios ambientales-IDEAM.

Huss, D, Bernardon, A, and Anderson, D, y Brun, J. (1996). *Principios de manejo de praderas naturales [en línea]*. Santiago: FAO.

ICA-Fedegán. (2020). Censo Pecuario Nacional-2019. Censo bovino en Colombia. Instituto Colombiano Agropecuario. Available at: https://www.ica.gov.co/areas/pecuaria/servicios/epidemiologia-veterinaria/censos-2016/censo-2019.aspx

IDEAM, IGAC, IAVH, INVEMAR, SINCHI e IIAP. (2007). *Ecosistemas continentales, costeros y marinos*. Bogotá, D.C.: Imprenta Nacional de Colombia.

IDEAM, PNUD, MADS, DNP, Cancillería de Colombia (2015). *Nuevos Escenarios de Cambio Climático para Colombia 2011–2100 Herramientas Científicas para la Toma de Decisiones–Enfoque Nacional-Regional: Tercera Comunicación Nacional de Cambio Climático*. Bogotá, Colombia: IDEAM.

IGAC (2015). *Suelos y tierras de Colombia*. Bogota DC, Colombia: Instituto Geográfico Agustín Codazzi.

Infante, A (2021). Diseño de sistemas productivos agroecológicos. En: CL Cecilia and VS Sigrid (Eds.). *Agroecología. Fundamentos y técnicas de producción, y experiencia en la Región de los Ríos. Chile. Libro INIA N° 45, 370 p*. Instituto de Investigaciones Agropecuarias. Osorno, Chile.

Josse, C, Cuesta, F, Navarro, G, Barrena, V, Cabrera, E, Chacón-Moreno, E, et al. (2009). *Ecosistemas de los Andes del Norte y Centro: Bolivia Colombia Ecuador, Perú y Venezuela*. Lima: Secretaría General de la Comunidad Andina Programa Regional ECOBONA-Intercooperation, CONDESAN-Proyecto Páramo Andino, Programa BioAndes, EcoCiencia NatureServe, IAvH, LTA-UNALM, ICAE-ULA CDC-UNALM, RUMBOL SRL.

Lentijo, G. M., Velásquez, A., Murgueitio, E., Zuluaga, A. F., and Gómez, M. (2022). *Ganadería para las aves: un canto a la sostenibilidad*. Bogotá, Colombia: Audubon, FEDEGAN, CIPAV, TNC. Puntoaparte Editores, 53.

León-Siccard, T (2014). *Perspectiva ambiental de la agroecología. La ciencia de los agroecosistemas*. Bogotá: Universidad Nacional de Colombia, IDEA. 398 pp.

León-Siccard, T (2021). *La Estructura Agroecológica Principal de los agroecosistemas: perspectivas teórico-prácticas*. Bogotá: Universidad Nacional de Colombia, Sede Bogotá; Instituto de Estudios Ambientales-IDEA Sede Bogotá. 223 p.

Llanos, E., Astigarraga, L., and Picasso, V. (2018). Energy and economic efficiency in grazing dairy systems under alternative intensification strategies. *Eur. J. Agron.* 92, 133–140. doi: 10.1016/j.eja.2017.10.010

Lopera, J. J., Márquez, S. M., Ochoa, D. E., Calle, Z., Sossa, C. P., and Murgueitio, E. (2015). Producción agroecológica de leche en el trópico de altura: sinergia entre restauración ecológica y sistemas silvopastoriles. *Revista Agroecología* 10, 79–85.

Lopera-Marín, J. J., Durana, R. C., Davidson, I. A., Lopera, O. A., Sossa, C. P., Galindo, O. A., et al. (2020). Manejo de los chupadores del kikuyo con transición agroecológica: Dos fincas silvopastoriles en laderas altoandinas orientadas hacia la ganadería sostenible enfrentan los insectos chupadores del kikuyo. *Revista DeCARNE* 47, 56–63.

MADR and MADS (2021). Lineamientos de política para la ganadería bovina sostenible—GBS 2021–2050. *Bogotá* 2021:50.

Mahecha, L., and Angulo, J. (2012). "Nutrient management in silvopastoral systems for economically and environmentally sustainable cattle production: a case study from Colombia" in *Soil fertility improvement and integrated nutrient management-A global perspective*. ed. J. K. Whalen (London, UK: Intech. 201–216.

Mahecha, L., Londoño, J., and Angulo, J. (2021). Agronomic and nutritional assessment of an intensive silvopastoral system: *Tithonia Diversifolia*, *Sambucus nigra*, *Cynodon nlemfuensis*, and *Urochloa plantaginea*. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* 92, 37–47. doi: 10.1007/s40011-021-01282-7

Malagón, D. (2003). Ensayo sobre tipología de suelos colombianos. Énfasis en génesis y aspectos ambientales. *Revista Academia Colombiana de Ciencias* XXVII, 319–342.

Márquez, S. M., Mosquera, R., Herrera, M., and Monedero, C. (2010). *Estudio de la absorción y distribución del clorpirifos en plantas de pasto Kikuyo (Pennisetum clandestinum Hochst ex chiov) cultivadas hidropónicamente Revista Colombiana de Ciencias Pecuaria*. vol. 23. Medellín, Colombia: Universidad de Antioquia.

Mauricio, R., Sandin, R., Murgueitio, E., Chará, J., and Flores, M. (2019). "Silvopastoral systems in Latin America for biodiversity, environmental, and socioeconomic improvements" in *Agroecosystem diversity*. eds. G. Lemaire, P. C. D. F. Carvalho, S. Kronberg and S. Recous. *1st edn.* (London, UK: Elsevier B.V), 287–297.

Milcu, A. I., Hanspach, J., Abusón, D., and Fischer, J. (2013). Cultural ecosystem services: a literature review and prospects for future research. *Ecol. Soc.* 18:44. doi: 10.5751/ES-05790-180344

Ministerio de Agricultura y Desarrollo Rural de Colombia (2020) *Plan de ordenamiento productivo*. Análisis prospectivo de la cadena láctea bovina colombiana. Bogotá, Colombia

Montagnini, F., Ibrahim, M., and Murgueitio, E. (2013). Silvopastoral systems and climate change mitigation in Latin America. *Bois et Forêts des Tropiques* 316, 3–16.

Montoya Uribe, S, Chará, J D, Murgueitio Restrepo, E, and Correa-Londoño, GA y Barahona-Rosales, R (2023) Producción forrajera y consumo en ganaderías colombianas con diversos sistemas de pastoreo incluyendo sistemas silvopastoriles. *Livest. Res. Rural. Dev.* 35:7

Morales, M., and Armenteras, D. (2013). Estado de conservación de los bosques de nieblas en los Andes colombianos, un análisis multiescalar. *Bol. Cient. Mus. Hist. Nat. Univ. Caldas* 17:1

Murgueitio, E. (2003). Impacto ambiental de la ganadería de leche en Colombia y alternativas de solución. *Livest. Res. Rural. Dev.* 15:78

Murgueitio, E (2008) Reconversión ambiental ganadera en laderas andinas. En: Kattan, GH, and Naranjo, LG. (Eds.). *Regiones biodiversas: herramientas para la planificación de sistemas regionales de áreas protegidas*. Cali, Colombia: WCS Colombia.

Murgueitio, E., Flores, M., Calle, Z., Chará, J., Barahona, R., Molina, C. H., et al. (2015). "Productividad en sistemas silvopastoriles intensivos en América Latina" in *Sistemas Agroforestales. Funciones productivas, socioeconómicas y ambientales. Serie Técnica Informe Técnico 402*. eds. F. Montagnini, E. Somarriba, E. Murgueitio, H. Fassola and B. Eibl (Turrialba, Fundación CIPAV, Cali: CATIE), 59–101.

Murgueitio, E., Gómez, M. A., Uribe, F., and Lopera, J. J. (2020). Análisis sobre la producción de leche sostenible. Producción sostenible de leche bovina con sistemas silvopastoriles intensivos en Colombia. *Revista Infortambo Andina. Marzo* 2020, 20–22.

Murgueitio, E., Uribe, F., Flores, M. X., Chará, J., Molina, J. J., Rivera, J. E., et al. (2016). *Ganadería de leche por la vía natural. El camino de los Sistemas Silvopastoriles Intensivos. Revista Horizonte Lechero. Cámara Nacional de Productores de Leche de Costa Rica*. Vol. 7. San José, Costa Rica: Cámara Nacional de Productores de Leche de Costa Rica. 26–29.

NAMA-Bovina Colombia (2021). Acción de mitigación nacionalmente apropiada de la ganadería bovina sostenible en Colombia. Bogota. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/114670/ReporteNAMA08_10_2021final.pdf?sequence=1

Nicholls, C (2013). Enfoques agroecológicos para incrementar la resiliencia de los sistemas agrícolas al cambio climático. En: CI Nicholls Estrada, LA Ríos Osorio and MA Altieri. *Agroecología y resiliencia socioecológica: adaptándose al cambio climático (No. 630.277 A281agr)*. Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), Madrid (España) Red Iberoamericana de Agroecología para el Desarrollo de Sistemas Agrícolas Resilientes al Cambio Climático (REDAGRES): Medellín, Colombia.

Ochoa, D E, Lopera, J J, Márquez, S M, Calle, Z, Giraldo, C, and Chará, J y Murgueitio, E (2017) Los sistemas silvopastoriles intensivos contribuyen a disminuir el ataque de chupadores en pasto kikuyo (*Cenchrus clandestinus*). *Livest. Res. Rural. Dev.* 29:82.

Orme, A. R. (2007). "The Tectonic Framework of South America" in *The physical geography of South America*. eds. T. T. Veblen, K. R. Young and A. R. Orme (Oxford: Oxford University Press), 12.

Orme, C. D. L., Davies, R. G., Burgess, M., Eigenbrod, F., Pickup, N., Olson, V. A., et al. (2005). Global hotspots of species richness are not congruent with endemism or threat. *Nature* 436, 1016–1019. doi: 10.1038/nature03850

Parodi, A., Valencia-Salazar, S., Loboguerrero, A. M., Martínez-Barón, D., Murgueitio, E., and Vázquez-Rowe, I. (2022). The sustainable transformation of the Colombian cattle sector: assessing its circularity. *PLoS Clim* 1:e0000074. doi: 10.1371/journal.pclm.0000074

Peri, P, Chará, J, Mauricio, R, Bussoni, A, Escalante, E, Sotomayor, A, et al. (2019). Implementación y producción en SSP de Sudamérica como alternativa productiva: Beneficios, limitaciones y desafíos. En: J. Rivera, P. Peri, J. Chará, M. Díaz, L. Colcombet and E Murgueitio. *Congreso internacional sobre sistemas silvopastoriles: por una producción sostenible*. Libro de Actas. Editorial CIPAV, Cali. 263–291 p.

Pezo, D. (2019). Intensificación sostenible de los sistemas ganaderos frente al cambio climático en América Latina y el Caribe: Estado del arte. *Monografía del BID* 685:84. doi: 10.18235/0001722

Pezo, D, and Ibrahim, M (1998). *Sistemas Silvopastoriles*. Turrialba Costa Rica: CR, CATIE.

Pinheiro, L. C. (2004). *Pastoreo Racional Voisin*. Buenos Aires, Argentina: Tecnología Agroecológica Para el Tercer Milenio Hemisferio Sur, 253.

Preston, T. R., Leng, R. A., and Gómez, M. E. (2021). Adapting systems of livestock production to be compatible with global commitments to restore the health of planet Earth; ecosystems that remove atmospheric carbon and provide, food, feed, and renewable energy. *Livest. Res. Rural. Dev.* 33:31

Primavesi, A. (2002). Optimizando las interacciones entre el clima, el suelo, los pastos y el ganado. *LEISA Revista de Agroecología* 18, 15–16.

Reyes, E., Bellagamba, A., Molina, J. J., Izquierdo, L., Deblitiz, C., Chará, J., et al. (2017). *Measuring sustainability on cattle ranches silvopastoral systems*. Braunschweig, Germany: Agribenchmark Briefing Paper.

Rivera, J. E., Arenas, F. A., Rivera, R., Benavides, L. M., Sánchez, J., and Barahona, R. (2014). Análisis de ciclo de vida en la producción de leche: comparación de dos hatos de lechería especializada. *Livest. Res. Rural. Dev.* 6:50.

Rivera, J. E., and Chará, J. (2021). CH_4 and N_2O emissions from cattle excreta: a review of main drivers and mitigation strategies in grazing systems. *Front. Sustain. Food Syst.* 2021:370. doi: 10.3389/FSUFS.2021.657936/BIBTEX

Rivera, D., and Rodríguez, C. (2011). *Guía divulgativa de criterios para la delimitación de páramos de Colombia. 2011. Ministerio de Ambiente, Vivienda y Desarrollo Territorial e Instituto de Investigación de Recursos Biológicos Alexander von Humboldt*. Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt. 68.

Rivera, J. E., Villegas, G., Chará, J., Durango, S. G., Romero, M. R., and Verchot, L. (2022). Effect of *Tithonia diversifolia* (Hemsl.) A. Gray intake on in vivo methane (CH_4) emission and milk production in dual-purpose cows in the Colombian Amazonian piedmont, Translational. *Anim. Sci.* 6, 1–12. doi: 10.1093/tas/txac139

Rodríguez, A., Arce, B., Boshell, F., and Barreto, N. (2019). Effect of climate variability on Collaria scenica (Hemiptera: Miridae) on the Bogotá plateau. *Agronomía Colombiana* 37, 47–61. doi: 10.15446/agron.colomb.v37n1.75954

Rodríguez, N., Armenteras, D., Morales, M., and Romero, M. (2006). *Ecosistemas de los Andes colombianos. Segunda edición. Instituto de Investigación de Recursos Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Bogotá (Colombia)*, 154.

Rotz, C. A., Holly, M., de Long, A., Egan, F., and Kleinman, P. J. (2020). An environmental assessment of grass-based dairy production in the northeastern United States. *Agric. Syst.* 184:102887. doi: 10.1016/j.agsy.2020.102887

Ruiz, J., Cerón-Muñoz, F., Barahona Rosales, R., and Bolívar-Vergara, D. (2019). Caracterización de los sistemas de producción bovina de leche según el nivel de intensificación y su relación con variables económicas y técnicas asociadas a la sustentabilidad. *Livest. Res. Rural. Dev.* 31, 1–21.

Salas-Zapata, W. A., Ríos-Osorio, L. A., and Álvarez Del Castillo, J. (2012). Marco conceptual para entender la sustentabilidad de los sistemas socioecológicos. *Ecologia Austral* 22, 74–79.

Savory, A., and Butterfield, J. (2016). "Holistic management: a new framework for decision making" in *A commonsense revolution to restore our environment. 3rd* ed (Washington D.C., USA: Island Press), 552.

Scatena, F. N., Bruijnzeel, L. A., Bubb, P., and Das, S. (2010). "Setting the stage" in *Tropical montane cloud forests: science for conservation and management*. eds. L. A. Bruijnzeel, F. N. Scatena and L. S. Hamilton (Cambridge: Cambridge University Press), 3–13.

Seré, C, Steinfeld, H, and Groenewold, J (1996). *World livestock production systems*. Rome: Food and Agriculture Organization of the United Nations.

Serrano-Tovar, S (2014). *Spatial analysis in MuSIASEM. The use of geographic information systems and land use applied to the integrated analysis of rural systems' metabolism* (Doctoral Dissertation. Barcelona: Universitat Autònoma de Barcelona).

Silva, A., Figueiredo, E., Bordonal, R., Moitinho, M., Teixeira, D., and La Scala, J. N. (2019). Greenhouse gas emissions in conversion from extensive pasture to other agricultural systems in the Andean region of Colombia. *Environ. Dev. Sustain.* 2019, 249–262. doi: 10.1007/s10668-017-0034-6

Snyder, R., and de Melo-Abreu, J. (2010). *Protección contra las heladas: fundamentos, práctica y economía*. Roma: FAO Organización de las Naciones Unidas para la Agricultura y la Alimentación. *1*. Publicaciones de Medio Ambiente, Cambio Climático y Bioenergía. 241 pp.

Tejedor, N., Álvarez, E., Caro, S. A., Murakami, A. A., Blundo, C., Espinoza, T. B., et al. (2012). Evaluación del estado de conservación de los bosques montanos en los Andes tropicales. *Revista Ecosistemas* 21, 148–166.

UPRA (2020) Plan de Ordenamiento Productivo de Cadena Láctea 2020-2039. Agosto. Available at: https://www.upra.gov.co/plan-de-ordenamiento-productivo-para-la-cadena-lactea.

USP (2022). Available at: http://uspleche.Ministry of Agriculture.gov.co/historico-precio-promedio-nacional.html

Valderrama, P (2021). Análisis prospectivo de la cadena láctea bovina colombiana Bogotá: UPRA. Available at: https://documents10184/166404/20210728_DT_Prospectiva_Leche1

Veltman, K., Rotz, C. A., Chase, L., Cooper, J., Forest, C. E., Ingraham, P. A., et al. (2021). Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. *Agric. Syst.* 192:103170. doi: 10.1016/j.agsy.2021.103170

Vergara, W. (2010). La ganadería extensiva y el problema agrario. El reto de un modelo de desarrollo rural sustentable para Colombia. *Revista de Ciencia Animal N*° 3, 45–53.

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. (2004). Resilience, adaptability, and transformability in social–ecological systems. *Ecol. Soc.* 9:5. doi: 10.5751/ES-00650-090205

World Bank (2021). Not the COW, the HOW: Increasing Livestock Productivity, Improving Natural Resource Management, and Enhancing Environmental Services in Colombia. Available at: https://www.worldbank.org/en/projects-operations/results/2021/03/01/enhancing-environmental-services-in-colombia

World Bank Group (2019) *"Mainstreaming sustainable cattle ranching project: business case" (English)*. Washington, DC. Study Commissioned from Technoserve by the World Bank.

Young, K. R. (2009). Andean land use and biodiversity: humanized landscapes in a time of change. *Ann. Mo. Bot. Gard.* 96, 492–507. doi: 10.3417/2008035

Zapata, A, and Tapasco, B (2016) *Sistemas silvopastoriles: aspectos teóricos y prácticos*. CARDER, CIPAV, Editorial CIPAV, Cali, Colombia.

Zuluaga, A, and Etter, A (2018) *Áreas aptas para la actividad ganadera en Colombia: Análisis espacial de los impactos ambientales y niveles de productividad de la ganadería. Biodiversidad 2017. Estado y tendencias de la biodiversidad continental de Colombia*. Instituto Alexander von Humboldt: Bogotá, Colombia.

Zuluaga, A., Etter, A., Nepstad, D., Chara, J., Stickler, C., and Warren, M. (2021). Colombia's pathway to a more sustainable cattle sector: a spatial multi-criteria analysis. *Land Use Policy* 109:105596. doi: 10.1016/J.LANDUSEPOL.2021.105596