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The economic and environmental sustainability dimensions of agriculture: a trade-off analysis of Italian farms

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Crop and livestock farms are central to achieving the 2030 Agenda goals and a sustainable agri-food system. However, the transition toward a sustainable agri-food system requires optimizing several economic and environmental farm targets that, interacting with one another, would lead to win-win opportunities, at least as desired by the European Union (EU) policies. Indeed, in recent years, the EU has fostered sustainable development in a logic of synergy between farms' environmental and economic performances. This work fits into the agricultural sustainability assessment with the aim of improving our understanding of the existence of synergy or a trade-off between the economic and environmental dimensions at a crop and livestock field and farm scale. Specifically, using a set of appropriate agricultural economic and environmental indicators, two composite indexes were created and used to perform trade-off analysis on 7.891 farms that participated in 2019 and 2020 in the Italian Farm Accountancy Data Network. The findings showed a trade-off between economic and environmental dimensions in all livestock sub-sectors and the cereals sector, while a synergy in the horticulture sector. Considering the new European sustainability policies on agriculture and global scenarios, the study significantly contributes to policymakers, practitioners, and academic debate on sustainability in agriculture.

KEYWORDS

common agricultural policy (CAP), crop and livestock farms, sustainability indexes, farm accountancy data network (FADN), sustainable transition

1 Introduction

In the face of runaway climate change, the loss of ecosystems and biological species, and rapid growth in inequality, humans face a shift to a sustainable development paradigm that requires changes in their economic system, institutions, and relationships with nature (Uitto, 2022). Within this framework, agriculture plays a significant role as both an important driver and a significant threat (Rockström et al., 2017; Velten et al., 2015). Indeed, agriculture significantly contributes to the success of all Sustainable Development Goals (SDGs) of Agenda 2030, and concerning ongoing population growth and increasing food demands, it is strategic in food security (Arru et al., 2022; Fackelmann et al., 2019; Godfray et al., 2010; Kanter et al., 2018). In particular, it is increasingly clear that the food system is linked not only to SDG 2 (aimed at ending hunger and achieving food security and improved nutrition) but also to other development challenges addressed in the SDGs, such as poverty alleviation (SDG

1), education (SDG 4), gender equality (SDG 5), energy use (SDG 7), economic growth and employment (SDG 8), sustainable consumption and production (SDG 12), climate change (SDG 13) and ecosystem management (SDG 15).

Agricultural production encounters several challenges related to sustainable development, which have long-term effects. These include the need to boost agricultural output, the adverse environmental impact of agriculture, but also its substantial role in enhancing human life quality. Those matters have brought attention to the relationship between sustainable development and agricultural production, underscoring the critical role of agricultural production's economic and environmental sustainability in ensuring the long-term sustainability of food systems and the well-being of current and future generations (Bi et al., 2024; Kalinowska et al., 2022).

A genuine sustainability transition in agriculture is vital for ensuring global food security, societal well-being, and environmental protection (Campagnolla et al., 2019; El Bilali, 2020).

This transition involves institutional, political, economic, and socio-cultural dimensions and actors (like farmers called to change several practices), with diverse impacts depending on factors like agro-ecological zone, farming system, cultural preferences, institutions, and policies (El Bilali, 2019; Kanter et al., 2018; Vermunt et al., 2020). The European Commission aims to set a global standard for sustainable food through various policies, such as the EU Green Deal and the Common Agricultural Policy (CAP; European Commission, 2020). These policies strive to harmonize sustainability objectives and mitigate trade-offs among different targets.

However, agriculture's sustainability is rather complex, with potential trade-offs such as biodiversity loss or soil pollution from fertilizers (Martinho, 2020). Therefore, understanding and managing these trade-offs is critical for effective policy and decision-making (Godfray et al., 2010; MEA, 2005). To guide this transition, it is essential to develop indices that assess the multifaceted nature of sustainability and evaluate potential outcomes (Conway and Barbier, 1990; Dumanski et al., 1998; Sidhoum et al., 2022).

Trade-off analysis in agricultural systems, which examines resource scarcity and opportunity costs, is increasingly important for understanding sustainability across different scales—global, regional, and individual farm levels (Breure et al., 2024; Crissman et al., 1998; Rufino et al., 2011; Stoorvogel et al., 2004). This analysis helps clarify the relationships between economic and environmental dimensions of sustainability, which vary based on stakeholder priorities and spatial scale—from global to local—(Kanter et al., 2018; Rufino et al., 2011). In particular, the individual crop field scale—where the primary goals are to maximize productivity and minimize environmental impacts while also balancing productivity, income, and social objectives at the farm level (Kanter et al., 2018; Rufino et al., 2011)—takes on particular importance: it is considered the most suitable for assessing and implementing sustainability measures (Kelly et al., 2018), and it is the focal point of most policies (OECD, 2001).

From these considerations, this study aims to address the following research question: "What is the relationship between the economic and environmental sustainability dimensions in different crop and livestock sectors?"

The paper builds on previous research that either focused on a single sector (Sau et al., 2023) or explored different regional contexts (Sidhoum et al., 2022). It investigates Italy, which has demonstrated significant progress and strong capabilities in sustainable agricultural resource management (Coluccia et al., 2020). Additionally, Italian farms, with their rich cultural, social, and political traditions and positive relationship with the environment and territorial areas, provide a valuable benchmark for examining the primary sector and its current challenges.

To answer this research question, the study analyzes data from 7,891 farms in Italy from 2019 and 2020, sourced from the Italian Farm Accountancy Data Network (FADN), that is a valuable source of information to carry out different analyses and addresses a wide range of policy analysis needs (Marongiu et al., 2021).

This paper makes several contributions. This research contributes to current academic discussions on agricultural sustainability by providing insights into trade-offs and synergies between economic and environmental dimensions. To our knowledge, it is the first effort to estimate the trade-offs between the economic and environmental dimensions of Italian agriculture using the FADN database. Additionally, it provides crucial insights for both national and international policymakers. Given that trade-off analysis is an effective method for evaluating the complex dynamics of farming systems, offering invaluable insights into their policy impacts, (Klapwijk et al., 2014; Špička et al., 2020), this paper enhances our understanding of the potential synergy or trade-off between the economic and environmental aspects at both the crop and livestock field and farm scale. It provides quantitative information on competing indicators that can help inform policy and decision-making. While new EU policies aim to foster synergies between sustainability dimensions, our findings indicate that a win-win scenario—where both environmental and economic goals are achieved simultaneously—occurs only in certain types of farms.

The paper is structured as follows: Section 2 outlines the research methodology and sample description, Section 3 presents the results, and Section 4 discusses the findings, concludes the paper, and offers recommendations for practitioners, academics, and policymakers.

2 Background

The European Commission (EC) is committed to establishing European food as the global standard for sustainability through several new policies, including the EU Green Deal, the Farm to Fork (F2F) and Biodiversity Strategies, Horizon Europe, Next Generation EU, and the Common Agricultural Policy (CAP). These policies aim to drive a just transition (European Commission, 2020) by fostering synergies and minimizing trade-offs among various sustainability dimensions and targets embedded in the European strategy. For instance, the CAP 2023–2027 focuses on combating climate change, protecting the environment, and conserving landscapes and biodiversity, while also promoting vibrant rural areas, ensuring fair incomes for farmers, boosting competitiveness, and enhancing farmers' roles in the food chain. Similarly, the F2F strategy aims to harness the economic benefits of transitioning to more sustainable practices (Mowlds, 2020), realizing win-win opportunities that improve sustainable development and profits in a logic of synergy between farms' environmental and economic dimensions.

However, each pathway involves varying sets and/or levels of environmental and socio-economic trade-offs and synergies that must be acknowledged and managed (Kanter et al., 2018). Positive outcomes can sometimes overshadowed by negative externalities, such as biodiversity loss or soil pollution from fertilizers and crop protection products (Martinho, 2020). Therefore, it is crucial to examine and manage the trade-offs between the potential benefits and negative impacts resulting from the interaction of food production with other aspects of sustainable agriculture (Godfray et al., 2010; MEA, 2005).

Previous research on these relationships within the agricultural sustainability paradigm has been inconclusive (Grzelak et al., 2022). Some studies suggest synergies between sustainability dimensions (Berre et al., 2014; Bonfiglio et al., 2017; Gómez-Limón and Sanchez-Fernandez, 2010; e.g., Grzelak et al., 2022; Picazo-Tadeo et al., 2011), while others highlight trade-offs (e.g., Briner et al., 2013; Calzadilla et al., 2010; Eigenbrod et al., 2009; Galdeano-Gómez et al., 2017; Jaklič et al., 2014; Sulewski et al., 2018). According to Sidhoum et al. (2022), achieving a successful transition requires optimizing interconnected economic, environmental, and social objectives, which can lead to unintended adverse effects in some cases, while trade-offs and synergies may occur in others.

For a successful agricultural sector transition, it is crucial to (i) develop indices that assess the multifaceted nature of sustainability and consider interrelation among its dimensions, thereby providing a concrete and actionable framework for decision-making at all levels (Conway and Barbier, 1990; Dumanski et al., 1998), (ii) monitor potential outcomes, evaluate whether setting goals are met or threatened, and recommend adjustments as needed (Kanter et al., 2018; Sidhoum et al., 2022).

In this field, a growing interest in agriculture's economic and environmental performance has been observed in the theoretical and empirical literature (Aldieri et al., 2019; Kanter et al., 2018; Sidhoum et al., 2022), along with a demand for farm-level sustainability indices based on a set of indicators (de Olde et al., 2016; Singh et al., 2012; van Huylenbroeck et al., 2000) that help in understanding the trade-offs between these dimensions to develop effective policies and practices.

In this context, providing a quick overview of the significant findings from recent studies focused on using indicators to measure and assess these trade-offs appears useful. First and foremost, it is evident that several studies have emphasized the need to manage these trade-offs effectively to balance food production with environmental conservation (Godfray et al., 2010). While some research suggests synergies between sustainability dimensions, others highlight significant trade-offs, particularly in cases involving biodiversity loss or soil pollution from agricultural inputs (Berre et al., 2014; Briner et al., 2013; Grzelak et al., 2022). To better understand and study these trade-offs, researchers have developed a variety of sustainability indices based on economic and environmental indicators (Conway and Barbier, 1990; Dumanski et al., 1998). A growing body of literature has focused on identifying and measuring these indicators at the farm level, with studies suggesting a mix of results across different agricultural systems. These works inform policy decisions and offer practical tools to help farmers and policymakers to address the complex trade-offs that arise between environmental sustainability and economic viability.

Summarizing, previous studies tend to differ and relate primarily based on three core themes: (i) the conceptual frameworks for sustainability assessment, (ii) the methodological approaches for indicator development, and (iii) the empirical insights into the trade-offs between environmental and economic performance at the farm level.

Within the first theme, a key similarity among the studies is their shared goal of balancing economic and environmental dimensions within the broader sustainability paradigm. Callens and Tyteca (1999) proposed a framework for integrating environmental sustainability with productive efficiency at the firm level. They emphasized the need for indicators reflecting economic performance and environmental impact, suggesting that firms must balance these aspects to achieve sustainable development. They provide foundational frameworks for integrating economic and environmental indicators, setting the stage for subsequent research. Their approach is one of the earliest to systematically link these dimensions, making it foundational for subsequent studies. Building on this foundation, Chopin et al. (2021) conducted an extensive review of sustainability assessment tools, frameworks, and indicator advancements. They highlighted key areas for improvement, emphasizing the necessity for more refined tools and indicators to effectively capture the complexities of farm sustainability. They built on these frameworks by refining tools and indicators, addressing the need for more accurate and context-specific assessments. Indeed, this is a crucial concern for policymakers seeking to harmonize environmental and economic goals in agriculture. This shift reflects an evolving understanding of sustainability, which requires not just the balance between economic and environmental goals but also accounting for the interactions between these dimensions and the socio-economic context of farms. In contrast, Pacini et al. (2004) and Medici et al. (2020) contribute to the theoretical discussion by demonstrating the applicability of multi-objective modeling and innovative practices in achieving sustainability goals. Pacini et al. (2004) employed ecological-economic modeling to support policymaking in Tuscany. Their approach integrates environmental and economic objectives, demonstrating the potential for multi-objective frameworks in agricultural policy. Medici et al. (2020) analyzed the environmental impacts of fruit cultivation from a business innovation perspective. Their study highlights the role of innovative practices in mitigating environmental effects while maintaining economic viability. Though focused on different regions and sectors, both studies reflect a broader convergence toward multi-objective and context-specific approaches to sustainability.

Concerning the second theme, the studies commonly rely on sustainability indicators, despite the various methodologies employed to develop these indicators. Callens and Tyteca (1999) advocate for developing indicators that balance productive efficiency and environmental sustainability, setting the stage for subsequent methodological advancements. Chopin et al. (2021) take a step further by reviewing existing tools and suggesting improvements in the design and application of sustainability indicators. Latruffe et al. (2016) contribute to the methodological discussion by promoting a multidimensional approach to sustainability assessment, using indicators that span economic, environmental, and social dimensions, providing a foundation for more open evaluations of farm sustainability. The practical application of the multidimensional approach proposed by Latruffe et al. (2016) and then developed by Gaviglio et al. (2017) highlighted how tailored indicators can be used to evaluate sustainability in region-specific contexts. The divergence in methodologies is most evident in the empirical studies. The methodological approach of Baldoni et al. (2017, 2018) highlights the urgent and important challenges of using environmental indicators to assess farm performance, revealing a complex relationship between increased productivity and negative environmental externalities. In contrast, Coppola et al. (2020) rely on income and economic viability indicators drawn from FADN data to evaluate the financial sustainability of Italian farms. These two approaches—one focused on environmental impacts, the other on economic outcomes—describe the methodological trade-offs involved in measuring sustainability across different dimensions.

Finally, it can be observed that while the conceptual frameworks and methodological approaches show convergence in their shared emphasis on sustainability, the empirical findings of the reviewed studies reveal significant differences in how these frameworks are implemented at the farm level, particularly in balancing trade-offs between environmental performance and economic viability. Empirical studies such as those by Baldoni et al. (2017, 2018), Coppola et al. (2020), and Cortignani et al. (2021) focus on farm-level interactions between productivity and environmental performance. They highlight the challenges and potential solutions for balancing these dimensions, emphasizing the importance of context-specific approaches. Baldoni et al. (2017) investigated the relationship between productivity and environmental performance, explicitly examining carbon footprint data from Lombardy farms. Their study reveals the complexities of balancing productivity with environmental impacts. Baldoni et al. (2018) further explored the intricate relationship between environmental performance and productivity, highlighting the challenges of achieving sustainable outcomes at the farm level. Coppola et al. (2020) analyzed Italian farms' income levels and economic viability using FADN data. Their findings highlight factors influencing farm income and sustainability, providing insights into the economic dimensions of farm sustainability. This comprehensive approach is echoed in the work of Gaviglio et al. (2017), who developed a tool for assessing farm sustainability in Italy. By focusing on the selection and adaptation of context-specific indicators, their tool provides practical insights into how tailored metrics can be used to evaluate farm sustainability by analyzing relevant case studies. Lastly, Westbury et al. (2011) used FADN data to assess the environmental performance of English arable and livestock farms, offering practical examples of how environmental indicators can inform farm management practices. Their work, along with other empirical studies, illustrates the potential for indicators to guide decision-making at the farm level and inform broader agricultural policies. Cortignani et al. (2021) further contribute to the empirical debate by examining adaptation strategies in response to climate change. They evaluated adaptation strategies to climate change in major Italian agricultural areas, assessing their impact on farm profitability. Their findings emphasize the need for effective adaptation measures to ensure farm sustainability and profitability. In contrast, Westbury et al. (2011) present a more optimistic view by demonstrating that environmentally friendly practices can lead to positive economic outcomes, mainly when supported by appropriate policy frameworks. They used FADN data to assess the environmental performance of English arable and livestock farms to provide valuable insights into how environmental indicators relate to farm practices and outcomes. They provide practical examples of how environmental indicators can be used to evaluate farm performance, further informing policy and practice.

The reviewed studies converge in recognizing the importance of balancing environmental and economic sustainability at the farm level. Considering both theoretical and empirical contributions, there is a shared emphasis on the need to refine tools and indicators to capture the multifaceted nature of sustainability. Callens and Tyteca (1999) and Chopin et al. (2021) point out the key theoretical groundwork, while the empirical research by Baldoni et al. (2017), Coppola et al. (2020), and others provide farm-level insights into how these trade-offs play out in practice. However, differences from the previous literature regarding both methodological and empirical findings highlight the complexities and implications of balancing environmental performance and economic feasibility in different contexts. What generally emerges is firstly the importance of context-specific approaches to sustainability, as trade-offs between environmental performance and economic viability can vary significantly depending on the region, farming system, and policy environment. Secondly, the contributions of these studies are crucial for policymakers as they emphasize the need for tailored strategies that balance the diverse goals of environmental protection, economic growth, and social well-being. They offer valuable insights into the trade-offs and potential solutions to achieve sustainability. As the discussion around sustainable farming continues, our paper aims to contribute to the debate by refining assessment tools, further exploring practices at the farm level (using indicators), and addressing the challenges identified in previous studies to advance sustainable agricultural practices.

3 Data and method

3.1 Data source

Data were gathered from the Italian FADN, a database widely used in the research of sustainability in agriculture (Bazzani et al., 2021; Boggia et al., 2022; Cardillo et al., 2023; Coppola et al., 2022; Dabkiene et al., 2021; Liberati et al., 2022) as monitors farms' income, cost, and agricultural holdings activities, beyond to offer pivotal information concerning the impact of the measures taken under public policies. In the Italian context, several studies have employed the FADN both to assess the impact of rural development policies at a micro-level (Cagliero et al., 2021; Cisilino et al., 2023; Cisilino et al., 2021) and to explore environmental issues with a focus on organic farming (Cisilino et al., 2019; Cisilino and Cesaro, 2009; Cisilino and Vanni, 2019).

Based on the desire to avoid conjectures based on specific years, the sample investigated includes all Italian agricultural farms that fall in both 2019 and 2020 (the last data years available) into two macro-sectors: crop farms (field crops, except cereals; cereals; horticulture; grape; olive; orchards; fruits) and livestock farms (sheep, goats-herbivore; milk; granivores). In this research, farming systems that involve both crop and livestock production (mixed farming) were not included in the sample since the FADN data do not allow precise and distinct identification of the environmental and economic performances of the two types of activities and a correct calculation of the relevant individual indicators. The sample included 7,927 farms (2,488 livestock farms and 5,439 crop farms). Moreover, because the outliers' values can distort statistical analyses and violate their assumptions, we removed them from the sample data using the Tukey Fence method (Tukey, 1977), a popular simple outlier detector for one-dimensional number arrays. It is calculated by creating a "fence" boundary with a 1.5 inter quartile range (IQR) distance beyond the 1st and 3rd quartiles. Any data beyond these fences are outliers. The check for outliers was performed by examining the economic dimension and precisely the net income indicator documented by the Italian FADN for each farm. Consequently, our total constant sample was reduced to 7,891 farms.

3.2 Research model

The research was conducted in four steps (see Figure 1).

As a first step, it was necessary to select indicators, which is a complex and decisive process (Gebara et al., 2024), as they must provide reliable information and be aligned and relevant to the research context and goals.

Afterward, all indicators were calculated for each farm, according to the data reported in the FADN.

The third step aims to evaluate the existence and extent of synergies or compromises between the two dimensions of sustainability. To this end, the following procedural steps were envisaged: (a) ranking of the indicators of each farm 0 to 1; (b) normalization of each indicator to reduce the different measurement scales to a standardized one; (c) develop composite economic and environmental indicators; (d) correlation analysis between composite indicators.

The last step concerns the analysis of the relationships between the individual indicators for each subsector, which will provide more information for understanding where the trade-off (or synergy) unfolds most.

3.3 Variables used in the analysis

Agricultural trade-off analysis relies on indicators (Giller et al., 2014). They must provide significant information to facilitate assessment and decision-making by farmers and policymakers beyond to increase farmers' awareness or understanding of the potentially important issues being monitored (Kanter et al., 2018; Pannell and Glenn, 2000).

The selection of the indicators (Step 1 of Figure 1) considered the following criteria (Dale and Beyeler, 2001; Pannell and Glenn, 2000): well-understood, unambiguous, and sensitive links between the indicator and what it represents; reliability and accuracy of brought information; sensitivity to natural and anthropogenic stresses to the system; capability of anticipating and preventing impending changes, as well as predicting changes that could be prevented through effective management.

Indicators in the FADN database were used to evaluate sustainability dimensions with specificities inherent to the sector type. Specifically, data from FADN integrated with Italian FADN was used. The latter provides more information and environmental and social variables relating to company management that exceed those required by community legislation, allowing national agricultural peculiarities to be considered (Turchetti et al., 2022).

It is important to highlight that indices based on monetary values can be influenced by price trends rather than the more or less efficient use or impact of input factors. This could cause performance asymmetry between farms. However, this effect is significantly mitigated by the fact that the survey takes 2 years and the high number of companies included in the sample.

Six economic indicators already applied in previous research (Bereżnicka, 2018; Coppola et al., 2022; Díaz de Otálora et al., 2021; Masi et al., 2021; Ripoll-Bosch et al., 2012; Špička et al., 2020) and already tested in our previous study (Sau et al., 2023) aimed to investigate, at the farm level, the relationship between economic and environmental dimensions of the dairy sheep sector, were used to describe agricultural productivity, cost, and profitability of farms. For each index, the FADN standard output codes used for their calculation are indicated.

- ECI1 (€): Farm Net Value added (FNVA) per agricultural work unit (AWU) (SE425). It is the primary income indicator in agriculture, reflecting the farm aptitude remuneration of all resources, including labor, land (rent), and capital (interest) costs, whether from external or family sources, and allows farms to be compared regardless of whether production factors are family or non-family. It equals total output (total production value) plus the balance of current subsidies and taxes, including the direct payments, minus intermediate consumption (specific costs and farm overheads) and depreciation. AWU is the full-time equivalent of employment.
- ECI2 (€): Total output per AWU (SE131/SE010). It is a measure of labor productivity, and includes individual product sales, in-house consumption, captive consumption, and closing stock changes.
- ECI3 (€): Total output per unit utilized agricultural area (UAA) (SE135/SE025) and livestock unit (LU) (SE206/SE080).
- ECI4 (€): Specific costs per UAA (SE284) and LU (SE309). Because it is the ratio of specific inputs (comprised of direct production costs, i.e., the costs of seed, fertilizers, feed, veterinary expenses, etc.) - that is, costs directly affect and can be uniquely associated with one production - to the total UAA or LU of the farm, it allows comparative analysis of firms' performance.
- ECI5 (%): Productivity of intermediate consumption (SE131/SE275). It is the ratio between total output and total specific costs (including inputs produced on the farm) and overheads arising from production in the accounting year. It estimates the output achieved per unit value spent as intermediate consumption and measures the economic health of a farm and its ability to develop without state intervention.
- ECI6 (%): Return on equity (ROE) (SE420/SE501). It is the ratio between the farm's net income (i.e., the remuneration to fixed factors of production of the farm—work, land, and capital—and the entrepreneur's risks—loss/profit—in the accounting year) and total assets. It measures the farm's resource efficiency, i.e., its additional income for every 1 value of a shareholder's investment.

A total of 11 indicators that are sensitive to both natural and human stressors, anticipatory of upcoming changes, and those that can be avoided thanks to the conduct of management (Dale and Beyeler, 2001) were considered in the assessment of the environmental dimension. Nine of them had previously been used in various combinations (Cardillo et al., 2023; Díaz de Otálora et al., 2021; Liberati et al., 2022; Masi et al., 2021; Meul et al., 2009; Riera et al.,

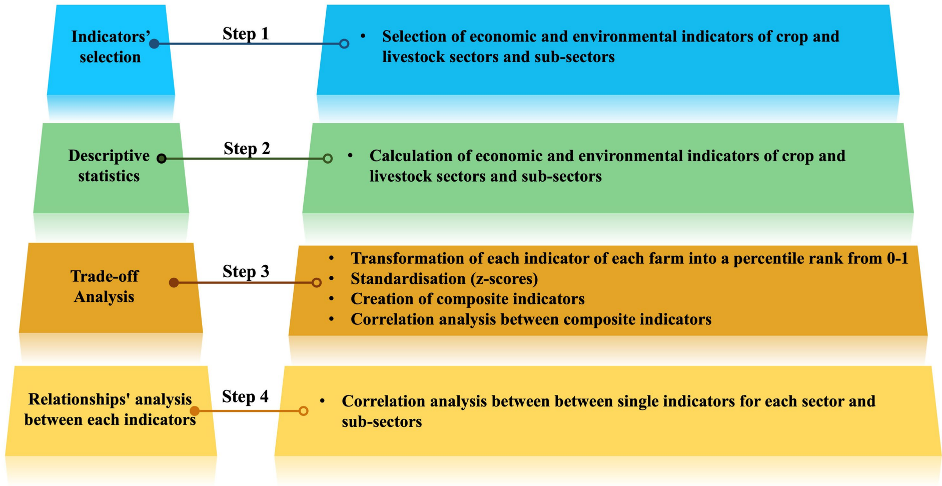

FIGURE 1
Research model.

2023; Špička et al., 2020; Weltin and Hüttel, 2023), while two were used for the first time in the agriculture trade-off analysis only by Sau et al. (2023), i.e., the animal emissions and carbon sequestration, because essential in assessing the environmental performance of farms since they fill in the gaps left by more generic indicators. All 11 indicators were already employed in our previous research (Sau et al., 2023).

- ENI1 (€/UAA): Organic fertilizers used. It is based on the comparison of the total cost of organic fertilizer disclosed in the Italian FADN (it includes humus, buffalo manure, horse manure, granivore manure, sheep and goat manure, and other animal manures) and the farm UAA (SE025). Farm scores increase with the use of organic fertilizers.
- ENI2 (€/UAA): Use of industrial mineral fertilizers per UAA. It is the ratio between the total cost of industrial mineral fertilizers indicated in the Italian FADN (it comprises the solid mineral and organic mineral solid fertilizers) and the farm UAA (SE025). Using fewer industrial mineral fertilizers results in better farm scores.
- ENI3 (€/UAA): Use of herbicides and pesticides per UAA. It is the ratio between crop protection (total cost of herbicides and pesticides indicated in the Italian FADN) and farm UAA (SE025). The fewer crop protections applied, the higher the farm scores.
- ENI4 (%): Use of water, energy, and fuels. It relates the total cost of water, energy, and fuels indicated in the Italian FADN to the total production (SE131). Lower consumption means a higher farm's score.
- ENI5 (%): Share of clover. Using data from the Italian FADN, the ratio between meadows hectares with leguminous crops and the company UAA (SE025) has been calculated.
- ENI6 (LU/UAA): Stocking density. It compares the total livestock units to business UAA (SE080/SE025).
- ENI7 (%): Multiannual and perennial crops per UAA. It is the ratio between the Multiannual and perennial crops (alfalfa; permanent, polyphyletic, and non-rotation generic grassland; productive uncultivated pastures; pastures) indicated in the Italian FADN and the farm's UAA (SE025).
- ENI8 (N.): Greening. It refers to the number of environmental measures[1] a farm complies with, as shown in the Italian FADN.
- ENI9 (N.): Renewable energy. Following Italian FADN, the farm's presence of renewable energy sources was evaluated with a binary value of 0 or 1.
- ENI10 (ton CO2eq/LU/yr): Animal emissions. It is the share of animal emissions per LU (CO2eq/SE080). It comprises three emission types elaborated using Italian FADN data and the refined Tier 1 method elaborated by the Intergovernmental Panel on Climate Change (IPCC, 2019), i.e., the enteric methane (CH4) emissions from fermentation occurring in the rumen (if present) and the CH4, nitrous oxide (N2O) emissions from manure management. As a result, these emissions have been converted into a single indicator that allows for measuring each farm's animal CO2eq emissions (see Appendix for details of calculation methods). The fewer emissions released, the higher the farm scores.
- ENI11 (ton CO2/UAA/yr): Carbon sequestration. It is the share of carbon sequestration per UAA (CO2/SE025). Using coefficients of potential carbon sequestration indicated in previous literature (Dondini et al., 2023; Giussani, 2014; Kumar et al., 2023; Richardson et al., 2019) and based on Italian FADN, the carbon sequestration.

3.4 Methodology

The second step of our research model (Figure 1) concerns the economic and environment indices calculation. Because the

1 The measures considered are following: Without diversification and EFA obligation; Crop diversification; EFA—Rotating Coppice; EFA—Elements characterizing the landscape; EFA—Buffer strips; EFA—Surfaces with nitrogen-fixing cultures; EFA—Agro-forestry area; EFA—Interlayer Surface; EFA—Terraces; EFA—Land left fallow; Permanent meadows not included in the Natura 2000 area; Permanent meadows falling within the Natura 2000 area.

analysis covered 2 years, all indicators were calculated as an average of the 2 years of data reported by the Italian FADN for each farm.

Several phases were carried out to carry out Step 3 of the research model of Figure 1 and answer our research question. It is necessary to highlight first of all that the agricultural sustainability assessment is very complex due to its dynamic character (Ikerd, 1993) and the requirement to interpret a multidimensional set of indicators that can use different scales or meaningful units of measurement (Talukder et al., 2017). Using composite indicators can overcome such problems as they capture and sum the complexity and multidimensionality of various development issues, allowing for cross-comparisons and evaluation of results (Munda and Saisana, 2011). Because of this, policymakers and stakeholders consider it advisable (Talukder et al., 2017).

Technically, the creation of composite indicators arises through preliminary normalization, which occurs in two stages:

- The ranking normalization, one of the most widely employed and used normalization techniques (Saisana and Saltelli, 2011). The single indicators of the economic (ECi) and environmental (ENi) dimensions for each farm (given by the average recorded in the 2 years of the analysis) are related to the max value to bring in the range of [0, 1]. In other words, the single score of each indicator is calculated based on the distance from the maximum value, causing the largest value on each indicator to equal unity and all others to represent a fraction of the largest value.
- The z-score normalization, technique suggested in the case of extreme values in a dataset (Nardo et al., 2005). The indicator score for a farm is then calculated by transforming each value (obtained by the previous stage) by subtracting its mean and dividing it by its standard deviation. In this way, all indicators are converted to a common scale with an average of zero (this avoids aggregation distortions caused by different indicators' means) and a standard deviation of one, and through a linear transformation, the difference between normalized values is preserved.

The subsequent phase involves the composite indicators construction. This work adopts the arithmetic mean, a common aggregation technique (OECD, 2008) where the normalized indicators are summed to compute the arithmetic mean. Although this methodology may be subject to the compensatory effect, this effect is negligible due to the research objective of evaluating the trade-off between the two dimensions in their entirety and not between individual indicators and the large sample size. In sum, the economic (EC) and environmental (EN) aggregated indicators are calculated as follows (see Equation 1):

$$EC = \frac{\sum_{n=6}^{1} ECI_i}{N}; \quad EN = \frac{\sum_{n=11}^{1} ENI_i}{N} \tag{1}$$

Step three concludes with the analysis of the trade-offs and synergies relationships between the economic and environmental dimensions calculation. This study used the Pearson correlation analysis, which was widely previously used in the trade-offs analysis (Raudsepp-Hearne et al., 2010; e.g., Špička et al., 2020). Specifically, the analysis was made for individual sectors and sub-sectors.

Finally, the relationship between indicators for each sector and sub-sector was investigated (Step 4 of Figure 1) using the Pearson correlation analysis on absolute score (average of 2 years for each indicator of each farm). This step provides additional pivotal information about the indicators that can most effectively generate trade-offs or synergies between economic and environmental indicators.

4 Results

4.1 Sample profile

The data shows that, overall, only a fifth of Italian farms included in our sample are run by women, and only 14% by young people, defined as those who are 40 years old or younger (as per the limit set by Italy based on Regulation (EU) 2021/2115 on CAP Strategic Plans). The same distribution is maintained within the division between the macro-sector of Crop and Livestock farms. Considering the crop farms, it emerges that the olive farms deviate considerably from this value regarding female employment (29%), while in the cereal farms, only 8% are young. In the livestock farms, women run only 16% of dairy cow livestock farms and young only 11% of granivores farms.

Regarding geographical distribution, at both a general and macro-sector level, 43% of farms operate in the North Italian regions. Significant deviations are instead recorded in the olive and herbivorous farms, which are present mainly in the central and island regions (80 and 49%, respectively). In general, only 13% of farms diversify (11% in crop farms and 15% in livestock farms, respectively). However, this value changes a lot within the subsectors, reaching 7 and 8% in the case of horticulture and olive farms or 25% in the case of granivore livestock farms.

The data shows that only 22% of farms and 16% of livestock farms produce organically. Very different and positive data is recorded instead in the olive and Orchard - Fruit productions (63 and 31%, respectively). Data are reported in Table 1.

While considering the elimination of the outliers farms from our sample, using data provided by the European Commission's agricultural and rural development department (European Commission, 2023a), it was possible to make some important economic comparisons with respect to the average of the European member countries.

Concerning the crop farms' ability to remunerate all farm resources, the index ECI1 showed that the average of 2019 and 2020, except for grape farms, all subcategories record values higher than the European average. In particular, it should be noted that cereals and orchards-fruit record 46 and 33% more than the European average, respectively. A similar trend is recorded in the ECI2 indicator, where grape farms record a lower value (−17%), and cereals and orchards-fruits are higher than the European average (+32 and 25%). Cereal farms (but also field crops and horticultural companies) record results significantly higher than the European average in terms of intermediate consumption productivity (ECI5). The ECI indicator 6 in all subcategories shows a high distance from the average, signifying a high variability in the efficiency of farms in the use of resources.

TABLE 1 Profile sample of the analyzed farms.

Agricultural activity	N. Farms	Gender		Young		Region		
		M	F	Yes	No	Nord	Centre	South and islands
Crop farms	5,412	4,238	1,174	706	4,706	2,288	1,730	1,394
Field crops (except cereals)	999	773	226	135	864	385	244	370
Cereals	793	656	137	66	727	432	125	236
Horticulture	788	647	141	115	673	356	188	244
Grape	1,179	889	290	141	1,038	588	280	311
Olive	515	368	147	95	420	41	411	63
Orchards - Fruits	1,138	905	233	154	984	486	482	170
Livestock farms	2,479	1,989	490	381	2,098	1,071	811	597
Granivores	1,266	340	84	48	376	245	33	146
Herbivores	789	986	280	217	1,049	310	616	340
Dairy cows	424	663	126	116	673	516	162	111
Total	7,891	6,227	1,664	1,087	6,804	3,359	2,541	1,991

Agricultural activity	Diversification		Organic		Total agriculture area (HA)			Livestock unit (LU)			
	Yes	No	Yes	No	0–100	101–200	201	0–50	51–100	101–150	>150
Crop farms	612	4,800	1,169	4,243	5,176	180	56	5,404	5	2	1
Field crops (except cereals)	146	853	152	847	923	55	21	993	3	2	1
Cereals	126	667	64	729	694	77	22	793	0	0	0
Horticulture	58	730	58	730	760	23	5	787	1	0	0
Grape	134	1,045	219	960	1,170	8	1	1,179	0	0	0
Olive	43	472	323	192	503	11	1	515	0	0	0
Orchards - Fruits	105	1,033	353	785	1,126	6	6	1,137	1	0	0
Livestock farms	376	2,103	400	2,079	2,136	250	93	1,263	517	195	504
Granivores	105	319	44	380	404	14	6	58	56	43	267
Herbivores	147	1,119	260	1,006	1,055	162	49	871	248	65	82
Dairy cows	124	665	96	693	677	74	38	334	213	87	155
Total	988	6,903	1,569	6,322	7,312	430	149	6,667	522	197	505

Source: Own data processing on FADN dataset.

Regarding livestock farms, herbivore farms record values much higher than the European average in every economic indicator. This can arise from the tradition of some Italian regions concerning this activity, which has also led them to develop better management of company resources. Another interesting fact is the greater incidence of specific livestock costs per LU in dairy cows and granivores farms. Data are reported in Table 2.

Since almost all environmental indicators are calculated using Italian FADN, comparing them with the European average is not allowed. An exception is index ENI6 (animal density), which showed that the farms analyzed showed values similar to the European averages. Almost all crop and livestock farms showed high variability in the ENI 1, 2, 3, 6, and 7, whereas the rest of the environmental indicators showed more homogeneity. Data are reported in Table 3.

4.2 Relationship between economic and environmental farms' dimensions

Table 4 shows the results of the trade-off analysis for all agricultural and livestock sectors, allowing us to determine the strength of the linear relationship of economic and environmental dimensions and its positive or negative value that can briefly express the trade-offs or synergies relationship among dimensions. At a macro-sector level, crop farms show a negative correlation, meaning that a positive increase in environmental indicators determines a simultaneous decrease in the economic performance of farms. However, from our analysis, only the cereal and horticulture sectors are statistically significant. What also emerges is that the latter has a synergy between the two dimensions of sustainability investigated. Regarding livestock enterprises, both at the macro-sector and

TABLE 2 Statistic of economic indicators for each sector and sub-sector.

Agricultural activity	ECI 1 (€)		ECI 2 (€)		ECI 3 (UAA) (€)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Crop farms	30,489.87	26,727.37	51,834.26	45,666.61	10,910.23	33,505.08
Field crops (except cereals)	30,040.58	23,682.26	54,221.70	43,117.90	3,504.16	8,109.47
Cereals	37,804.77	39,408.96	73,858.83	70,814.65	1,434.30	641.24
Horticulture	32,392.01	26,131.84	60,130.73	47,357.69	42,057.00	78,829.69
Grape	29,846.20	25,912.87	46,730.13	38,890.16	8,608.23	9,809.46
Olive	22,304.71	17,836.97	31,645.79	23,229.12	2,658.24	2,357.63
Orchards - Fruits	28,840.91	20,971.97	43,070.37	27,511.01	8,566.86	7,542.51
Livestock farms	41,303.50	36,309.40	83,961.82	101,730.83	0.00	0.00
Herbivores	32,915.43	31,335.71	61,239.17	103,886.75	0.00	0.00
Dairy cows	45,778.00	31,652.83	91,244.36	64,062.73	0.00	0.00
Granivores	58,022.64	48,910.07	138,256.51	126,914.34	0.00	0.00

Agricultural activity	ECI 3 (LU) (€)		ECI 4 (€)		ECI 5 (%)		ECI 6 (%)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Crop farms	0.00	0.00	5,512.79	19,402.87	2.58	1.47	0.27	3.59
Field crops (except cereals)	0.00	0.00	1,887.87	3774.03	2.29	1.10	0.16	0.98
Cereals	0.00	0.00	907.63	442.32	1.99	0.66	0.32	5.31
Horticulture	0.00	0.00	22,927.05	46,448.60	2.47	1.58	0.32	1.90
Grape	0.00	0.00	3,312.51	4,368.24	2.85	1.51	0.37	5.92
Olive	0.00	0.00	1,518.30	1,393.85	2.76	1.52	0.22	1.45
Orchards - Fruits	0.00	0.00	3,932.85	3,707.97	2.95	1.80	0.21	1.03
Livestock farms	1,526.18	1,307.59	1,000.03	1,001.74	2.35	1.42	0.28	4.10
Herbivores	1,272.71	1,054.78	864.22	1,000.94	2.51	1.44	0.15	0.18
Dairy cows	2,182.82	898.41	1,274.51	677.26	2.05	1.06	0.15	0.16
Granivores	1,061.07	1,993.01	894.76	1,349.50	2.45	1.78	0.92	9.88

Source: Own data processing on FADN dataset.

sub-sector levels, the results show significant negative relationships, revealing a situation whereby increasing the value of one dimension leads to a reduction in the value of the other.

4.3 Relationship between economic and environmental indicators

The step four of research model (Figure 1) aims to analyses the relationship between economic and environmental indicator for each sector and subsector. To this end, Pearson correlation was applied, and correlation matrix are illustrated in the Appendix C.

Concerning the Crop sector, results suggest that the economic indicators most related to the environmental dimension are ECI 3, ECI4 and ECI5, that is, the total output and specific cost per UAA and the ratio between total output and total specific and overhead costs. Specifically, we found that industrial mineral fertilizers per UAA (ENI2) use negatively correlated with the total output per UAA and the productivity of intermediate consumption. This means that a decrease in the use of industrial mineral fertilizers would jeopardize production and the ability of farms to develop without state intervention. The same goes for adhering to greening measures. No wonder the diametrically opposite behavior of the environmental indicators ENI2 and ENI8 compared to the specific costs per UAA (ECI4) instead, that is, the two environmental indicators and the economic one move in tandem.

Looking at the horticulture subsector, the only one that showed synergy between economic and environmental indicators, results revealed that indicators ENI4, ENI6, and ENI9 are not related to any economic indicators, whereas ENI 1 was adversely related only to the NVA per AWU. The relationship between adhering to greening measures and economic indicators follows the macro-sector trend (except ECI6) but with greater magnitude.

Regarding the livestock sector, it is unsurprising that the ENI 1 and ENI 2 (use of organic and industrial mineral fertilizers) indicators are not correlated with any economic indicators. Six out of 11 environmental indicators (ENI3, ENI4, ENI7, ENI 10, ENI11) are significantly and negatively correlated with the primary income indicator in agriculture (ECI1). This means that, for example, in the face of a request to reduce animal emissions (ENI10), company

TABLE 3 Statistic of environmental indicators for each sector and sub-sector.

Agricultural activity	ENI 1 (€/UAA)		ENI 2 (€/UAA)		ENI 3 (€/UAA)		ENI 4 (%)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Crop farms	52.63	723.47	292.53	2622.35	35.73	178.79	0.01	0.07
Field crops (except cereals)	30.97	264.12	173.08	1,381.99	17.20	71.95	0.01	0.10
Cereals	19.25	178.05	186.31	1,228.65	20.00	65.01	0.01	0.07
Horticulture	129.90	989.43	1,148.11	6,055.66	45.57	274.27	0.01	0.04
Grape	13.62	78.49	91.91	519.79	46.47	161.37	0.01	0.09
Olive	43.22	490.98	131.34	1,288.12	6.70	37.47	0.01	0.05
Orchards - Fruits	86.08	1,267.51	159.77	1,728.27	58.15	251.83	0.01	0.04
Livestock farms	202.81	9,315.06	164.28	1,935.89	8.21	44.82	0.02	0.13
Herbivores	381.49	13,033.22	147.03	1,832.59	2,0.44	15.30	0,0.01	0.08
Dairy cows	17.61	240.87	148.24	1,311.73	4.22	22.12	0.02	0.10
Granivores	13.92	152.39	245,0.66	2,949.19	32.89	97.05	0,0.07	0.23

Agricultural activity	ENI 5 (%)		ENI 6 (LU/UAA)		ENI 7 (%)		ENI 8 (N.)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Crop farms	1.34	5.20	0.01	0.10	3.45	8.95	1.05	0,59
Field crops (except cereals)	3.76	8.32	0.03	0.20	11.03	15.17	1.39	0.62
Cereals	1.49	4.93	0.01	0.03	1.43	3.39	1.54	0.52
Horticulture	1.25	4.61	0.01	0.06	1.53	5.69	0.78	0.73
Grape	0.47	3.76	0.01	0.08	2.09	6.08	0.82	0.45
Olive	0.57	3.28	0.00	0.03	1.03	4.03	1.00	0.23
Orchards - Fruits	0.42	3.17	0.01	0.09	2.03	6.39	0.90	0.39
Livestock farms	2.16	6.74	17.04	109.70	27.56	20.15	1.13	0.45
Herbivores	2.91	7.72	2.49	16.14	31.20	18.20	1.12	0.40
Dairy cows	1.31	5.34	3.31	4.23	31.40	19.80	1.14	0.40
Granivores	1.52	5.61	86.03	252.83	9.58	16.32	1.15	0.63

Agricultural activity	ENI 9 (N.)		ENI 10 (ton CO2eq/LU/yr)		ENI 11 (ton CO2/UAA/yr)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Crop farms	0.05	0.22	0.06	0.40	0.26	0.44
Field crops (except cereals)	0.06	0.22	0.15	0.60	0.59	0.59
Cereals	0.08	0.26	0.07	0.41	0.51	0.47
Horticulture	0.04	0.20	0.05	0.34	0.18	0.37
Grape	0.07	0.25	0.04	0.26	0.10	0.28
Olive	0.03	0.17	0.02	0.20	0.10	0.22
Orchards - Fruits	0.05	0.21	0.06	0.39	0.09	0.24
Livestock farms	0.10	0.29	3.07	2.52	0.70	0.46
Herbivores	0.06	0.23	2.62	0.78	0.81	0.44
Dairy cows	0.10	0.29	3.86	1.87	0.66	0.43
Granivores	0.21	0.40	2.96	5.20	0.46	0.47

Source: Own data processing on FADN dataset.

profitability will decrease (also proven by a negative relationship between this environmental indicator and the ROE). Analyzing the relationships between the environmental indicators and the economic indicator ECI2, except for the ENI10 indicator, produced the same evidence. Four environmental indicators (ENI3, ENI8, ENI9, ENI10) are positively correlated with the total output per LU, while only three

TABLE 4 Trade-off analysis results for each sector and sub-sector.

Agricultural activity	Correlation coefficient	*p*-value
Crop farms	−0.02727	0.0448**
Field crops (except cereals)	−0.05075	0.1089
Cereals	−0.10375	0.0034***
Horticulture	0.077856	0.0289**
Grape	−0.04358	0.1347
Olive	0.044226	0.3165
Orchards - Fruits	−0.02782	0.3484
Livestock farms	−0.23212	0.0000***
Sheep. goats (herbivores)	−0.15015	0.0000***
Dairy cows	−0.26923	0.0000***
Granivores	−0.12932	0.0077***

*,**,*** Statistically significance for $p < 0.1$, $p < 0.05$ and $p < 0.01$, respectively. Source: our analysis based on FADN data.

(ENI4, ENI6, ENI7) with ECI5 (which measures the economic health of farm).

5 Summary of main findings

Summarizing the key general findings, it emerged that:

- Achieving a balance between maximizing economic output and minimizing environmental impacts requires improved optimization of economic and environmental goals.
- More in-depth research is needed to assess the sustainability of agricultural production using multiple indicators.
- The underrepresentation of women and young people in Italian farming highlights the need for stronger policies to promote female entrepreneurship and support younger farmers.
- There is a low level of farm diversification.
- While some farms make strides toward sustainability, significant variability remains, especially in the use of fertilizers and pesticides. Italian agriculture still has a long way to go before fully transitioning to sustainable practices.
- There is also a trade-off between environmental regulations and economic outcomes, particularly for livestock farms, where reducing emissions might hurt economic indicators like profitability.

The main results related to environmental and economic indicators are as follows:

- Reduction in animal emissions: A decrease in animal emissions negatively impacts four out of six economic indicators, including the ROE, reducing livestock farms' operational efficiency and profitability.
- Improvement of environmental indicators: Efforts to improve six out of eleven environmental indicators (ENI3, ENI4, ENI7, ENI10, ENI11) would lead to a decline in the farm's ability to remunerate all resources (reflected in the economic indicator ECI1) and a decrease in the total output per AWU.
- Impact on the livestock farming sector: These changes may reduce the attractiveness of livestock farming, worsening the challenges faced by an already stressed sector with fewer people willing or able to enter the industry.
- Impact on crop subsectors: Two significant relationships emerged, one negative for the cereals sector and one positive for the horticulture sector.

6 Discussion

Previous studies have recognized the need for in-depth research on the evaluation of agriculture production using multiple indicators to comprehensively investigate and balance the competing goals of maximizing farmer profits and minimizing the adverse environmental effects of production by using environmental resources efficiently (White et al., 2020).

However, despite the increasing studies of synergies and trade-offs between sustainability dimensions, knowledge of the interrelationships between economic and environmental dimensions at the crop and livestock farm analysis level and levers to foster the sustainable transition of agriculture and livestock systems is still limited. This paper adds to the current discussion of the proper indicators to analyze agriculture sustainability dimensions in the context of Italian farms.

Before addressing our research question specifics, it is worth highlighting the significant matters that arose from analyzing our sample.

The results related to women-run farms and young farmers show on the one hand need for more incisive in promoting female entrepreneurship in agriculture, considering that in many family businesses, women are sometimes just nominally entrepreneurs because of family strategy, although they are actually employed by the farm (Gidarakou, 2015), and play a pivotal role as many times they are the only ones who start and develop new business on the farm (Lans et al., 2020). In this sense, rapid implementation of action is necessary to achieve the CAP's objective of promoting employment, growth, and gender equality, including the participation of women in agriculture. On the other hand, the results confirm previous studies that recorded young Italian farmer's dramatic decrease (Dias et al., 2019; ISTAT, 2022) and highlight the need for policies supporting them in starting their businesses, considering that the farmer's age also affects how issues relating to environmental changes and degradation of natural resources are addressed (Addo, 2018; Pindado and Sánchez, 2017; Zagata and Sutherland, 2015). The importance of this issue is underlined by the fact that one of the 10 Key policy objectives of the CAP 2023–27 is the generational renewal, since "a vibrant agricultural sector needs skilled and innovative young farmers to respond to societal demands, from quality food to environmental public goods" (European Commission, 2024).

Furthermore, our sample reveals a low level of farm diversification, although it has improved compared to the previous decade, reflecting the impact of the pandemic on non-agricultural activities (ISTAT, 2022). Nonetheless, our findings indicate that the European Union's ambitious Farm to Fork Strategy goal of reaching 25% organic farmland by 2030 seems achievable for Italian crop farms, reaffirming the organic sector's importance in the Italian food market (Casolani et al., 2021; Liberatore et al., 2018).

To answer our research question, firstly, each economic and environmental indicator was calculated for each farm, and, secondly, two composite indexes were elaborated to perform the trade-off analysis. As regards economic indicators, our sample of farms, although freed from outliers, shows high variability. Regarding ROE, in particular, its high standard deviation indicates high variability among farms in their efficiency in originating profits and how the economic crisis may have affected farms' financial performance differently. Also, in this case, the policymakers' role in implementing actions to foster the CAP's objectives of increasing competitiveness and improving farmers' position in the value chain appears fundamental. Some environmental indicators also showed great variability, especially in using organic and industrial fertilizers and pesticides. This shows the need for targeted actions to incentivize non-virtuous farmers and not discourage virtuous ones from acting in a way that contributes to the achievement of the CAP goals of climate change mitigation, efficient natural resource management and halting and reversing biodiversity loss will be achieved.

Our findings showed that the road ahead for a successful Italian agricultural sector transformation to meet multiple sustainability goals is still very long since there is a trade-off between maximizing short-term production and ensuring long-term sustainability. The modern agricultural system is called to provide more than just food, fiber, feed, and fuel to rural communities and the economy at large, but also to actively contribute to achieving SDGs, especially minimizing environmental impact from land-use practices and enhancing equitable social outcomes as well as to ensuring "sustainable food production systems and implement resilient agricultural practices that increase productivity and production" (target 2.4, Agenda 2030). Then, with the Farm to Fork (European Commission, 2020) and CAP 2023–2027, the EU's objective of bringing agriculture toward a more environmentally sustainable paradigm was further reinforced by arguing that in doing so, food accessibility should be preserved, the competitiveness of EU supply chains and promoting fair trade should be improving, while generating more honest economic returns at the same time. However, our findings showed that farms' primary productivity and economic revenues would suffer due to these changes and reinforce concerns already expressed, according to which a high level of climate ambition could negatively affect agricultural production and prices (Barreiro-Hurle et al., 2021).

To be precise, the two macro-sectors showed a trade-off between the two dimensions investigated, as well as all sub-sectors of livestock production.

It is known that livestock is responsible for much of agriculture's greenhouse gas emissions [65% of total Italian agricultural emissions and 5.2% of total national emissions in 2018, with a reduction of 12 and 40% compared to 1900 and 1970, respectively—ISPRA, 2020]. Despite all this, it should be noted that livestock farms play a crucial role in ecosystem services as key components of agroecosystems (Hoffmann et al., 2014). While a good part of the farms' revenue is essentially linked to public subsidies, the ecosystem services provided by them, especially by those that produce in extensive or semi-extensive ways in inland areas—which are increasingly recognized as strategic for Italy to address the ecological transition and food crises (Marotta and Nazzaro, 2023)—, are significant, and, therefore, such productions should be encouraged and enhanced to continue to operate mainly in marginal areas, which would otherwise be abandoned, with serious repercussions also on an environmental level (Cerrato et al., 2023). Besides, promoting employment, growth, and local development in rural and marginal areas is one of the CAP's 10 objectives.

The ecological transition and food and energy crises have revealed the issue of inner areas, which seem to have become strategic in Italy despite their vulnerabilities. In addition, Italian livestock systems also bear cultural values, such as those related to rural traditions, which are highly valuable to the tourism industry.

This study also reveals that a decline in the farm's ability to generate economic returns could make livestock farming less attractive, worsening the challenges in a sector already facing declining participation (Duval et al., 2021).

In summary, in this trade-off situation, exacerbating attention toward the environmental dimension would cause economic damage not only to the farms—which would thus be more inclined to abandon their activities—but also to the environment itself and other sectors linked to it, with consequent impoverishment of entire geographical areas.

It should be remembered that the CAP was envisioned and designed by the founders of the European Economic Community to respond primarily to security questions, that is, increasing productivity in agriculture to ensure a fair living standard for the agricultural population and providing secure and affordable food supplies to consumers. At present, farmers face several risks that can adversely affect their income, including production, market, and financial risks, beyond unexpected and unpredictable crises that affect their income and consumer prices (Ahmad et al., 2023; Komarek et al., 2020). Moreover, challenges in the geopolitical panorama have opened the debate on national strategic autonomy and food sovereignty and have brought food safety policies back to food security to the forefront, and with those, the responsibility of European and national institutions to guarantee access to food (Pulina, 2022). In the past few decades, and increasingly since the 2003 reforms, due to the growing attention paid to environmental compatibility themes, production themes have gradually lost importance, and issues related to supply security have been overlooked in the belief that world markets will continue to provide agricultural and food products at a reasonable price for Europeans, thus allowing in the meantime to promote sustainability, biodiversity, and eco-compatibility in the EU. However, it has become increasingly apparent the need to consider both environmental sustainability and production themes when making Agricultural Policy, as the recent crises showed the fallacy of global markets and inadequately to meet the Europeans' primary needs, which find themselves having to protect their food sovereignty.

EU cereal production is projected to be 4.3% below the 5-year average in 2023/24 due to adverse weather conditions (European Commission, 2023b), highlighting the need to reconsider European environmental objectives, such as reducing chemical pesticides by 50% by 2030. Actions aimed at reducing the use of herbicides, pesticides, water, energy, and fuels, while promoting carbon sequestration, negatively affect economic measures like farm net value added, total output per AWU, and productivity. Our findings should prompt a reevaluation of European environmental objectives. While it is argued that the changes brought about by the new rules would be gradual to minimize any impact on food safety, the trade-off between environmental and economic considerations in the Italian and international cereal production scenario does not seem consistent with European goals and the win-win perspective of current European policies and strategies. It has been found that efforts to decrease the use of herbicides and pesticides, water, energy, and fuels, while increasing the cultivation of multiannual and perennial crops for UAA and carbon sequestration, have negative impacts on several economic factors: farm net value added and Total output for AWU, total output per UAA and productivity of intermediate consumption.

In contrast, the horticultural sector, prominent in Mediterranean countries like Italy, benefits from environmentally friendly practices. Since consumers and public opinion are increasingly interested in high-quality food products produced by environmentally friendly methods, policies that promote environmentally friendly practices and foster a favorable economic climate – for example, among other, those aimed at the diffusion of technologies that improve the quality of fruits and vegetables for consumers and society's environmental concerns, as well as those aimed at strengthening market ties, developing market incentives, and promoting sustainable certification programs, or, again, precision agriculture, whose adoption in Italy is still behind (Troiano et al., 2023)—could, at the same time, benefit farms' economic performance. Our findings confirm previous studies (i.e., Kumar et al., 2023) that see sustainable horticultural practices as a win-win solution since they contribute to natural resource conservation, nutrient needs, environmental enhancement, and economic growth. However, a noteworthy fact is that our results show that an increase in the use of organic fertilizers leads to a reduction in the farm net value added per AWU, and the increase in the Share of clover and Carbon sequestration implies a reduction, albeit with a low magnitude, of ROE.

In line with the aim of the agricultural sustainability assessment of assisting decision-makers in determining which actions are appropriate for moving toward sustainable agriculture (Ness et al., 2007), this work offers various contributions to policymakers. Since farm-level decisions are crucial to determining the effects of the food system on society and the environment, and measurement and evaluation of farm-level agricultural sustainability is an important step toward achieving a sustainable food system by supporting evidence-based policymaking (Robling et al., 2023), this paper examines sustainability practices at the first-level of implementation, which is the most crucial level for assessing the impact of sustainability measures. By examining not just one dimension of sustainability in the context of crop production and livestock farming to reflect the multifaceted concept of sustainability and through several economic and environmental indicators, this article provides a more realistic picture of the relationship between economic and environmental dimensions in crops and livestock farms.

Overall, the trade-off analysis of Italian farms underscores the importance of adopting a holistic and integrated approach to agricultural sustainability at the EU level. By addressing both economic and environmental dimensions, policy- and decision-makers can work toward building a resilient and sustainable agricultural sector that meets the needs of present and future generations. Specifically, among the main policy implications, the trade-off analysis of Italian farms provides valuable insights into the complex relationship between economic viability and environmental stewardship within the agricultural sector. Policymakers are tasked with balancing the need for agricultural production to support food security and rural livelihoods with the imperative to mitigate environmental degradation and address climate change. Achieving this balance requires a better understanding of the trade-offs involved, as well as targeted interventions to promote sustainable agricultural practices.

Demonstrating the existence of trade-offs between those dimensions, except for horticulture farms, is crucial because it enables politicians to look at that, probably, the green transition they strive to achieve as not combining environmental sustainability with economic profitability. The findings of the trade-off analysis provide important considerations: by identifying areas where economic and environmental objectives may conflict, considering the different agricultural sectors as environments with specific needs, policymakers can tailor interventions to mitigate trade-offs and promote synergies between economic and environmental sustainability. Moreover, the insights from the analysis can inform the design and implementation of EU agricultural policies to ensure that they effectively address both economic and environmental sustainability dimensions.

The European new strategies and CAP rightly embrace the thesis that to achieve SDGs, agriculture needs to transition toward a more sustainable production model. An alternative to the strategies' review could be to guarantee greater agricultural and livestock farmers' economic support in terms of aid for agriculture and animals for those promoting practices with low environmental impact or aimed at enhancing positive environmental amenities. In this respect, the direction already advanced in previous research (Faccioni et al., 2019; Madau et al., 2022; Plieninger et al., 2012) could be to switch from the traditional concept of subsidies to payment for targeted ecosystem services that farms provide but are not properly priced through market mechanisms. This may involve incentivizing sustainable farming practices, supporting agroecological approaches, and promoting resource-efficient production systems.

Our findings also show the need to foster female entrepreneurship and young farms, which are fundamental to guarantee the durability of the crop and livestock sectors, recognizing they are crucial in the light of the social role due to the ecosystem services provided.

This paper offers pivotal contributions to the academic debate on sustainability in the agriculture sector. It follows several authors who have urged utilizing a set of indicators to assess farm sustainability (de Olde et al., 2016; Singh et al., 2012; van Huylenbroeck et al., 2000) and, due to inconclusive previous studies, a deeper investigation into economic and environmental relationships within the agricultural sustainability paradigm (Grzelak et al., 2022), highlighting that, in agreement with Sidhoum et al. (2022), there is an interconnected set of economic and environmental objectives that must be optimized, resulting in trade-offs in some situations and synergies in others.

Finally, as regards the implications for practitioners, since our results show that now, in most cases, there is a trade-off between economic and environmental performance, farmers should invest more in training to be able to adopt new environmental practices that beyond to safeguard the environment, lead to cost savings, so as not to succumb to increasingly stringent European ecological goals.

7 Conclusion

Agriculture plays a central role in sustainable development and is central to achieving the goals of Agenda 2030 (Kanter et al., 2018). The European Green Deal and its F2F strategy recognize agriculture as a priority economic sector contributing to various sustainability goals, including social well-being, healthy ecosystems, and food and nutrition security. However, despite investments in the Common Agricultural Policy (CAP), agriculture continues to generate negative externalities such as biodiversity loss and greenhouse gas emissions. Rural areas also face issues like abandonment and heritage loss. A growing body of research emphasizes the need for better balancing agricultural economic and environmental performance. However, there remains limited understanding of these trade-offs at farm and sector levels.

The study focuses on Italian farms and reveals that only 20% are managed by women, with a decline in young farmers. This calls for policies to support female entrepreneurship and younger generations in agriculture. Additionally, farm diversification is low, and while organic farming growth seems achievable, meeting EU targets might challenge economic returns. The research confirms the existence of trade-offs between economic and environmental goals, particularly in livestock farming, where emissions reductions harm profitability. Crop farms also face challenges with policies aimed at reducing industrial fertilizers, potentially reducing production. However, the horticultural sector shows promise as a win-win scenario for both economic and environmental goals.

The findings suggest the need for a more integrated approach to agricultural sustainability, balancing economic viability with environmental stewardship. Policymakers are urged to design interventions addressing sustainability and productivity challenges, while recognizing the sector's multifaceted role in food security, ecosystem services, and rural development.

Our research is affected by some limitations. First, inputs and outputs of agricultural systems are constrained by location-specific natural, social, and cultural circumstances. Therefore, analyses focused on individual contexts rather than at a national level could reveal different realities. Future research can involve comparisons at a national, regional, or individual locality level or even between lowland, hill, or mountainous areas, thus digging up possible best practices usable as examples. Second, when the FADN will be converted into a Farm Sustainability Data Network (FSDN), future research can expand our research to the social dimension to give even more emphasis to the multidimensionality of sustainability and highlight the type of relationship between all three of its dimensions. Third, considering that sustainability also encompasses the social aspect, it will be valuable to conduct a similar analysis once the Farm Sustainability Data Network (FSDN) becomes accessible (2025 should be the first year of data collection, which will therefore be available in 2026–2027). This analysis will help ascertain social indicators' impact on the environmental and economic dimensions. Fourth, we must recognize the limitations of the FADN database, which, despite being one of the most reliable and most used databases in literature, may have to deal with deficient data especially when information needed was not collected because the database was not designed to answer any given research question, which can raise possible sample bias or estimation (European Commission. Statistical Office of the European Union, 2020). Furthermore, as often happens, the discretion in selecting economic and environmental indicators could influence the conclusions of the analysis (Lebacq et al., 2013). Future research could retrace our analysis using other or additional indicators. However, because such indicators were already used in previous studies, those limitations do not impair our pivotal contributions to academics, practitioners, and policymakers.

Data availability statement

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

Author contributions

BA: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. FC: Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Validation, Writing – review & editing. PS: Conceptualization, Methodology, Writing – review & editing. RF: Conceptualization, Project administration, Supervision, Writing – review & editing. PP: Conceptualization, Project administration, Supervision, Writing – review & editing. FM: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, 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.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1474903/full#supplementary-material

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