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This issue of Bio-Based and Applied Economics is dedicated to Luca Salvatici, featuring one of his last writings.
Luca passed away on May 2025, prematurely, far too soon. He was a curious, passionate, rigorous, and tireless scholar whose value was internationally recognized. He dedicated himself to many roles and, above all, passionately taught many young, and now not-so-young, researchers. He leaves an indelible memory among his colleagues.

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The social sustainability of European agriculture facing old and new challenges. Issues, methods and policies

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In the last couple of decades, the scientific and political debate, as well as the discourse in the broad society, gave a great deal of attention to the sustainability implications of the ways production and consumption are carried out worldwide (Scoones, 2007; Fisher & Barth, 2014; Verbanov, 2019; Rodriguez-Dono & Hernández-Fernández, 2021). Clear enough, this interest touches directly also the agricultural sector (Mockshell & Kamanda, 2018; Junker et al., 2019). At the same time, agriculture is both affected by consequences of unsustainable practices enacted within the sector, as well as by what is going on in other segments of the economy and of the society. This is true for all the three dimensions of sustainability: environmental, economic and social (El Bilali & Hassen, 2021).

However, so far, analyses about environmental sustainability, and partly about its economic dimension, advanced quite significantly both with respect to the concept itself and to its measures (Yu & Wu, 2018; Coburn at al., 2024). Differently, reflections on what social sustainability precisely is, which aspects it encompasses and on what are the most suited measures lag far behind (Latruffe et al., 2016). Probably the reason is that the topic still presents itself as extremely multifaceted, magmatic and elusive.

Notwithstanding, challenges and contradictions associated to old, still unresolved, structural knots and bottlenecks, as well as the ongoing social transformations and tensions, increasingly convey attention on it and filling the gap of knowledge has become truly urgent.

This urgency is also witnessed by the contents of the two perspective documents recently issued by the EU, i.e. "Strategic Dialogue on the Future of EU Agriculture" (Strategic dialogue, 2024) and "A Vision for Agriculture and Food. Shaping together an attractive farming and agri-food sector for future generations" (European Commission, 2025; Arfini et al., 2025). These documents -which aim at tracing the direction of the future pathways of the European policies for agriculture, food and rural areas- explicitly and implicitly address, among others, many aspects that fall in the domain of social sustainability. Among these, it is worth to cite a few ones on which the two documents particularly insist.

At the very root of the many social threats faced by European agriculture and rural society there is its acute demographic imbalance. A progressively ageing and shrinking workforce and population is incapable of assuring vitality and continuity to the primary sector and rural areas. In many EU countries the problem dates from decades ago, in other is more recent, as it is anyhow related the so-called agricultural exodus. However, it is nowadays fuelled by increasing competition among different production systems worldwide and by the difficulties of family businesses to survive in global value chains dominated by giant firms in the upstream and downstream stages. All these pressures end up in reducing the attractiveness of agriculture, especially for younger potential entrants. This contributes to the depopulation and marginalization of rural areas, creating a vitious circle in which the deterioration of living conditions acts as an additional deterrent to enter the sector. Difficult access to land -especially the better quality, more productive ones and in densely populated areas- exacerbates the demographic imbalance.

Beside issues related to family farms and family labour force, the agricultural labour market mixes up marginality and precariousness that, together with the even more complex migration issues, pose serious social sustainability threats. Gender justice is also part of the social sustainability issue of European agriculture as women's working conditions are still affected by inequalities.

Environmental degradation and climate change, of which agriculture is both victim and responsible, are not only relevant issues in themselves, but also have deep implications on farmers' health as well as on healthiness and safety of the products and services that the sector delivers to citizens and consumers. As for the healthiness of food and diets, this falls not only in the domain of agriculture and of the processing industry, but it is also -or even primarily- connected to the consumer's choice, which, in turn, relies on the so called multidimensional "food environment", made of knowledge, information, traditions and habits, socio-cultural influences and norms, public food procurement and policies against food poverty, and so on and so forth. All these features crosscut all the spheres of sustainability, fully falling also in its social domain.

From this very quick review it clearly emerges how relevant the topic of social sustainability is worldwide and how much urgent some of its facets are for the future of the EU agriculture and rural society. This is why in 2024 AIEAA decided to devote its annual Conference to the theme. The Conference, held in Bari June 20-21, was titled: *The social sustainability of European agriculture facing old and new challenges. Issues, methods and policies*. This Special Issue of BAE collects a selection of 7 papers presented at the 13th AIEAA Conference that contribute to the scientific debate of sustainability in its broad sense.

The first paper here included is from Anton et al. (2025) from OECD. This is the expanded text of one of the keynote lectures at the Conference and is titled *Towards a new policy narrative for agriculture: capturing social sustainability issues*. The paper provides a broad reasoning about the different aspects encompassed by social sustainability issues in agriculture. It starts by accounting for the many difficulties in the definition itself. In providing the boundaries of the concept, the authors focus on contextual specificities and cross-sector implications. The core question addressed is about the lack of data and consequent difficulties in measurement. The authors review the path followed along two decades by researchers and institutions for defining and measuring the environmental dimension of sustainability, in order to grasp insights that may be useful to the additional challenge posed by the social sustainability, most recently placed in the spotlight. In the search for an easy measure that is also highly correlated with the main social issues in agriculture, they propose to first look at indices of income inequalities.

The paper by Martella et al. (2025) "*Promoting natural capital conservation: a bet for socioeconomic development of marginal areas*" revolves around socioeconomic marginalization and environmental sustainability. The aim of the paper is to explore factors which can promote/enhance the well-being of marginalized areas through the push of the local economy. The focus is on a small marginal area in Central Italy where the ecological balance is positive. Based on this premise, the authors propose a branding strategy that leverage of environmental sustainability of local production, to get the goal of raising the market value of the products and the farmers' income, thus contributing to the protection of their natural capital and to sustaining the local economy of the marginal area.

The third selected paper by Moino et al. (2025) is titled *Bridging the Gap: The Impact of Compensatory Measures on Mountain Farming in Piedmont*. The study presented, based on 3,171 observations from FADN 2012-2022, assesses the impact of the Rural Development Program on income disparities between mountainous and non-mountainous areas in Piedmont, Italy. Findings of a pooled multivariate regression indicate that significant income disparities are primarily observed in small farms specialized in cattle and sheep and goats. Compensatory allowance support helps to partially reduce the gap. Policy strategies to entirely bridge the gap are discussed.

Mazzulla and Raggi (2025) are the authors of a paper titled *Do economic performance and innovation have a relationship? Evidence from Operational Groups in the Italian agri-food sector*. They investigate the potential interdependence between an environment that fosters innovation and the economic performance of agriculture. More in details, they seek to determine whether the economic performance of farms in regions with established Operational Groups (OG) is better than that of farms where OGs have not yet been implemented. Data come from Innovarurale website and ORBIS database (2013-2022), and estimations include three staggered difference-in-differences (DID) models. Results show a positive association between the presence of OGs in a region and an improved economic performance.

The paper by Okoye et al. (2025) is titled "*Technological Integration in Agricultural Practices of a sample of Italian livestock farms*". Based on Census data, the paper explores the current state and determinants of digital technology adoption across Italian livestock farms. A logistic regression model assesses the likelihood of technology adoption. Results show that dairy cattle and buffalo are more likely to integrate digital tools like decision support systems, cloud services, and monitoring devices. Differently, meat cattle, small ruminants, and pig farms lag. Key determinants include broadband connectivity, ownership structure, education and age.

The adoption of digital technologies is at the core also of another contribution titled *Assessing the social impacts of Digital Agriculture Technology Solutions: a practical tool*, by Bianchi et al. (2025). The Authors argue that Digital Agriculture Technology Solutions (DATSs) can improve the social benefits for the farmers. Integrating top-down and bottom-up approaches, a Social Sustainability Assessment Framework was developed and tested on 60 farmers across 20 European countries, with a heterogeneous composition. The research allowed for an investigation of the social impacts of DATSs in terms of labour evolution, education and learning, and generational change. The results demonstrate the positive effects of DATSs on the social sphere of sustainability, as well as the importance of integrating this type of analysis in their evaluation.

Another paper included in this selection, by Ferro et al. (2025), addresses workers' welfare issues. The contribution is titled *Impacts of heatwaves on agricultural workers: An analysis of adaptation measures* and evaluates the effectiveness of different coping strategies. Exploratory interviews and structured questionnaires were employed to identify key challenges; data were collected from nine farms located in Northeastern Italy, all committed in improving working conditions. The so-called Analytic Hierarchy Process was used to evaluate the perceived effectiveness of adaptation measures according to three criteria: acceptability, flexibility, and timeliness. Findings indicate that, in the absence of adaptation strategies, productivity losses may reach up to 30%. The study underscores the need for structured thermal risk assessment protocols and provides recommendations to worker-centred adaptation policies in agriculture.

Adenuga and Jack (2025) contribute with the paper *Factors influencing land rental market participation: a case study in Northern Ireland*. The objective of their study is to analyse factors influencing participation in the land rental market in Northern Ireland where the sale of agricultural land is limited with a constrained tenanted sector. Principal component analysis and multinomial logistic regression model are used on data from 1,466 farmland owners. Results show that land rental market participation is impacted by motivational and socioeconomic factors. Authors argue that incentives for early and easy retirement of older farmers will increase land access of young farmers and consequently improve the land rental market.

The last paper included in this selection is titled *Agriculture and Environment: the inclusion of Italy in the SIMPLE and SIMPLE-G models* and is by Vaquero Piñeiro et al. (2025). The paper explores the interactions between economic and environmental issue in agriculture and proposes an expansion of the Simplified International Model of Agricultural Prices, Land Use and Environment (SIMPLE) model – which addresses national agricultural trends-plus its gridded version (SIMPLE-G) – which offers a detailed, spatially disaggregated analysis. This second model allows for assessing local impacts. In particular, they build a new database for Italy, in order to compute both aggregate and georeferenced data for the country.

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Towards a new policy narrative for agriculture: capturing social sustainability issues

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Abstract. Awareness about issues related to inequality and well-being in agriculture is increasing, with some evidence of inequalities affecting e.g. women, youth, and migrant farmworkers, that hinder their access to income, land, health, education, and training. Despite the increasing policy interest around social sustainability, tackling social issues in agriculture is complex due to lack of consensus in definition, contextual specificities, data gaps and needs to apply non-sectoral policies. Two decades ago, environmental sustainability faced similar challenges but is now mainstreamed in agricultural policy making. Climate change measurement and analysis played a pivotal role in creating a new agri-environmental policy narrative. Expanding agricultural sustainability from the green transition towards a just transition will require a game changer that is measurable and highly correlated with main social issues. Could an investment in measuring income inequalities play this role and facilitate a new social sustainability perspective in agricultural policies?

Keywords: social sustainability, green transition, income inequalities, inclusiveness, well-being.

1. INTRODUCTION

The goal of sustainability over time is recognised as one of the most fundamental principles in global policy making, typically covering three pillars: economic, environmental and social sustainability (Giddings et al., 2002). To advance sustainable development, the agricultural sector thus needs to contribute to all three dimensions (Janker & Mann, 2020; FAO, 2022). Traditionally, the sustainability debate in agriculture has focused mainly on economic aspects and, more recently, on the environment. Economic sustainability, building competitiveness and productivity growth, has been prominent in agricultural policies. Over the past two decades, together with other environmental concerns, climate change and its effects on economic growth and environmental outcomes have come to the forefront of global agriculture policy dialogues (Olesen & Bindi, 2002; Howden et al., 2007). The need to accelerate a green transition in agriculture has led to an increased focus of agriculture and food systems policies on climate-smart strategies to move

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farms and rural communities towards net zero emissions and better management of the environment (Asai et al., 2023).

The income gap between agriculture and other economic sectors has been a long-lasting argument to justify support to farmers, in particular in the early times after the Second World War (Gardner, 1992). Recent data show that farm income in the EU Member States has been increasing, even if there may still be in some cases a gap compared to other sectors (Matthews, 2024). On the other hand, the lack of economic opportunities for the farming sector, declining services and lower well-being standards in rural areas remained prominent, witness the farmer protests that emerged in Europe in 2023-2024 (Finger et al., 2024; Matthews, 2024).

In recent decades, the social aspects have been rarely discussed as main policy drivers in agriculture and are seen as a cause or a consequence of environmental or economic problems, rather than a stand-alone goal. However, recent evidence shows that farmers, farmworkers and their families in rural areas of OECD countries are facing a diversity of social issues that are of an increasing concern for policy makers (Asai & Antón, 2024). For instance, in Switzerland, female farm family workers work around 75-80 hours a week, but only about half of them (55%) are paid for their work (Moser & Saner, 2022). In the United Kingdom, over 50% of workers in agriculture, forestry and fishing were suffering from work-related Musculoskeletal Disorders (MSDs) (HSE, 2023), while in Australia one farmer dies by suicide every 10 days, a rate 59% higher than non-farmers (Sartor, 2021). In the United States, the net farm income of African American farmers is 10% of the average of other farmers (Collins et al., 2023).

Most of these issues are related to inequality and quality of life (e.g. physical and mental health) that are not a new phenomenon in agriculture. However, people's awareness of the related risks is increasing. For instance, more frequent extreme weather events result in farm income losses, which may be perceived as critical risks by famers, exacerbating the uncertainty on the sustainability of the sector and, potentially, impacting mental illness and higher rates of suicide (Daghagh Yazd et al., 2019; Riethmuller et al., 2023). Social issues are returning from a new lens: skewed distribution of income and of low-income risk among farmers and farmworkers reflect inequalities and potential social exclusion, which is a concern for citizens and policy makers.

Tackling social issues has gained increasing policy importance, also in agriculture, as reflected in the food systems approach (OECD, 2021). However, the lack of data and evidence has been identified as a constraint to identify and address some social issues, including related to gender, illness and injuries in the farm, and immigrant farmworkers (Giner et al., 2022; Merisalu et al., 2019; Antonioli et al., 2023). Accordingly, there is no widely acknowledged methodology for quantifying and analysing the social dimension of sustainability, neither on the criteria to be used when assessing the concept (Saleh & Ehlers, 2023; Janker & Mann, 2020).

The overall goal of this paper is to identify opportunities to advance towards social sustainability goals in agriculture when designing, implementing and monitoring policies. How can the agriculture and food policy community develop a narrative and the required evidence to respond to existing social sustainability issues? We first review the green transition in agriculture according to recent agricultural policy trends in OECD countries. In particular, we assess critical conditions that transformed the policy narrative by mainstreaming environmental sustainability, led by climate change and the efforts to measure its linkages to agriculture. Second, we explore the main dimensions of social issues in agriculture, and their data and measurement challenges that impede further understanding and analysing social sustainability concerns. Finally, we explore the role of income as potential catalyst to advance on the social sustainability agenda. Income is measurable and could be analysed from a new social sustainability perspective, focused on income inequalities and well-being, facilitating the advancement of the policy agenda from a necessary green transition to a green and inclusive transition in agriculture.

2. HOW THE ENVIRONMENT BECAME A MAIN DRIVER IN RECENT AGRICULTURAL POLICY TRENDS

Agricultural policies were significantly reformed in the 1990´s and 2000s in the United States, the European Union and in other OECD countries. For instance, the reforms of the EU´s Common Agricultural Policy (CAP) prior to the mid-2000s were successful in reducing producer support, notably market price support, while progressively "decoupling" support from production, with payments per hectare that do not require any specific production and are more effective in transferring support to farmers. The main goal of these reforms was of an economic nature: reducing the distortions associated to the government support to the sector and reaching farmers more effectively.

A shift on composition and level of support was observed not only in the European Union, but across

OECD countries, where successive reforms have led to increased market orientation and more efficient forms of support. It is also reflected in the share of the most production- and trade-distorting forms of support, which has also decreased. Given that such support (market price support, coupled direct payments and input support) potentially also contributes to negative environmental outcomes, these reforms also contributed to improve environmental sustainability, even if this was not the main objective (Bureau & Antón, 2022)

Since these reforms took place, there has also been an increasing scope of environmental requirements attached to the CAP payments (Figure 1). Since 2010, the European Union's Producer Support Estimate (PSE) level and composition have remained almost unchanged, though increasingly with input constraints attached to payments, reflecting a greater integration of environmental and climate objectives (OECD, 2023; OECD, 2024).

To reflect this evolution of agricultural policy objectives and impacts, a variety of agri-environmental indicators has been developed by countries and international organisations to track the environmental performance of the farming sector, particularly during the last two decades. For instance, the OECD agri-environmental database (OECD, 2023) shows trends and levels of a broad range of indicators, including on agricultural land use change, fertiliser use, water abstraction, on-farm energy consumption, GHG emissions and nutrient balances (Figure 2). These indicators were selected on the basis of data availability, and environmental and policy relevance. They provide an accurate comparable measurement of the main environmental pressures associated with agricultural activities. The OECD agri-environmental database allows to assess performance comparing trends across countries and between agricultural output growth and environmental outcomes. For instance, in the last three decades OECD countries significantly increased output while, at the same time, reduced nutrient balances. Trends in other environmental outcomes such as GHG emissions and farmland bird index are less promising.

Regardless of the performance of each country, the development of agri-environmental indicators has been an integral part of a new narrative that has increased the focus of agricultural policies on environmental sustainability. The measurement of these sustainability outcomes helps to develop a common understanding of the environmental goals and their links with agricultural production, practices and policies. These indicators have also inspired and informed attempts to combine economic and environmental performance into an environmentally sustainable productivity index in agriculture (Cobourn et al., 2024).

Climate change has been a global game changer or "catalysts" in the environmental policy agenda and,

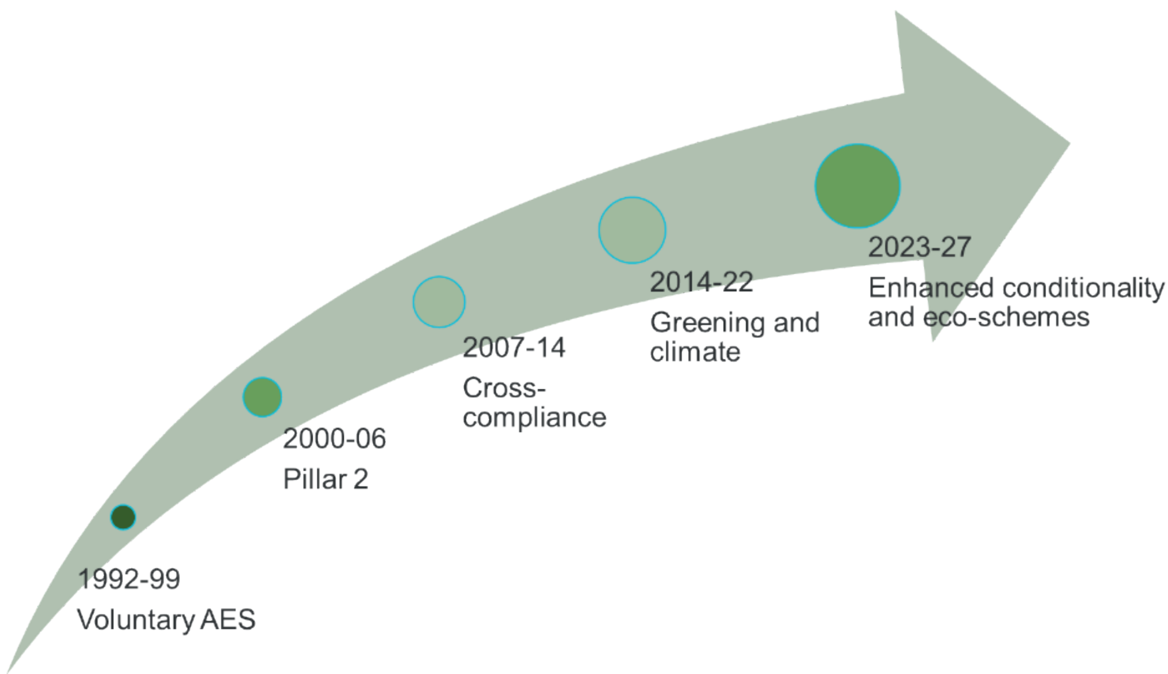

Figure 1. Integration of policy instruments with environmental and climate objectives in the Common Agricultural Policy in the European Union.

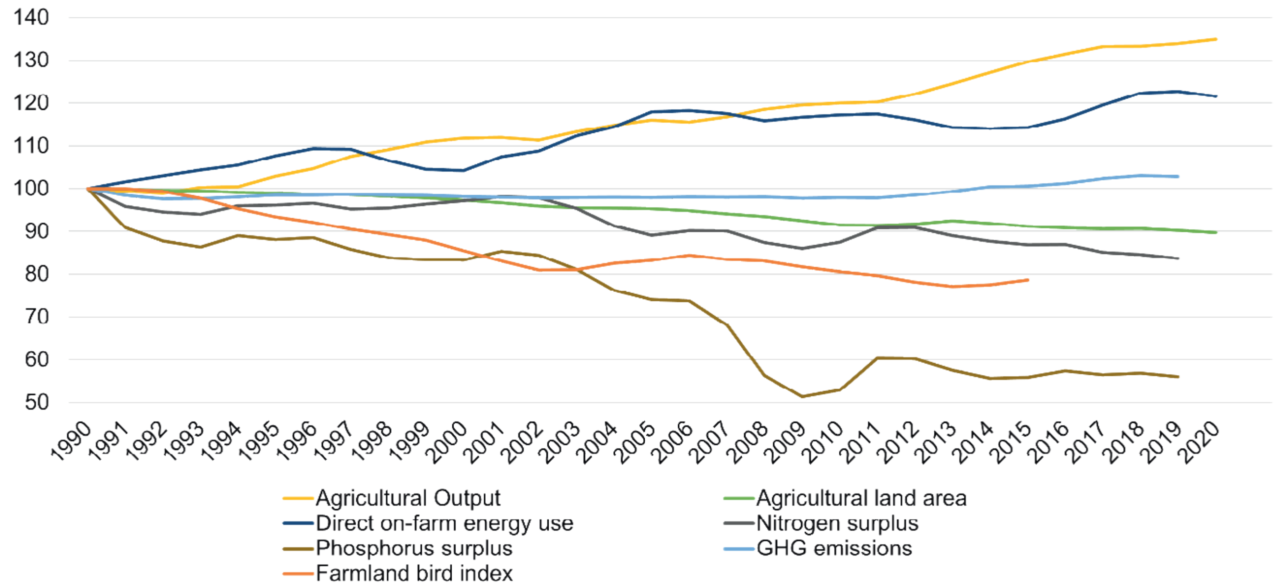

Figure 2. OECD Agri-environmental database. Source: OECD Agri-Environmental Indicator data base (OECD Data Explorer).

to a great extent, also in the agricultural sustainability debate. Indeed, climate change is a shared environmental concern and a global public good that has contributed to growing awareness on environmental sustainability (Figure 3) reflected in the European Green Deal EGD. Each country's and each sector's GHG emissions contribute cumulatively to the increase of the overall concentration of GHGs in the atmosphere, and then mitigating climate change through reduced emissions is a common goal for which there are already comparable methods to measure, and relevant indicators have been developed accordingly. Climate change also brings multiple related agri-environmental issues together because there are significant correlations among them. For instance, there are links between different emissions, water quality and nutrient imbalance, and between emissions and biodiversity. The work of the International Pannel on Climate Change (IPCC) has informed policymaking and international negotiations, including the UNFCC and the Paris Agreement, and has triggered and embedded a large body of research on measuring and understanding the environmental impacts of different economic activities and alternative policies (Guerrero, 2021; Lankoski, 2016; OECD, 2022; DeBoe, 2020). The analysis of climate change and of its relations to the agricultural sector not only has contributed to a new narrative that increasingly puts farmers in the driving seat of the contribution of agriculture to the environment, but it has also stimulated the development of a broad range of agri-environmental policies and regulations.

3. WHAT ARE THE POLICY CHALLENGES TO ADVANCE TOWARDS SOCIAL SUSTAINABILITY?

The food systems approach to policy making has incorporated not only agri-environmental concerns, but also consumer concerns and social issues (OECD, 2021), resulting in a growing concern for policy makers and research communities to improve well-being of farmers and their communities (Asai & Antón, 2024). Well-being of farmers is affected by a broad range of factors, which can be classified in four main groups: (1) Factors affecting farmers' economic well-being (such as income and wealth); (2) Factors affecting the quality of life, including work and job quality; (3) Factors affecting the well-being of the community; and (4) Factors affecting the well-being of women, Indigenous Peoples and specific social groups.

Figure 3. Climate change as a game changer in environmental sustainability

As regards as the economic factors, regional inequalities and the urban-rural divide challenge the well-being of rural areas (Meloni et al., 2024; OECD, 2020). Based on the analysis of household disposable income in 25 European countries, Meloni et al. (2024) found that the income of rural households is lower than that of non-rural households. The proximity to urban centres plays an important role in shaping well-being of rural residents, including farmers (OECD, 2020). Rural places situated in closer proximity to urban centres exploit benefits from infrastructure development (e.g. hospitals and schools) and transportation because of improved access to human capital, external markets, and a wide array of services and environmental amenities. Remote areas, in contrast, face the largest challenges regarding connectivity, causing higher costs for transportation, infrastructure and service provision that affect the well-being of residents in these areas (OECD, 2020; OECD/EC-JRC, 2021).

Given that agricultural sector faces double challenges of aging and rural depopulation, encouraging generational renewal is a top priority for many countries. Nevertheless, young farmers encounter multiple obstacles both prior to entry and once in the sector (Campi et al., 2024). These obstacles include capital constraints, regulatory complexities, access to land and housing, lower access to services compared to other jobs, and lack of the networks needed to access resources. Negative social views of farming due to e.g. hard-working conditions, degrade the attractiveness of the profession and discourage new entrants (Campi et al., 2024). Furthermore, a 'brain drain' of young talents from rural areas challenges generational renewal (Kalantaryan et al., 2021; Zagata & Sutherland, 2015). Other studies also show that farms in more isolated regions are less prone to be inherited by the following generation (Aldanondo Ochoa et al., 2007).

As for the factors affecting the quality of life, agriculture is known for one of the most hazardous sectors worldwide, with numerous studies reporting elevated levels of occupational fatalities, injuries, and illnesses (WHO, 2004). As regards the working conditions, farmers may face long working hours, in particular during peak production seasons and under labour shortages (Marlenga et al., 2010; Hostiou et al., 2020). It was recently found that farmers working longer than 40 hours per week may be at higher risk for fatigue-related injury and illness (Elliott et al., 2022). In many cases farmers and those working in agriculture are also exposed to chemical pesticides, and this is linked to chronic illnesses such as cancer, and heart, respiratory and neurological diseases (Dhananjayan & Ravichandran, 2018).

Occupational stress, associated with longer working hours, compliance with increasing government regulations, weather volatility, and financial pressures is another factor that may have negative effects on quality of life and in some cases it can lead to mental health issues for farmers and their families (Farm Management Canada, 2020; Brennan et al., 2021; Daghagh Yazd et al., 2019). A range of ongoing occupational stressors associated with farming may contribute to place farmers at an elevated risk of suicide (Purc-Stephenson et al., 2023): evidence from Australia, France and the United States shows higher suicide rates of farmers than those working in other sectors (Miller & Rudolphi, 2022; Page & Fragar, 2002; Bossard et al., 2016; Hostiou et al., 2020).

Securing equal opportunities to work in safe conditions and the same access to care and health services is highly important for the individual well-being. The literature shows that in the farming sector such conditions are not always met and are challenged by climate change and structural transformations. Studies in Canada highlight three barriers for providing mental care services for farmers: accessibility of health services in rural areas; stigma around mental health in the agricultural community; and lack of health professionals who are familiar with the agricultural context (Farm Management Canada, 2020; Hagen et al., 2019).

Social capital is another important dimension of social sustainability and is key for higher community well-being. Inclusiveness may be achieved through better connections between people and in particular cultural events and leisure activities can lead to a higher sense of civic engagement for farmers and improved co-operation with other members of the community (Halstead et al., 2021; Rivera et al., 2018). Moreover, community involvement, trust and support can help people tackle challenges and opportunities, and contribute to improve individual well-being and resilience, helping individuals and communities to recover from, and more successfully adapt and transform in response to adverse events (Aldrich & Meyer, 2014; Adger, 2010). In contrast, rural crime, discrimination and social isolation lead to distrust among community members and lack of a sense of belonging, adversely impacting community well-being (Deller & Deller, 2010; Smith, 2020). The ongoing ageing and depopulation trends in rural areas may exacerbate this negative phenomenon.

Finally, there are unique challenges often faced by Women, Indigenous Peoples, and specific social groups, such as migrant farmworkers and people with disabilities, due to social and economic barriers and biases that hinder their access to income, land, food, health, education and training, and other services (OECD/FAO, 2016;

Todd et al., 2024; ILO, 2023). Women tend to encounter longer unpaid working hours more often than men and have lower social security entitlements (FAO, 2020). In the European Union, only 31.6% of farm managers were female in 2020 (OECD, 2023), while in the United States, 7% of all farms were operated solely by women in 2017-2020 (Todd et al., 2024). These figures imply that women's role in agricultural decision making, and farm and land ownership remains relatively modest.

For Indigenous Peoples the main inequalities concern their access to land (including land that was taken from their ancestors), education and training, as well as capital, which remains a significant barrier for Indigenous entrepreneurs and business owners (OECD, 2019). Migrant farmworkers often are (informally) hired on a casual, piecework or seasonal basis, and their work often involves long hours and difficult conditions under high risk of illnesses and injuries, while being insufficiently covered by social security (UN, 2009; Martin, 2016).

The actors and territories involved on these social issues are very heterogeneous and the challenges facing farmers and farmworkers are diverse. Different social circumstances may require different policies and tools and need targeted analysis. Furthermore, the bargaining position of farmers and farmworkers differs across locations and sectors and is a main source of inequalities both along the agrifood value chain and within the farming sector.

In the past decade, several OECD countries have incorporated social issues in the policies and programmes led by their respective ministries of agriculture. For example, generational renewal and social conditionality on employment conditions and on-farm safety and health are part of the goals and measures included under the European Union's Common Agricultural Policy 2023-27 (OECD, 2023). Both Canada and New Zealand implement specific agricultural measures for Indigenous Communities, while, in the United States, the Department of Agriculture administers programmes that benefit the so defined "socially disadvantaged farmers and ranchers" (Todd et al., 2024; Asai & Antón, 2024). In Italy and Japan, the ministries fund "social farming" initiatives to create more inclusive opportunities for vulnerable groups at community level, such as promoting agricultural employment for persons with disabilities (Guirong & Oba, 2023; Borsotto & Giarè, 2020).

Table 1 presents an overview of five case studies from OECD countries with examples on how governments have approached issues of inequality and other social issues in agriculture: the definition of the issue, the policy rationale and the specific policy measures. Across these policy examples, policy makers have looked beyond traditional sectoral policies and seek to target social issues from a broader policy perspective, as agricultural policies are often not designed for the purpose of tackling these issues. The main types of policies in the toolbox applied in these examples are targeted measures on health, skills, training, social protection, legal reforms, research and data. Existing agricultural policies are not targeted to identified social issues and they are used only as accompanying measures (Switzerland) or potential sources of funding (Italy).

4. MEASURING SOCIAL SUSTAINABILITY PERFORMANCE

The lack of appropriate data is a further challenge to advance in the social sustainability agenda in agriculture, making important social issues invisible to both policy makers and citizens. Greater understanding of issues around inequality and inclusiveness and the best policy approaches to address them requires appropriate data, indicators and measurement (Asai & Antón, 2024; Giner et al., 2022), which is challenging due to complexity, a missing social sustainability framework, lack of data and unstandardized indicators (Brennan et al., 2020; Janker & Mann, 2020). Figure 5 summarises the three main challenges associated with measuring social sustainability performance in agriculture: the lack of a clear and agreed definition of social sustainability; the data gaps to define and identify social issues; and the challenge to quantify social issues in indicators. Even if agri-environmental sustainability faces similar challenges, there has been a significant advancement in the last two decades as reflected in the set of agreed OECD agri-environmental indicators in Figure 2.

Despite the increasing interest, the common understanding of what constitutes social sustainability and how it might be achieved is limited (Janker et al., 2019; Asai & Antón, 2024; Nowack et al., 2022). Social sustainability is still considered as subjective and there is no consensus on the different aspects it should entail (Janker & Mann, 2020; Saleh & Ehlers, 2023). A universal definition is lacking and there is no widely acknowledged methodology for quantifying and assessing the social dimension of sustainability. Indicators on contracts, gender gaps and socioeconomic characteristics of the farming population are a good starting point. However, Janker & Mann (2020) performed an analysis of 87 farm-related social sustainability assessment tools finding a diversity of approaches: some tools are based on human rights and working rights according to the UN and ILO conventions and look for working conditions

Table 1. Policy examples and their policy interventions to address social issues.

Country	Social issues at stake	Rationale for policy interventions	Main policy instruments
Canada (Case 1)	Increasing number of farmers suffering from mental health problems.	Mitigate factors of farmers' stress that could affect mental health	Support farmer mental health research Promote mental health literacy in agricultural communities
Switzerland (Case 2)	Many family members (e.g. wives) who work on the farm receive no financial renumeration and social protection.	Equal treatment across workers in agriculture and with other sectors	From 2027, extend social protection coverage to partners on farms as a precondition for direct payment
Italy (Case 3)	Lack of effective social and health services in some rural areas, and limited care services for vulnerable groups.	Inclusiveness opportunities for vulnerable groups through the Social Farming (SF) practices	Set-up networks for diversification of agricultural activities, (e.g. healthcare, education) and to carry SF
New Zealand (Case 4)	Economic pressures, demographic and social changes, and mental health challenge well-being of farmers and other citizens in remote rural communities.	Support "rural community hubs" to build social relationships and rural resilience	Start-up funding to help establish the "rural community hub" where people meet, discuss issues, have workshops etc.
Japan (Case 5)	Limited job opportunities for people with disabilities while agricultural sector faces an acute shortage of labour force.	Equal access to jobs and sources of income for persons with disabilities. Reduce labour shortages in agricultural sector	Provide training courses and support to develop user-friendly facilities that reduce barriers to employment faced by persons with disabilities.

Source: Based on Asai & Anton (2024).
Note: Information covers a selection of case studies collected from governments and experts in those case study countries/regions in the period of June 2023 - Feb 2024.

indicators, while others assess farmers' perceptions of their quality of life.

Social issues may remain hidden if there is no data able to identify and define them. Evidence suggests that there is still a large gap between agricultural sector-specific (e.g. the Census of Agriculture) and economy-wide data on social issues (Asai & Antón, 2024). In many OECD countries, farmers represent a very small share of the total population and they are often under-sampled in general surveys that tend to be non-representative of the farmer population. For instance, although the EU's Income and Living Conditions survey (EU-SILC)[1] was not created for the assessment of farmers' welfare, it allows for the identification of farmers and farm households (Marino et al., 2023). An attempt to analyse the income gaps between farm and non-farm households in EU Member states using EU-SILC was confronted to too small samples of farm households to allow a representative distributional analysis (Rocchi et al., 2020; Marino et al., 2021; Marino et al., 2023).

Having a small sample size poses a critical limitation on the use of general datasets for exploring social issues in agriculture, especially when focusing on smaller subgroups within farming populations, notably those that are disadvantaged or vulnerable. Considering that the family farm remains the most common type of farm in many countries, women often engage in family unpaid labour that might not be recorded in statistics, which makes it difficult to acknowledge and assess (Giner et al., 2022). Regarding the racial and ethnic minorities in agriculture, some countries like the United States have a questionnaire on racial and ethnic, under- or un-reported cases are frequent due to incomplete survey responses with respect to race and ethnicity information (Lacy, 2023).

The surveys regularly conducted in the agricultural sector, including the Farm Accountancy Data Network (FADN) in Europe and the Agricultural Resource Management Survey (ARMS) in the United States, are pri-

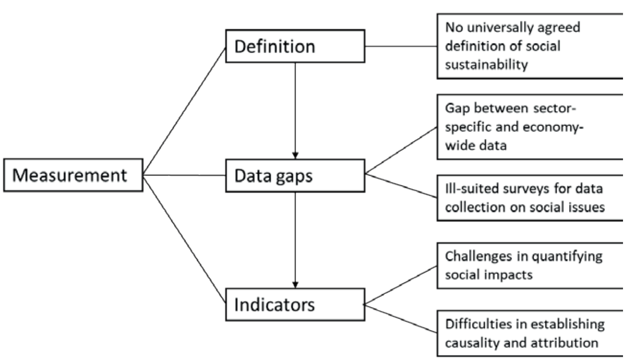

Figure 4. Schematic presentation of the challenges for the measurement of social sustainability in agriculture.

[1] EU-SILC is a harmonised household survey that collects multidimensional microdata on income, poverty, social exclusion and living conditions in Europe.

marily intended for economic purposes. Although there are ongoing initiatives to expand the scope of these surveys (e.g. from FADN to Farm Sustainability Data Network (FSDN) reflecting the CAP's evolution towards sustainability), they may still not be well-suited to analyse social issues. Furthermore, most of the existing sectoral surveys focus on farmers, yet there are substantial data gaps regarding farmworkers, especially migrant and seasonal farmworkers, despite their important role in the agricultural sector in many countries (Ryan, 2023; Ramos et al., 2020). In economy-wide household surveys farm households are under-sampled, and migrant and seasonal farmworkers are not captured because they normally focus on the resident population (Kalantaryan et al., 2021). Some countries like Italy and the United States collect some data on seasonal foreign farmworkers (Antonioli et al., 2023; Castillo et al., 2022).

The self-employed status of many farmers is likely resulting in the under-reporting of incidents (e.g. accidents, injuries, illness and suicides). Studies from European countries found that farmers and farmworkers are unlikely to report injuries if they do not have an incentive such as insurance benefits (Merisalu et al., 2019). In areas such as mental health, it is difficult to ask sensitive questions on personal health or social relations through a survey (Brennan et al., 2020). Several studies highlight that a large share of actual cases of mental illness or suicide may be underreported due to social stigma in rural areas (Purc-Stephenson et al., 2023; Miller & Rudolphi, 2022). Finally, there are personal and social sensitivities that are country specific and make data collection on social issues particularly challenging. For instance, some countries such as Finland, Norway and Sweden, explicitly forbid the collection of statistics on ethnic identity (OECD, 2019). These data gaps make it harder to develop indicators to monitor and tackle social issues and to identify target groups.

Because social issues are complex and vary across countries and regions, context-specific data and analytical methods are used, requiring more qualitative indicators than for environmental and economic issues. Such indicators are subject to a high degree of subjectivity (Kelly et al., 2018) and are difficult to harmonise. The choice of social sustainability indicators is not only the result of a neutral scientific analysis, but also of societal choice reflecting a diversity of views.

Finally, another challenge is identifying drivers that hinder some aspects of well-being in a manner that is specific for farmers or their communities (Asai & Antón, 2024). This analysis is critical to identify the need for policies that specifically tackle social sustainability in an agricultural context. Information regarding these driving factors and causal relations is frequently limited. There is a risk of a vicious circle between the shortage of data for identifying policy demands and the lack of clear policy priorities for funding data initiatives.

5. LOOKING FOR A CATALYST ON SOCIAL SUSTAINABILITY

Therefore, despite the increasing policy interest around the dimensions that affect the well-being of farmers, their families and farmworkers, and that of the communities in which they live, defining and tackling social issues in agriculture is complex. There are four main bottlenecks summarised in Figure 5. First, there is no consensus on what constitutes a social issue. The nature of social sustainability includes social processes and interactions that emerge within a community and makes it difficult to identify a coherent, clear and utilisable definition (Eizenberg & Jabareen, 2017). Moreover, subjectivity often comes into play in people's judgments that a particular state of affairs constitutes a social issue (Kulik, 2023). This is frequent in any analysis of agriculture, but in the case of social issues the driving factors go beyond complex production conditions into personal, health and community linkages.

Second, social issues are often context specific and addressing them requires considering different perspectives and sensitivities of stakeholders. Urban-rural inequalities play an important role in shaping well-being of rural residents, including farmers (OECD, 2020; Meloni et al., 2023). Thus, social issues can benefit from a place-based approach because they are associated with a specific location. Possible solutions often derive from the local context, and policy interventions are often away from the traditional agricultural policy areas (OECD, 2020; Asai et al., 2023).

Third, tackling social issues requires policies that go beyond traditional sectoral programmes. Agricultural policies focus mainly on economic and environmen-

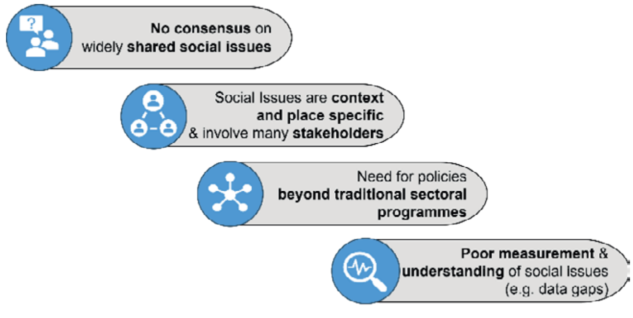

Figure 5. The four main bottlenecks in addressing social issues.

tal outcomes of the sector, often leaving social objectives and implications to other policy areas. However, the agricultural sector is only a small player for social policy partners and its specificities and policy context may be overlooked. As confirmed by the five policy examples in Table 1, defining and tackling social issues in agriculture requires policies beyond traditional sectoral programmes (Asai et al., 2023; Janker & Mann, 2020; Saleh & Ehlers, 2023).

Finally, as discussed in section 4, social issues are often poorly measured due to the lack of data and data infrastructure, and subsequent unstandardised indicators. The trade-offs between social and economic sustainability are, therefore, difficult to assess. For instance, how better working conditions affect productivity.

Considering these bottlenecks, a game changer seems necessary to advance on the social sustainability agenda in agriculture, similarly to what climate change measurement and analysis represented in the context of the green transition. This does not mean that social sustainability must come after environmental sustainability in a sequential manner. Policy trends towards environmental and social sustainability may have the same policy roots, but they may need different triggers to effectively become main drivers of policy changes and impacts.

The policy agenda for a more inclusive transition could benefit from an indicator that is easily measurable and highly correlated with social sustainability issues, and that allows cross-comparison among countries, regions and social groups. Income inequality has a good potential to play a catalyst role on social sustainability, since it meets several critical conditions. Although not perfect, income inequality is a widely social concern and affects all the population, and it is also correlated to many dimensions that are currently characterising the social sustainability debate in agriculture, including health, gender, marginalized groups, decent work and social capital. Of course, a complete analysis of social issues should also include access to public services and infrastructure that also contribute to well-being.

Together with wealth, income largely determines the ability of individuals to meet their basic needs (e.g. food, housing, healthcare, transportation, education) and to make choices that contribute to security, satisfaction and personal fulfilment (Meloni et al., 2024; OECD, 2020; Meloni et al., 2023). Thus, addressing income-related inequalities is critical to achieve overall economic well-being. In the agricultural policy debate, such issues have been discussed for a long time to justify policy support aiming to address the assumption of lower income in agriculture business as compared to other production activities (Rocchi et al., 2020; Katchova, 2008). However, the social sustainability debate would benefit from a broader perspective on income, by looking not only at the level of farm income, but also looking at: the farm household income and income of those working in farming and food sector; the income distribution differences by gender and with other sectors; and the differences among agricultural, rural and non-rural households. It should also entail by focusing on policies tackling income inequalities and their impacts on low household income and poverty among those making their living from agriculture, rather than focusing solely on increasing farm income (OECD, 2023; OECD, 2003).

Recent studies show that in the European Union farm household incomes on average are not particularly lower compared to non-farm household incomes (Rocchi et al., 2020; Marino et al., 2021; Mittenzwei et al., 2024), while others have shown that income inequality and poverty are greater in the farm community compared to the non-farm community (de Frahan et al., 2017). However, the lack of data is the main constraint for an accurate assessment. Administrative, political, and technical obstacles hinder the collection of comprehensive farm household data and currently there is no reliable system to allow income comparisons among farmers, farm workers and those in other sectors of the economy (Hill & Bradley, 2015; ECA, 2016; OECD, 2023).

Improving the understanding of the income distribution issues related to farms, farm households and rural households could help to move forwards the social sustainability agenda also from an agricultural policy perspective. As showed in figure 6, in the context of the CAP, direct payments to farmers decoupled from production, which represent an important part of farm income, have been increasingly linked to several environmental requirements under conditionality. However, direct payments are distributed to households based on the amount of land used rather than on their overall household income. A full sustainable (social and environmental) transition would lead to a shift in the policy mix towards more targeted payments to farm households suffering from low-income, and to result-based agri-environmental payments (OECD, 2023).

In addition to these targeted payments, other EU and national agricultural policies could contribute to the inclusive transition. For example, EU rural development policy includes a range of measures some of which may increase the attractiveness of rural areas and promote agricultural entrepreneurship. The provision of public services such as education, health and transport is particularly relevant to improve well-being and social sustainability. Social conditionality was also introduced in the CAP 2023-27, with the overall objective of link-

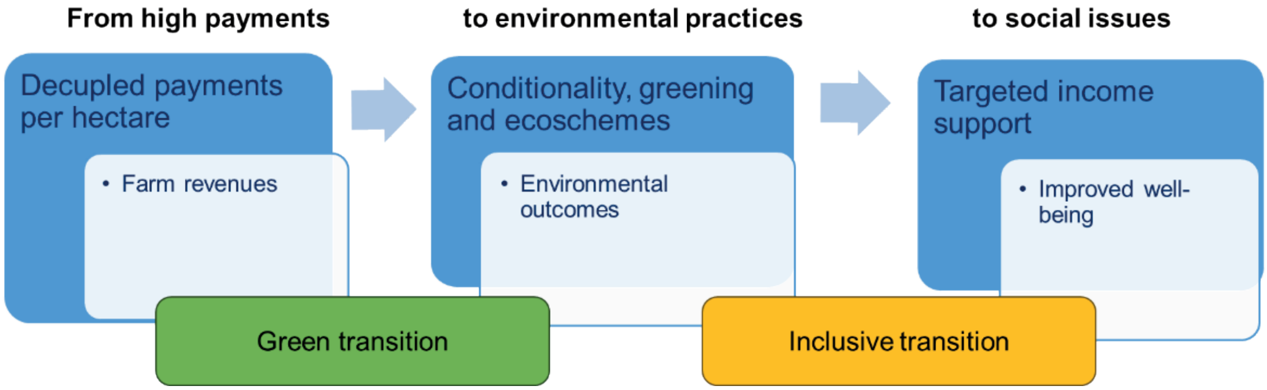

Figure 6. Policy pathways towards a green and inclusive transition in agriculture.

ing farmer payments to compliance with certain labour laws. Although all these policy tools have potential to improve, among other, the well-being and working conditions of farmers and the agricultural labour force, they are not targeted to income distribution issues.

Stronger evidence on disposable income could allow to have a better understanding of the standard of living of farmers, since income is strongly interlinked with key dimensions of well-being including, among other, job quality, housing, health and work-life balance. Thus, improving the availability and access to micro-economic datasets for the assessment of the income aspect of policies not only at farm level but at the household level could be a very important step in monitoring and tackling social sustainability issues in agriculture.

Such a data investment would provide policy makers with a proxy for the well-being of farm households and then a tool to better define the rationale of income support and to target it to legitimate social objectives (OECD, 2023). A more accurate measurement of total farm household income would also allow to assess the potential impact of agriculture policies as compared to non-sectoral policies such as social policies on income and ensuring livelihoods, as well as to contributing to other social sustainability objectives. Data availability and needed investments to measure farm household income deserves a separate in-depth analysis.

6. CONCLUSIONS

Social issues are gaining momentum in research and policy discussions on agricultural sustainability. This is the result of multiple drivers, including increasing anecdotal evidence of inequalities and quality of life issues that are specific to the agricultural sector. Similarly to environmental issues twenty years ago, social sustainability today lacks a clear and shared definition, and a common and well-established metrics to tackle its complexity and its multiple and interrelated dimensions. Measuring and analysing climate change, together with other agri-environmental indicators, has contributed to create a new agri-environmental policy narrative based on metrics related to the environmental sustainability of agriculture.

Recently, governments have made efforts to focus their policies on achieving agricultural "sustainable productivity growth" (SPG) (OECD, 2024). The concept of SPG is based on the idea of increasing productivity while reducing the pressures on the environment. The need to also cover the social aspects of sustainability has emerged in the discussion on measuring the SPG (OECD, 2024). The main difficulty of measuring social sustainability performance is its many dimensions and context-specificity (Asai & Antón, 2024; Janker & Mann, 2020)

Despite this limitation and other existing bottlenecks in addressing social sustainability, an increasing number of governments has started to approach the issues of inequality, inclusiveness and other social issues in agriculture. Since agricultural policies are often not designed for the purpose of tackling social issues, seeking for cross-sectoral approaches and collaboration with other policy areas and stakeholders can help to design policy mixes targeted to the sector's social concerns. However, the lessons from agri-environmental sustainability show that to advance on the social sustainability agenda a new narrative is needed based on clear definitions and metrics. The design and implementation of suitable policy mixes needs an evidence-based approach to respond to the most pressing social issues.

In a context where available statistical tools are not sufficient to measure the well-being of farm households and farm workers, measuring income inequalities could be a catalyst to advance on the research and policy agenda on social sustainability through both a new narrative and a new set of indicators. In particular, more reliable data on agricultural household income could be an important first step to design more effective and targeted income support that responds to social sustainability concerns. Investing on data to build a new evidence-based narrative on the sustainable transition of agriculture, that needs to be greener, but also more inclusive and socially sustainable.

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Promoting natural capital conservation: a bet for socioeconomic development of marginal areas

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Abstract. The aim of this paper is to enhance the well-being of marginalized areas by improving their local economy, considering the correlation between socioeconomic marginalization and environmental sustainability. These two objectives are at the core of the international and European policy agenda, but they are not often merged in one action. Within this study, we selected a marginal area in central Italy and assessed its environmental sustainability, using the method of the ecological balance. The results show that this territory has the capacity to provide an amount of natural capital greater than the ecological footprint generated by local production activities, thus the value of the ecological balance is positive. Then, we discussed how local policies can favor processes focused on agricultural products coming from areas recognized as sustainable. Environmental sustainability can be work as a branding strategy, which can raise the market value of the products and the farmers' income, thus supporting the economic development of marginal areas and promoting the protection of their natural capital.

Keywords: sustainability, marginality, ecological balance, agriculture, rural policy.

1. INTRODUCTION

The socioeconomic development of marginal areas is one of the most important targets of European policies, due to their generalized diffusion. About 45% of European territory consists of regions presenting strong marginality characteristics (De Toni et al., 2021).

In countries where a large part of the territory is covered by marginal areas, as in the case of Italy, the policy makers are engaged in facing the implementation of specific interventions to fill the development gaps that often characterize such areas (Kang et al., 2013a). Socioeconomic marginality, indeed, is associated with negative characteristics such as isolation, low income, depopulation, old age of residents, weak connections with urban areas, few infrastructures and a significant share of the local income being based on agricultural production (Arshad et al., 2021).

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However, there are also some positive aspects in marginal areas, such as immaterial assets, which are important to promote their development: biodiversity, varied agroecosystems, wide availability of natural resources, just to name a few (Ahmadzai et al., 2021; Balzan et al., 2018). This evidence has led to the general and often implicit perception that marginality is associated with sustainability. The point is not whether this perception is true; rather, what do we mean by (socioeconomic) "marginality" and (environmental) "sustainability".

This study, carried out within the Spoke 7 of PNRR Agritech project ("*Integrated models for the development of marginal areas to promote multifunctional production systems enhancing agro-ecological and socio-economic sustainability*"), aims to face and discuss this point.

More specifically, this paper has three main objectives.

The first one is to give a clear definition of socioeconomic marginality and select a marginal area inside the province of Viterbo (Italy) that matches such definition.

The second one is to adopt a definition of environmental sustainability and assess if the selected marginal area may be declared as sustainable. To accomplish this objective the focus has been placed on the agricultural sector rather than on the whole local economic system. This choice is justified by two main reasons. First, agriculture is the only economic sector that directly manages natural resources, represented by farmland. Second, the idea of food from a sustainable production system mainly refers more to agricultural practices than to the other stages of the supply chain.

The third one is to discuss how specific actions supported by local institutions can favor processes to promote agricultural products coming from an area recognized as sustainable to raise their market value, thus increasing the farmers' income and supporting the economic development of a marginal area.

As asserted by Basile and Cavallo (2020), regional and cohesion policies of national governments and the European Union typically address internal or marginal areas. However, the objective of this paper is not to discuss the national or regional measures more suitable for the development of marginal areas. This work looks at valorization process of local economy as a possible "*bottom-up*" action, able to identify a territorial brand linked to specific characteristics of marginal areas (Banini and Pollice, 2015). This appears to be an interesting topic also considering that, despite its significance, research on the connections between place branding and sustainable development is still limited in the scientific literature (Aguilera-Cora et al., 2024).

To achieve these objectives the paper is structured as follows.

The background is divided into two subsections. In the first one we discuss what a marginal area is, what does marginality mean, which the marginality indicators are and why the idea of sustainability is so often linked to marginal areas. In the second one, we present the definition of environmental sustainability as the spatial condition where the natural capital maintenance is ensured. The methodology section is also split in two parts. One describes the process adopted to identify a marginal area as a group of municipalities in a province. The other explains how the environmental sustainability of an agricultural system can be evaluated by means of an ecological balance. The results section reports on the outcome of the marginal area selection process and the description of its main characteristics. The ecological balance assessment of the selected area's agricultural system follows. The results obtained are then discussed to underline their coherence with previous studies and in terms of policy implications of sustainability conditions. The paper ends with some final considerations related to the opportunity of valorizing the environmental dimension of the marginal areas.

2. BACKGROUND

2.1. The concept of marginality and marginal areas characteristics

Rural areas cover a wide part of the Italian territory. Many of these areas face the issue of overcoming the developmental gaps with urban areas and the consequent negative phenomena such as depopulation, ageing and loss of primary services. This topic is particularly relevant in a country like Italy, where the internal areas suffer isolation and socioeconomic problems.

For this reason, these areas are specifically considered as the target of many European (Oecd and European Commission, 2020) and national policies, such as the "National Strategy for Inner Areas" (SNAI), to support their revitalization with a "place-based" approach, where the focus of the policies are the specific qualities of each area and its local production system (De Toni et al., 2021).

In addressing these issues, the regions with the above characteristics are often defined as marginal areas, yet it is not so common to find a clear meaning of what "marginality" really is. Therefore, a definition of marginality is needed for the task of identifying and shaping the boundaries of a marginal area.

The general idea underlying the concept of marginal areas, a notion frequently used by researchers and policy makers, is often associated with a complex condition of disadvantage according to both geographic characteristics and socioeconomic aspects. Sometimes this term is also used like a synonym for abandoned, degraded, unused or under-used area (Sallustio et al., 2018).

To provide a more comprehensive definition, it should be noted that there is a widely shared understanding that socio-economic marginality refers to situations of territorial disadvantage that undermines the vitality, competitiveness and development potential of a region (Arshad et al, 2021). These are areas with a very low population density and a negative demographic trend, along with a minimal presence of basic services (Malikova et al., 2016). Furthermore, a region is considered marginal because it is significantly distant from essential services and is also characterized by geomorphological conditions that lead to structural deficiencies in transportation routes, which in turn affect the location of settlements and productive activities (Lucas, 2012; Vendemmia et al., 2021). A territory far from primary services and weakly connected to infrastructures and networks is marginal because these conditions affect the establishment of farms and industries (Meini et al., 2017). Marginality also involves a structural weakening of the local system's capacity to react, caused by the simultaneous occurrence of a combination of recessive effects (Carrosio and Osti, 2017).

Due to the uneven geographical distribution of development conditions, such as structures, activities resources, knowledge and so on, resources available to develop local systems do not operate everywhere with the same intensity, increasing the risk of socioeconomic marginality (Sotte, 2016). On the other hand, if we associate the territorial conditions of marginality to the specific characteristics of the economic local production system, the economic system itself can represent a development driver, provided that is possible to promote its positive environmental dimension (Ahmadzai et al., 2021).

Given a definition of marginality, it is important to clarify that, as a phenomenon, it can be measured, detected, and quantified based on coherent economic, social, territorial, environmental, and demographic indicators within a specific area. As well as the possible definitions, even the indicators of socioeconomic marginality are varied and often interrelated. Commonly used indicators include income levels, employment status, education and access to basic services such as healthcare, housing and social protection. Other indicators may include participation in informal labor markets, vulnerability to economic shocks and social isolation (Vendemmia et al., 2021). Indicators help both with identifying the area at risk of marginalization and providing a framework for assessing the effectiveness of policies aimed at reducing inequality and promoting social and economic development (De Toni et al., 2021).

In choosing indicators it is important to consider that marginality is both a relative and dynamic condition: relative because it can only be defined through comparison with different situations, either spatial or socio-economic; dynamic because various causes can influence its level, as well as changes in terms of comparison or in the factors considered important in defining it (Ahmadzai et al., 2021). To identify marginal areas as a group of municipalities, data related to selected indicators should be collected at municipal level.

Moreover, it is appropriate that such aggregation corresponds to an administrative authority. This is important because only in the presence of an authority that aggregates the municipalities it is possible to apply policies to develop the marginal area, involving the participation of economic actors and the engagement of local administrations and stakeholders (Covino R., 2017).

2.2. Definition and assessment of environmental sustainability

Agriculture, like all productive activities, uses natural resources to obtain the material and energy inputs needed to carry out production processes and to absorb residues, such as waste and greenhouse gas emissions. However, unlike other sectors, agriculture has the potential to directly contribute to the supply of natural resources with different types of farmlands. The property of agricultural system of managing natural resources and economic activities at the same time offers the opportunity of directly comparing availability and consumption of natural capital in a certain area. It is thus possible to assess a real ecological balance (Franco, 2021a).

In this regard, there is a broad consensus in the scientific community that ecological footprint (Wackernagel and Rees, 1996), is a suitable methodology to compare supply and demand of natural resources, therefore assessing the environmental sustainability of economic processes (Moldan et al., 2012; Neumayer, 2013). The environmental sustainability discussed here, refers to the ability of the ecosystems to support given economic effects. Specifically, the approach used in this study, evaluates a type of environmental sustainability defined as "*strong*", which assumes the conservation of natural capital as a basic condition, where the use of natural resources must avoid the deterioration of their reserve. This methodology is not limited to the analysis of single economic activities, but it is also applicable for entire regions, thus providing the possibility to operate at different scales, as highlighted in many studies focused on agricultural sector (Niccolucci et al., 2008; Cerutti et al., 2013; Galli et al., 2014; Martella et al., 2023; Biagetti et al., 2023a).

To proceed with the assessment of an ecological balance in agriculture, the first step is represented by the delimitation of the space involved in the assessment. Then, it is essential to define the key indicators for calculation. The availability of natural resources present in the defined area is measured by Biocapacity (BC), while Ecological Footprint (EF) quantifies the impact of economic activities carried out in the same area. EF translates the natural capital required by cultivation and livestock management in terms of biologically productive areas, in a way that such demand can be compared with the carrying capacity of the agricultural ecosystem (Franco, 2021b). This makes it possible to determine the condition of environmental sustainability or unsustainability as the result of the Ecological Balance (EB = BC - EF).

BC, EF and EB are expressed using a standardized unit of measurement, defined as global hectare (gha). This metric represents the average biological productivity of one hectare of the world's surface, calculated by dividing the planet's total capacity to provide natural resources by the number of hectares of land surface (Kitzes and Wackernagel, 2009; Galli, 2015). The Yield Factor (YF), specific to each country, and the Equivalence Factor (EQF), are the two parameters used to convert physical land hectares to final global hectares, with values varying by both land type and year considered (Borucke et al., 2013).

The ecological balance, and consequently the validation of the sustainability condition, can be applied to different typologies of agricultural systems, from a single crop to a farm, up to an entire region (Biagetti et al., 2023b). In this study, which focuses on the assessment of the sustainability of the agricultural sector in marginal areas, the boundary within which the supply and demand of natural capital must be assessed is represented by the total agricultural area inside a predefined group of municipalities.

3. METHODOLOGY

3.1. Delimitation of marginal areas within a region

To identify marginal areas within a region, as pointed out in the background section, many approaches can be applied. In this study, considering the focus on the socio-economic dimension and the outcome of a literature overview on this topic, three indicators were chosen: old-age index, depopulation rate and per capita income. These indicators synthetize the marginality condition in terms of aging and decline of the local population and residents' impoverishment (De Toni et al., 2021; Vendemmia et al., 2021). In this study such indicators for each municipality in the selected region are calculated as follows:

- Old-age index (2023): resident population older than 65, divided by resident population younger than 14 (ISTAT, 2024a);
- Population variation (2001-2023): resident population variation between 2023 and 2001 divided by resident population in 2001 (ISTAT, 2024a);
- Per capita income (2023): total taxable income divided by resident population (Ministero dell'Economia e delle Finanze 2024).

For every municipality in the province of Viterbo, the indicator values are classified in the range 1 (low marginality) to 5 (high marginality) coherently with the categories reported in table 1. In this way three new marginality indicators, respectively I_{AGE}, I_{DEP} and I_{INC}, are defined.

Categories in table 1 were set considering the values distribution of the three indicators in the municipalities of Viterbo province. It follows that I_{AGE}, I_{DEP}, I_{INC} measure a relative (local) level of marginality. Furthermore, considering that the Italian old-age index is 1.93, the population variation is 3.5% and the income per capita is 14,590 €, what is marginal within Viterbo province is even more marginal in a national perspective. Therefore, the highest values of I_{AGE}, I_{DEP}, I_{INC} can be associated with an absolute marginal condition.

Then, for each municipality (i) the index of marginality I_{MARi} is calculated using the following relation:

$$I_{MARi} = \text{round}\left((I_{AGEi} + I_{DEPi} + I_{INCi})/3\right) \tag{1}$$

Once each municipality is characterized with an individual marginality score, it's necessary to define a marginal area where to assess the environmental sustainability of the local agricultural system. Such delimitation should consider at least two criteria: all the municipalities included in the area have a high enough level of marginality; the municipalities aggregation corresponds to an administrative body (or, at least, to a rec-

Table 1. Categories associated with different levels of marginality.

Level of Marginality	Old-age index	Population variation	Income per capita (€)
1	< 1.5	> +15%	> 14,000
2	1.5 - 2.0	+5% - +15%	13,000 - 14,000
3	2.0 - 2.5	–5% - +5%	12,000 - 13,000
4	2.5 - 3.0	–15% - –5%	11,000 - 12,000
5	> 3.0	< –15%	< 11,000

ognized legal entity) that is in the position to define and implement actions at local level. Therefore, the second step of the methodology is to border the marginal area that will be the object of sustainability evaluation and, at the same time, to identify the related governance institution that can promote specific actions for supporting the valorization of local products.

For this purpose, after identifying all the possible k municipality aggregations in the selected region (the province of Viterbo in our case), a variable *t* is defined. Such variable can have only two values: $t_{ij} = 1$ if the municipality i belongs to aggregation j; $t_{ij} = 0$ if the municipality i does not belong to aggregation j.

Using this variable, it is possible to assess the overall marginality of the aggregation j as

$$M_j = \frac{\sum_{i=1}^{n}(I_{MARi}\ x\ t_{ij})}{n_j} \quad (2)$$

Once measured the marginality for each territorial aggregation, the one with the highest M_j can be chosen. This will be the area of which the sustainability of the agricultural system will be assessed.

3.2. The Ecological Balance for sustainability assessment

To evaluate the condition of deficit/surplus of natural capital in a delimited agricultural system a comparison between its supply and demand may be established. Such an ecological balance (EB) is calculated as the difference between the system's overall biological productivity (BioCapacity - BC) and the impact of production activities (Ecological Footprint - EF): EB = BC – EF (Martella et al., 2023)

The amount of natural capital in the area (BC_{TOT}) is determined by the bio-productivity of different types of farmland: cropland (BC_{CROP}), forest land (BC_{FOR}), semi-natural areas (pastures, shrublands, ...) (BC_{ASN}), other surfaces (buildings, roads, ...) (BC_{OTH}), water (BC_{WAT}).

The values of BC_{FOR}, BC_{ASN}, BC_{OTH} are determined following the standard ecological footprint methodology (Wackernagel and Rees, 1996) by converting the relative area through standard coefficients YF (yield factor) and EQF (equivalence factor) provided by Global Footprint Network (GFN, 2024).

The biocapacity associated with cropland is also calculated following the standard methodology, but the overall value is assessed by summing up the bio-productivity of each one (i) of the n crops cultivated in the area, as suggested by Passeri et al. (2013):

$$BC_{CROP} = \sum_{i=1}^{n} A_j \times \frac{Yp_j}{Yw_j} \times EQF_{CROP} \quad (3)$$

where A_j indicates the cultivated area, Yp_j the crop average yield in the area, Yw_j the crop world average yield (FAO, 2024).

Concerning the term BC_{WAT}, is quite difficult to carry out a detailed analysis on the watersheds inside the farms within the area under analysis. Therefore, the biocapacity of this typology of land cover is included in BC_{OTH}.

The demand for natural capital, measured by the total ecological footprint (EF_{TOT}) is calculated through the sum of three farm activities impacts: cultivations (EF_{CROP}), livestock (EF_{LIV}), others (EF_{OTH}).

EF_{CROP} can be calculated following the methodology proposed by Passeri et al. (2013), which identifies two sources of impact: overproduction (EFovp) and use of inputs (EFinp). The first one is related to the bias between the observed yield and the yield that can be obtained in natural conditions, i.e., without using inputs. The second one expresses the area of bio-productive land required to absorb the effects of input use. The assessment of these two components, both referring to calculation methodology and coefficients used, is explained in detail in Blasi et al. (2016) and Franco (2021b).

The impact of livestock farming activities in terms of natural capital demand can be estimated as suggested in Biagetti et al. (2023b). The impact for each (j) of the m types of livestock farms in the area ($EFliv_j$) is calculated in terms of bio-productive land needed for absorbing the emissions caused by input utilization and by enteric fermentation and management of animal manure, making use of specific conversion coefficients available in the literature (Coderoni et al., 2013; Mancini et al., 2016).

Finally, EF_{OTH} includes the impact of labor use, energy and fuel consumption for operation and maintenance of farms areas not directly affected by production processes.

Therefore, the negative term of the ecological balance is calculated as follows:

$$EF_{TOT} = \sum_{i=1}^{n}\left(EFovp_i + EFinp_i\right) + \sum_{j=1}^{m} EFliv_j + EF_{OTH} \quad (4)$$

EB, as well as all the components of BC and EF, are measured in global hectares (gha). However, to explain the outcome of the ecological balance in clearer terms, it is possible to convert the EB value in "real" hectares of a specific land cover. If we choose forest as land cover and consider the average biological productivity of an average Italian forest, an index of ecological performance (I_{EP}) may be defined. Such an index expresses the hectares of Italian forest, in terms of natural capital, that is made available (if EB>0) or subtracted (if EB<0) for each hectare of the study area.

4. RESULTS

4.1. Delimitation of the marginal area

According to the methodology presented in the previous section, the old-age index, population variation and per capita income were calculated for all the 60 municipalities in the province of Viterbo. All data were extracted from Italian bureau of census (ISTAT, 2024a) database, except the taxable income that was obtained from the Ministry of Finance (MF) website.

Then the indicators I_{AGE}, I_{DEP}, I_{INC} were assessed applying the classes reported in table 1. For each municipality i these values were combined to obtain the marginality index I_{MARi}. All the values of variable, indicators and I_{MAR} are listed in table A1 of the Appendix.

The next step was to identify the territorial aggregations within the province of Viterbo. These are the following: Inner area Alta Tuscia, Biodistrict of Bolsena lake, Biodistrict of Maremma, Biodistrict of Amerina road and Forre, Local Action Group Alto Lazio, Local Action Group Teverina, Local Action Group Etrusco Cimino, Local Action Group Amerina Agro Falisco, Local Action Group Tuscia Romana, Mountain community Alta Tuscia Laziale, Mountain community of Cimini (rural district).

Table 2 lists the names of territorial aggregation, the number of the municipalities and the marginality level Mj.

The aggregation with the highest level of marginality is the Local Action Group (LAG) Alto Lazio with a Mj equal to 4.27 followed by mountain community Alta Tuscia Laziale (4.13). All municipalities that are also included in the LAG Alto Lazio belong to this second aggregation. Considering this point and, moreover, the peculiarities of a LAG with respect to a mountain community in terms of policy intervention, the LAG Alto Lazio was preferred. Therefore, this area was chosen to calculate the environmental sustainability of the agricultural system and verify the possibility of increasing the value of local products through an environmental claim.

Figure 1 shows the values of I_{MAR} for the Viterbo province municipalities and the boundaries of the LAG Alto Lazio. Table 3 lists the municipalities which belong to LAG Alto Lazio and their main characteristics.

It could be useful to point out that a Local Action Group is a public-private partnership set up as an association with recognized legal personality, that has the mission to implement a strategic local development plan as defined in measure 19 of the 2014-2020 Lazio Regional Development Plan. The LAG decision-making is managed by the Board of directors composed of a maximum number of five members. This kind of administrative local authority has the advantage of bringing decision making processes closer to the territory, enhancing the real strengths and allowing broad and direct participation of local communities.

This feature fits with the area selection requirement, because only by involving local authorities, stakeholders' environmental policies and actions are more effective in developing a marginal area.

4.2. The Ecological Balance of LAG Alto Lazio

Primary data on the agricultural sector in LAG Alto Lazio area was obtained through the 7th General Census of Agriculture (ISTAT, 2024b). The information collected includes data on the crop mix, in terms of major cultivation types and dimensions, and livestock, in terms of species and number of animals. Processing ISTAT data is a key element for obtaining detailed information

Table 2. List of municipality aggregation in Viterbo province

Aggregation Code	Aggregation Name	Municipalities (nj)	M_j
A1	Inner area Alta Tuscia	22	3.91
A2	Biodistrict of Bolsena Lake	17	3.59
A3	Biodistrict of Maremma	2	2.50
A4	Biodistrict Via Amerina and Forre	13	3.08
A5	LAG Alto Lazio	15	4.27
A6	LAG in Teverina	11	3.55
A7	LAG Etrusco Cimino	9	3.22
A8	LAG Amerina Agro Falisco	10	2.80
A9	LAG Tuscia Romana	6	2.83
A10	Mountain community Alta Tuscia Laziale	8	4.13
A11	Mountain community of Cimini	10	3.10

Source: Our elaboration.

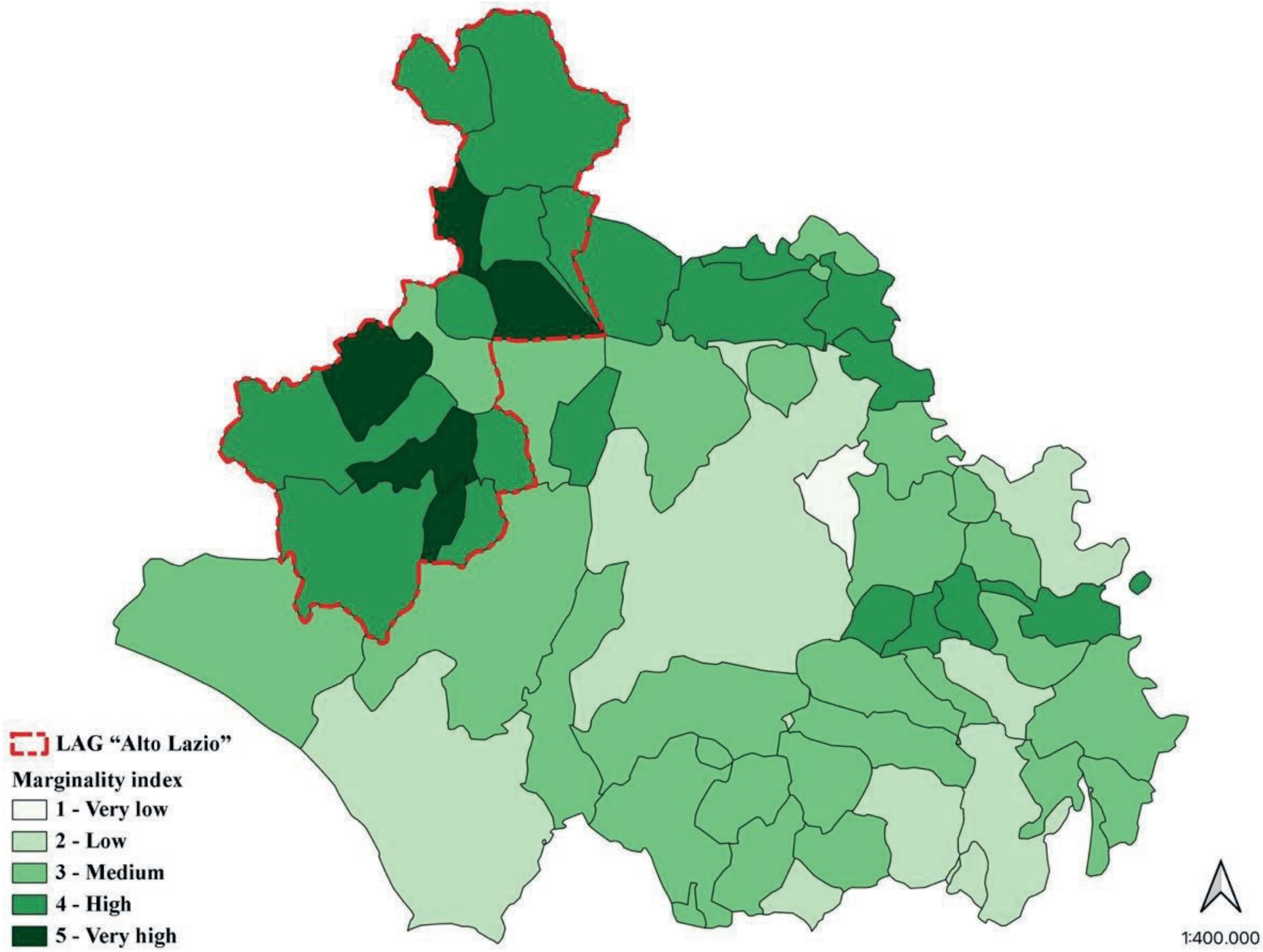

Figure 1. IMAR of Viterbo province municipalities and LAG Alto Lazio boundaries.

on land use, such as crops and bio productive areas, as well as statistics on the number and type of livestock. Then, all information on the cultivation techniques (yield, work, machinery, inputs) was obtained from the FADN database for the year 2021 and 2022 (FADN, 2024). The technical information contained in the FADN provides a solid basis for the analysis of different agronomic practices and their consequent implications on the LAG territory.

The data analysis revealed that total farmland of the LAG Alto Lazio covers 49,905 hectares, which is about 67% of the whole area. As shown in table 4, the total farm area is allocated 76% to cropland, 18% to forest land, and the remaining 5% to semi-natural areas (identified with grazing land) and other surfaces.

Focusing on cropland, the LAG area shows a general heterogeneity of cultivations, which can be divided into three main categories (Figure 2): leguminous fodder and temporary pastures (42.6%), mainly linked to livestock practices; a group of three major crops: olive trees, durum wheat, barley (28.5%); a group of many minor crops, including other cereals, vegetables and fruit trees, characterized by low-incidence surfaces (28.9%).

Regarding livestock (see table 5), the main categories include laying hens and broilers, which constitute 52.6% of the total, followed by sheep, representing 39%. The remaining portion is divided between pigs (4.3%) and other species, such as cattle, horses and goats (4.1%).

The analysis performed on the LAG Alto Lazio farmland made it possible to evaluate the environmental sustainability of the local agricultural system. The assessment, based on the comparison between biocapacity (BC) of different types of land use and the ecological footprint (EF) of agricultural activities, was carried out following the methodology explained in the previous section and using the data elaborated from ISTAT and FADN databases and the coefficient described in the cited literature. The results are synthetized in table 6.

Table 3. Main characteristics of LAG Alto Lazio municipalities

Municipality	Old-age index	Depopul. Rate	Income p.c. (€)	I_{MAR}	Area (km^2)	Agricultural area (km^2)	Population
Acquapendente	3.11	-8.9%	13,117	4	131.71	46.08	5,271
Arlena di Castro	3.21	-2.9%	11,001	4	21.87	14.88	842
Canino	2.44	-0.7%	10,806	4	123.50	76.27	5,036
Cellere	4.02	-17.7%	11,138	5	32.70	25.46	1,071
Farnese	4.25	-19.4%	11,924	5	52.38	23.78	1,393
Gradoli	4.49	-16.3%	11,607	5	37.50	7.11	1,252
Grotte di Castro	3.82	-20.2%	13,389	4	33.42	16.88	2,369
Ischia di Castro	2.92	-13.2%	10,966	4	104.95	55.94	2,138
Latera	6.23	-25.0%	12,063	4	22.66	9.24	767
Onano	3.33	-23.6%	10,215	5	24.60	11.29	893
Piansano	3.69	-13.2%	11,898	4	26.61	18.39	1,928
Proceno	5.89	-17.6%	12,032	4	41.90	26.36	521
San Lorenzo Nuovo	3.21	-2.6%	12,001	4	27.99	8.51	2,013
Tessennano	5.39	-33.1%	11,961	5	14.60	11.40	281
Valentano	2.91	-5.7%	13,297	3	43.29	26.75	2,768
Total					739.68	378.34	28,543

Source: Our elaboration on ISTAT (2024a) and MF (2024a).

Table 4. Subdivision of farmland among land cover typologies in LAG "Alto Lazio"

Municipality	Total (ha)	Crop land	Forest Land	Semi-Natural Areas	Other surfaces
Acquapendente	7,127	64.7%	31.0%	1.3%	3.0%
Arlena di Castro	1,634	91.1%	5.9%	0.4%	2.6%
Canino	10,039	76.0%	12.9%	1.0%	10.1%
Cellere	2,925	87.0%	9.8%	0.6%	2.6%
Farnese	2,997	79.4%	16.4%	2.3%	1.9%
Gradoli	941	75.7%	19.0%	1.9%	3.4%
Grotte di Castro	2,165	78.0%	17.1%	2.4%	2.5%
Ischia di Castro	8,499	65.8%	28.5%	1.1%	4.6%
Latera	1,361	67.9%	28.7%	0.8%	2.6%
Onano	1,394	81.0%	15.1%	1.6%	2.3%
Piansano	2,003	91.8%	3.6%	1.5%	3.1%
Proceno	3,132	84.2%	11.9%	1.5%	2.4%
San Lorenzo Nuovo	1,113	76.6%	17.7%	1.7%	4.0%
Tessennano	1,395	81.8%	14.4%	2.2%	1.6%
Valentano	3,182	84.1%	12.3%	1.8%	1.8%
Total	49,907	75.8%	18.4%	1.3%	4.4%

Source: ISTAT, (2024b).

As can be seen, the LAG agricultural system has the capacity to make a natural capital amount (BC_{TOT}=131,370 gha) greater than the ecological footprint generated by local production activities (EF_{TOT} = 117,419 gha) available. The positive value of the ecological balance (EB = 13,961 gha) signifies a condition of environmental sustainability where available natural resources are not exploited beyond their regenerative capacity.

The BC of cropland represents the most significant component of the overall BC (almost 80%), and it is able to fully sustain the impacts generated by the cultivation activities. A significant aspect that emerged from the analysis is the ability of forests and grazing land to offset approximately 97% of the impact generated by livestock (EF_{LIV}) and other activities (EF_{OTH}).

To explain the outcome of ecological balance more

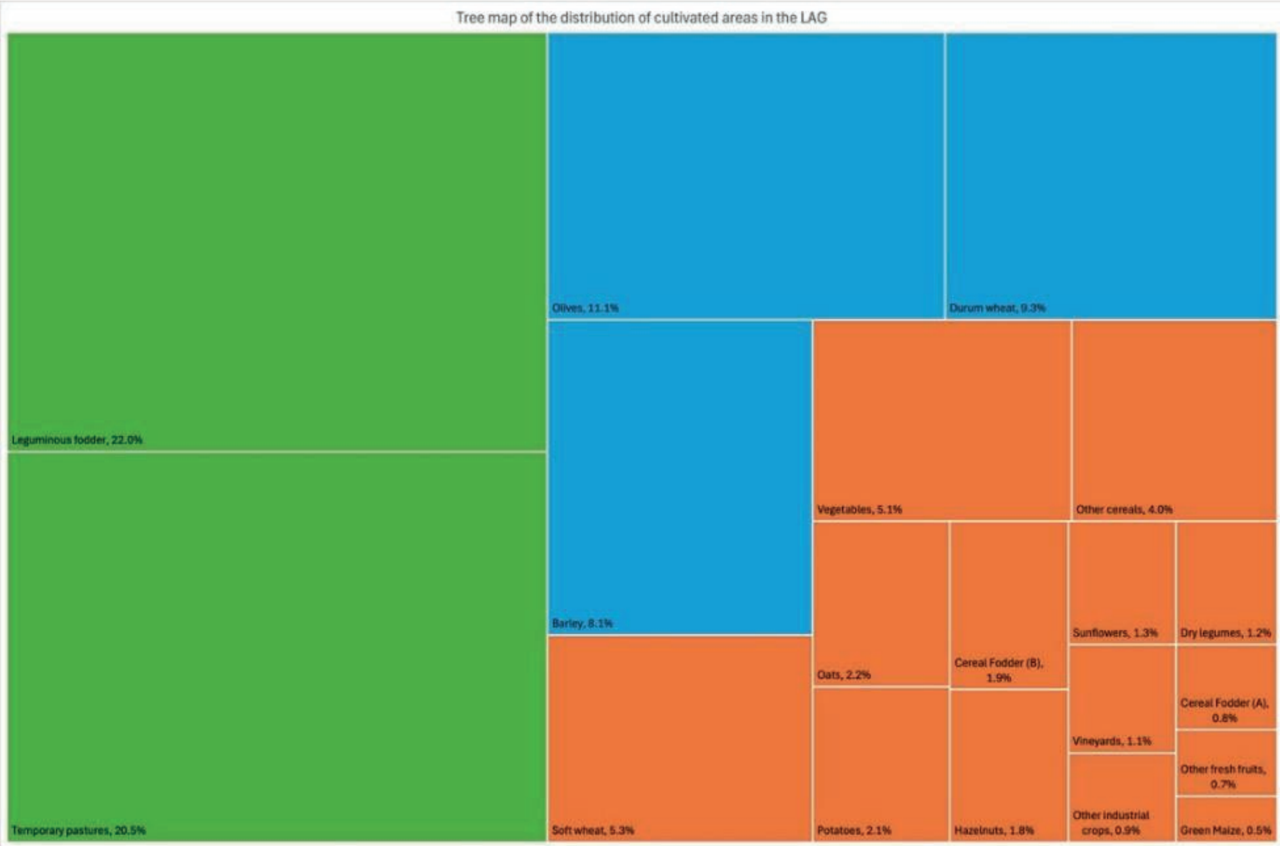

Figure 2. Tree map of LAG Alto Lazio distribution of UAA. Source: Our elaboration on ISTAT (2024b).

Table 5. Composition of livestock (number of heads) in LAG Alto Lazio.

Livestock	Heads
Cattle	
Dairy cow	348
Other cattle	5,794
Equines	
Horses	293
Other equines	29
Sheep	68,109
Goats	763
Pigs	
Sows	489
Other pigs	7,033
Poultry	
Laying hens	77,395
Broilers	14,591

Source: Our elaboration on ISTAT (2024b).

Table 6. Ecological balance of LAG Alto Lazio

BioCapacity	gha	Ecological Footprint	gha
Cropland	104,353	Crops	93,521
Forested land	19,785	Livestock	16,229
Semi-natural areas	3,512	Other activities	7,669
Other surfaces	3,730		
Total BC	131,380	Total EF	117,419
Ecological Balance (EB)	+ 13,961		

Source: Our elaboration.

explicitly, the I_{EP} was assessed. Its value, equal to 0.13, shows that every hectare of the LAG agricultural system hectares made available to the community, beyond its agricultural productivity, the natural resources equivalent to 0.13 ha of average Italian forest. This result emphasizes the area's ability to maintain a positive balance between used and regenerated resources and to actively contribute to the improvement of overall environmental quality. The I_{EP} represents a key parameter for assessing the efficiency with which natural resources are managed by the farming systems as a whole, thus providing a clear picture of the overall sustainability of agricultural practices in the LAG Alto Lazio territory.

5. DISCUSSION

Although the topic of socioeconomic marginality has sparked extensive scientific and political debate in recent years, accurately and comprehensively assessing the phenomenon - especially in terms of extent and location - is not an easy task. Moreover, the concept of marginality is highly subjective and, together with the variety of definitions, indicators and methodological approaches used (Peterson and Galbraith, 1932; Csikós and Tóth, 2023), complicates comparisons with similar studies. Marginal areas can emerge in a wide range of socio-ecological systems, from deserts to rainforests, and thus vary in their conceptualization (Lipper et al., 2006). These areas are generally perceived as "limited" in their ability to sustain human activities due to persistent biophysical and/or socioeconomic constraints.

In our study, socioeconomic marginality was assessed using three key indicators, as indicated in the methodology. The results show that Alto Lazio LAG is the area with the highest values for the combination of such key indicators (old age index, population change and per capita income), with a marginality index of 4.27 in the range 1 to 5. This suggests that the region is characterized by a vulnerable economy and a significant social development gap.

In these conditions, especially for the marginal regions where the agricultural sector plays a relevant role, the crops and livestock intensification could be seen as a possible strategy for local socioeconomic development. Nevertheless, it is evident how a similar solution presents significant environmental risks. Indeed, the practices for rising agricultural productivity with the aim of greater profitability often lead to increase exploitation of natural resources, with intensive use of pesticides and fertilizers, with harmful consequences for local ecosystems (Hazell and Wood, 2008; Barbier, 2010). In this sense, marginal areas are not only land to be exploited, but places with a precious biological capacity that must be used in a sustainable way (Sallustio et al., 2018). Agricultural activity in marginal areas should be view from this perspective, considering how productive techniques, crop selection and human-environment relationships pose tangible problems in terms of environmental impact (Kanianska, 2016).

Referring to LAG Alto Lazio, the value of the ecological balance gives a positive result, highlighting how the heterogeneity of land covers and the presence of forested and semi-natural areas within the agricultural land are essential not only biodiversity conservation but also for ensuring the sustainability of farming systems. This outcome of our case study suggests how marginal areas are often characterized by a land use pattern that can advantage the environmental sustainability of local agricultural system. Several studies have discussed the relationships between marginality and environmental issues, such as water quality, soil degradation, biodiversity and climate change mitigation (Fisher et al., 2002; O'Connor et al., 2005; Searchinger et al., 2008; Kang et al., 2013b). Even if these studies raise concerns about the environmental risks linked to some fragility in land use in marginal areas, the outcome of our study clearly indicates that the combination of marginality and sustainable agriculture should not be seen as separate concepts, but rather as two sides of the same coin. While marginal areas present significant challenges, they also offer opportunities for more ecological and resilient agriculture. Therefore, our study confirms that agriculture can play two basic roles: as a producer of agricultural goods and as a custodian of the ecosystem.

By improving sustainable agricultural practices, production can be optimized while minimizing environmental impact. This approach not only helps protect natural capital, but also promotes economic and social development in rural areas, creating a virtuous circle that benefits both local communities and the ecosystem at large. Furthermore, environmental sustainability can be seen as a branding strategy, also at territorial level, with the result that consumers will tend to perceive brands as adding value to the product and their place of origin (Nakaishi and Chapman, 2024). The effects of this strategic leverage have been analyzed in several studies, showing how integrating sustainability into branding increases consumers' willingness to pay a higher price for the product (Franco and Cicatiello, 2018).

6. CONCLUSIONS

The main aim of this study was to find out how to develop the local economy of marginal areas and thus increase their well-being. We focus on the link between socio-economic marginality and environmental sustainability and find that in the literature there are many examples of marginal areas that are also environmentally sustainable.

As agriculture is often the main productive activity in marginal areas, promoting sustainable agricultural practices can be the key both to increase the value of local food production and strengthen the overall identity of the territory. This approach not only protects the natural capital, but also promotes the resilience of rural communities.

We chose the Alto Lazio LAG as a case study due to its high socio-economic marginality and the type of governance that allows political intervention. We then evaluated the environmental sustainability of the LAG agricultural system using an environmental balance approach and came to positive conclusions. Breeding activities, that generally have a high impact on environmental sustainability, are present in this marginal area, but other agricultural production combined with a good management system clearly compensate for this and achieve a positive ecological balance.

Marginal areas possess the potential for sustainable production and self-development without adversely affecting the ecosystem, particularly through the implementation of virtuous local production systems exemplified by the Alto Lazio LAG. Consequently, it can be stated that this agricultural model is commendable; if local authorities promote and enhance it, it could serve as an effective mechanism to bridge the development gap in marginal areas while simultaneously safeguarding the environment.

The study also focused on identifying opportunities for sustainability claims and certification processes that could enhance the value of local agriculture and food production. This tool is needed to effectively convey to consumers, in a clear and quantifiable manner, the beneficial impact of local agricultural production systems on the environment.

The promotion of agricultural sustainability, fully respecting ecosystem limits, if accompanied by a recognized certification and resulting from the active involvement of stakeholders, can serve as a strategic lever for the economic development of local agricultural production. This approach not only strengthens territorial competitiveness but also helps to create a more inclusive and environmentally respectful growth model.

We are aware of the limits of our results, due to a partial accounting for the territory sustainability, since we considered only the agricultural production system. Furthermore, implementation challenges might arise due to potential discrepancies between the overarching territorial vision and its practical application at the individual farm level.

Further investigations are necessary, incorporating a stakeholder engagement process that involves local policymakers and relevant actors. This approach aims to elucidate their vision of development while emphasizing the potential costs and benefits associated with the transition.

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APPENDIX

Table A1. Marginality indicators of Viterbo province municipalities.

Municipality	Old-age index	I_{AGE}	Depop. rate	I_{DEP}	Income per capita	I_{INC}	I_{MAR}
Acquapendente	3,11	5	-8,9%	4	13.117	2	4
Arlena di Castro	3,21	5	-2,9%	3	11.001	4	4
Bagnoregio	3,35	5	-6,7%	4	13.025	2	4
Barbarano Romano	3,55	5	5,5%	2	13.146	2	3
Bassano in Teverina	2,77	4	11,7%	2	12.075	3	3
Bassano Romano	2,50	4	7,7%	2	12.352	3	3
Blera	2,48	3	-7,1%	4	12.143	3	3
Bolsena	3,97	5	-9,7%	4	12.119	3	4
Bomarzo	2,26	3	4,0%	3	12.406	3	3
Calcata	1,99	2	6,6%	2	10.386	5	3
Canepina	2,22	3	-5,6%	4	11.665	4	4
Canino	2,44	3	-0,7%	3	10.806	5	4
Capodimonte	3,87	5	-0,9%	3	14.215	1	3
Capranica	1,91	2	13,1%	2	11.795	4	3
Caprarola	2,22	3	-0,7%	3	11.502	4	3
Carbognano	1,86	2	1,3%	3	10.980	5	3
Castel Sant’Elia	1,86	2	14,1%	2	10.578	5	3
Castiglione in Teverina	2,16	3	0,6%	3	11.933	4	3
Celleno	2,55	4	-2,2%	3	12.290	3	3
Cellere	4,02	5	-17,7%	5	11.138	4	5
Civita Castellana	2,23	3	0,5%	3	12.491	3	3
Civitella d’Agliano	3,33	5	-16,8%	5	12.100	3	4
Corchiano	1,86	2	7,5%	2	10.307	5	3
Fabrica di Roma	1,74	2	23,5%	1	11.716	4	2
Faleria	2,29	3	15,2%	1	11.778	4	3
Farnese	4,25	5	-19,4%	5	11.924	4	5
Gallese	2,65	4	-6,5%	4	12.105	3	4
Gradoli	4,49	5	-16,3%	5	11.607	4	5
Graffignano	2,67	4	-7,9%	4	11.759	4	4
Grotte di Castro	3,82	5	-20,2%	5	13.389	2	4
Ischia di Castro	2,92	4	-13,2%	4	10.966	5	4
Latera	6,23	5	-25,0%	5	12.063	3	4
Lubriano	2,70	4	-6,2%	4	11.970	4	4
Marta	2,83	4	-5,8%	4	12.261	3	4
Montalto di Castro	2,21	3	14,0%	2	12.649	3	3
Monte Romano	2,06	3	-3,5%	3	13.569	2	3
Montefiascone	2,41	3	2,6%	3	13.181	2	3
Monterosi	1,32	1	102,1%	1	11.677	4	2
Nepi	1,79	2	20,2%	1	11.762	4	2
Onano	3,33	5	-23,6%	5	10.215	5	5
Oriolo Romano	2,13	3	27,4%	1	12.464	3	2
Orte	1,71	2	16,6%	1	13.055	2	2
Piansano	3,69	5	-13,2%	4	11.898	4	4
Proceno	5,89	5	-17,6%	5	12.032	3	4
Ronciglione	2,32	3	13,2%	2	12.232	3	3
San Lorenzo Nuovo	3,21	5	-2,6%	3	12.001	3	4

(Continued)

Table A1. (Continued).

Municipality	Old-age index	I_{AGE}	Depop. rate	I_{DEP}	Income per capita	I_{INC}	I_{MAR}
Soriano nel Cimino	2,50	3	-2,8%	3	11.728	4	3
Sutri	2,40	3	32,0%	1	12.959	3	2
Tarquinia	2,32	3	5,7%	2	13.901	2	2
Tessennano	5,39	5	-33,1%	5	11.961	4	5
Tuscania	2,31	3	6,6%	2	11.788	4	3
Valentano	2,91	4	-5,7%	4	13.297	2	3
Vallerano	2,54	4	-3,7%	3	11.724	4	4
Vasanello	1,96	2	2,4%	3	12.322	3	3
Vejano	2,51	4	3,0%	3	12.715	3	3
Vetralla	2,09	3	11,6%	2	12.292	3	3
Vignanello	2,38	3	-8,8%	4	10.664	5	4
Villa San Giovanni in T.	2,97	4	3,4%	3	12.668	3	3
Viterbo	2,02	3	11,6%	2	14.440	1	2
Vitorchiano	1,18	1	63,2%	1	13.619	2	1

Source: Our elaboration on ISTAT (2024a) and MF (2023).

Table A2. Membership of Viterbo province municipalities to single aggregations.

Municipality	I_{MAR}	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Acquapendente	4	1	1	0	0	1	0	0	0	0	1	0
Arlena di Castro	4	1	0	0	0	1	0	0	0	0	0	0
Bagnoregio	4	0	1	0	0	0	1	0	0	0	0	0
Barbarano Romano	3	0	0	0	0	0	0	0	0	1	0	0
Bassano in Teverina	3	0	0	0	0	0	0	0	0	0	0	0
Bassano Romano	3	0	0	0	0	0	0	0	0	1	0	0
Blera	3	0	0	0	0	0	0	0	0	1	0	0
Bolsena	4	1	1	0	0	0	1	0	0	0	0	0
Bomarzo	3	0	0	0	0	0	1	0	0	0	0	0
Calcata	3	0	0	0	1	0	0	0	1	0	0	0
Canepina	4	0	0	0	1	0	0	1	0	0	0	1
Canino	4	1	1	0	0	1	0	0	0	0	0	0
Capodimonte	3	1	1	0	0	0	1	0	0	0	0	0
Capranica	3	0	0	0	0	0	0	1	0	0	0	1
Caprarola	3	0	0	0	0	0	0	1	0	0	0	1
Carbognano	3	0	0	0	0	0	0	1	0	0	0	1
Castel Sant'Elia	3	0	0	0	1	0	0	0	1	0	0	0
Castiglione in Teverina	3	0	0	0	0	0	1	0	0	0	0	0
Celleno	3	0	1	0	0	0	1	0	0	0	0	0
Cellere	5	1	1	0	0	1	0	0	0	0	0	0
Civita Castellana	3	0	0	0	1	0	0	0	1	0	0	0
Civitella d'Agliano	4	0	0	0	0	0	1	0	0	0	0	0
Corchiano	3	0	0	0	1	0	0	0	1	0	0	0
Fabrica di Roma	2	0	0	0	1	0	0	0	1	0	0	0
Faleria	3	0	0	0	1	0	0	0	1	0	0	0
Farnese	5	1	1	0	0	1	0	0	0	0	0	0
Gallese	4	0	0	0	1	0	0	0	1	0	0	0

(Continued)

Table A2. (Continued).

Municipality	I_{MAR}	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Gradoli	5	1	1	0	0	1	0	0	0	0	1	0
Graffignano	4	0	0	0	0	0	1	0	0	0	0	0
Grotte di Castro	4	1	1	0	0	1	0	0	0	0	1	0
Ischia di Castro	4	1	1	0	0	1	0	0	0	0	0	0
Latera	4	1	1	0	0	1	0	0	0	0	1	0
Lubriano	4	0	0	0	0	0	1	0	0	0	0	0
Marta	4	1	1	0	0	0	1	0	0	0	0	0
Montalto di Castro	3	1	0	0	0	0	0	0	0	0	0	0
Monte Romano	3	0	0	1	0	0	0	0	0	0	0	0
Montefiascone	3	1	1	0	0	0	1	0	0	0	0	0
Monterosi	2	0	0	0	0	0	0	0	0	0	0	0
Nepi	2	0	0	0	1	0	0	0	1	0	0	0
Onano	5	1	0	0	0	1	0	0	0	0	1	0
Oriolo Romano	2	0	0	0	0	0	0	0	0	1	0	0
Orte	2	0	0	0	1	0	0	0	1	0	0	0
Piansano	4	1	1	0	0	1	0	0	0	0	0	0
Proceno	4	1	0	0	0	1	0	0	0	0	1	0
Ronciglione	3	0	0	0	0	0	0	1	0	0	0	1
San Lorenzo Nuovo	4	1	1	0	0	1	0	0	0	0	1	0
Soriano nel Cimino	3	0	0	0	0	0	0	0	0	0	0	1
Sutri	2	0	0	0	0	0	0	1	0	0	0	0
Tarquinia	2	1	0	1	0	0	0	0	0	0	0	0
Tessennano	5	1	0	0	0	1	0	0	0	0	0	0
Tuscania	3	1	0	0	0	0	0	0	0	0	0	0
Valentano	3	1	1	0	0	1	0	0	0	0	1	0
Vallerano	4	0	0	0	1	0	0	1	0	0	0	1
Vasanello	3	0	0	0	1	0	0	0	1	0	0	0
Vejano	3	0	0	0	0	0	0	0	0	1	0	0
Vetralla	3	0	0	0	0	0	0	1	0	0	0	1
Vignanello	4	0	0	0	1	0	0	1	0	0	0	1
Villa San Giovanni in T.	3	0	0	0	0	0	0	0	0	1	0	0
Viterbo	2	0	0	0	0	0	0	0	0	0	0	0
Vitorchiano	1	0	0	0	0	0	0	0	0	0	0	1

Source: Our elaboration.

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Bridging the gap: the impact of compensatory measures on mountain farming in Piedmont

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Abstract. This study examines the impact of the Rural Development Program (RDP) on reducing income disparities between farms in mountainous and non-mountainous areas in Piedmont, Italy. Using Farm Accounting Data Network data from 2012–2022, the analysis focuses on cattle, sheep and goats, and fruit farms, with 525 farms (3,171 observations; 36% in mountainous areas). A pooled multivariate regression assesses income disparities excluding RDP support, RDP's effectiveness in mitigating gaps, and the role of compensatory allowance. The findings indicate that significant income disparities are primarily observed in small farms specialized in cattle and sheep and goats, with mountain farms facing a net shortfall of €1,319 and €2,384 per hectare, respectively. While compensatory allowance support helps reduce this gap – by 8.93% for cattle farms and 5.28% for sheep and goat farms – a substantial disparity remains. Bridging the gap entirely would require doubling compensatory payments to €340 per hectare, though alternative strategies are discussed.

Keywords: FADN, compensatory allowance, mountain areas, income gap.

1. INTRODUCTION

Mountain agriculture in Europe faces critical challenges due to the natural constraints of these regions, often classified as Areas with Natural Constraints (ANCs) under Regulation (EU) No. 1305/2013, Art. 32. Previously termed Less Favoured Areas (LFAs) under the Common Agricultural Policy (CAP), these regions face challenges such as steep slopes, adverse climates, and poorer soil fertility, which collectively restrict arable land and require labour-intensive farming practices. These limitations lead to higher production costs and reduce profitability, causing many farmers in mountainous regions to abandon agricultural activities (Giannakis & Bruggeman, 2015; Strijker, 2004). Such abandonment contributes to depopulation, economic decline, and the loss of agro-biodiversity and traditional landscapes (Cesaro & Marongiu, 2013). To counteract these adverse trends, the European Union (EU) has historically provided targeted support to ANC within the CAP

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framework, aiming to mitigate the biophysical disadvantages and sustain agricultural livelihoods in ANCs.

The effectiveness of ANC and LFA support measures has been widely studied, with mixed findings (Romagnoli et al., 2021). For instance, Borsotto et al. (2010) questioned the effectiveness of these subsidies across different European contexts, while Ferto et al. (2022) and Klima et al. (2020) observed heterogeneity in outcomes based on regional applications. Oxousi (2012) conducted a comparative analysis on farm performance, finding that while ANC support plays a key role in the profitability of mountain and other disadvantaged farms, mountainous farms still struggle compared to those in less favoured, but more productive, areas. Similarly, Wieliczko et al. (2018) identified significant disparities in production efficiency and economic performance between farms receiving ANC support and those that do not, indicating that while ANC payments partially help mitigate economic disadvantages, they do not fully compensate for them.

As the ANC policy evolved, the 2014–2020 Rural Development Program (RDP) introduced refined eligibility criteria to direct support toward regions with genuine biophysical constraints. ANC support remains a crucial tool for maintaining agricultural activities, preserving rural landscapes, and preventing land abandonment in vulnerable regions (Whitaker, 2024; Veveris et al., 2014). In mountainous regions, these payments significantly contribute to rural sustainability, by retaining population, enhancing business viability, and preserving environmental and territorial integrity (Cooper et al., 2006; Dax et al., 2021).

While the impact of ANC support has been widely studied, limited research has assessed its effectiveness in reducing economic disparities between mountainous and non-mountainous farms in specific regional contexts. This study aims to address this gap by analyzing the adequacy of compensatory allowance (CA) in mitigating income inequalities in mountain agriculture, focusing on the Piedmont region. Unlike previous research, which has often relied on cross-country or aggregated assessments (Poláková, 2019), this study adopts a context-specific approach using Farm Accountancy Data Network (FADN) data. By evaluating the financial resources required to ensure that compensatory measures effectively offset the economic disadvantages faced by mountain farmers, this research provides a robust policy assessment and contributes to a more precise understanding of rural development interventions (Romagnoli et al., 2021).

The choice of Piedmont, a region in northern Italy, as a case study is justified by its diverse agricultural landscape, which includes both mountain and lowland areas, allowing for a meaningful comparison between farms operating under different environmental constraints. Covering over 52% mountainous territory, Piedmont includes both the Apennine and Alpine ranges, where depopulation, agricultural abandonment, and the difficulties faced by small, isolated communities are pronounced (Ferlaino, 2019). Livestock farming, central to Piedmont's mountainous areas, relies on limited resources and small, family-run farms, which differ substantially from lowland agriculture (ISTAT, 2020). EU programs have increasingly addressed these issues, although the region's administrative fragmentation, characterised by numerous small municipalities, complicates local development management. This makes Piedmont a compelling case for understanding the complexities of mountain development and the critical role of targeted policies in fostering sustainability.

To properly interpret the methodology and findings, it is essential to understand the structure of the CA under the RDP, established under Regulation (EC) No. 1698/2005. During the 2007–2013 programming period, the CA was implemented through Measure 211, while in the 2014–2020 period, it was integrated into Measure 13.1, both aimed at providing direct financial support to farmers in mountainous areas to offset the economic disadvantages imposed by challenging terrain and climate conditions. Measure 13.1 allocated approximately 60 million euros annually to mountain farmers in Piedmont, succeeding Measure 211, which had provided 52.5 million euros in the previous programming period (Cagliero et al., 2018; NUVAL Piemonte, 2016). These measures play a crucial role in sustaining agriculture, supporting socio-economic stability, and preserving landscapes in disadvantaged areas (Ferlaino, 2019; Regione Piemonte, 2016). However, the CA is not automatically granted to all farmers but is subject to eligibility criteria based on land use and farm characteristics. The amount of support varies depending on the agricultural system and the level of disadvantage. Additionally, to prioritize small and medium-sized farms, payments decrease as farm size increases: farms with less than 20 hectares receive 100% of the allowance, those between 20 and 40 hectares receive 70%, those between 40 and 70 hectares receive 40%, those between 70 and 100 hectares receive 10%, while farms over 100 hectares are not eligible for support. This tiered approach reflects the strategic importance of maintaining agricultural activity in mountainous areas and ensuring that support is directed toward those most affected by structural disadvantages (Regione Piemonte, 2016).

The results of this study are specific to the Piedmont region, as they reflect the particular agricultural, economic, and policy context of this territory. While the per-hectare CA is a common feature of ANC support across the EU, its implementation varies in structure, budget allocation, and eligibility criteria, depending on national and regional regulations (e.g., differences in budget distribution, farm eligibility rules, and administrative procedures). Consequently, the findings may not be directly replicable in other regions, as variations in policy design could influence the effectiveness of CA in addressing economic disparities. However, this study offers a methodological framework that can be adapted for analyzing other mountain regions, particularly within the Alpine arc, where similar agricultural and economic constraints exist. Expanding the analysis to additional regions would facilitate a broader evaluation of ANC policy effectiveness and identify potential areas for policy refinement.

The paper is organised as follows: Section 2 presents the data and methodology, including analytical frameworks; Section 3 reports the results of the policy impact analysis; Section 4 discusses findings with an emphasis on policy implications; and Section 5 concludes, suggesting directions for future research and policy improvements.

2. DATA AND RESEARCH METHODOLOGY

2.1. Data collection

The analysis is based on data from the FADN, which collects harmonized data annually, offering microeconomic insights into income trends and the structural economic dynamics of farms across Europe. For this study, we used data from the Italian survey, which includes approximately 11,000 farms each year (CREA, 2025).

From this dataset, we selected farms located in the Piedmont region with a standard output – defined as the average monetary value of agricultural products at farm-gate prices – exceeding €8,000, in order to focus on commercial farms. We further restricted the sample to those farms engaged in farming types (FT) – FADN classifications based on the relative importance of each agricultural activity within the farm – typical of the Piedmont mountainous area, specifically farms specialised in cattle, sheep and goats, and fruit production. The analysis covers a ten-year period, from 2012 to 2022.

To distinguish between farms in mountainous and non-mountainous areas, we used the receipt of the CA as a classification criterion. Farms receiving this support were classified as located in mountainous areas, while those not receiving it were considered non-mountainous. This approach was adopted since the FADN database defines farm altitude based on the farm center, which may not always correspond to the actual location of the arable land. Using CA support as a proxy provided a more reliable way to identify mountain farms. Moreover, this classification appears consistent, as available data show that, on average, 88% of the total eligible regional hectares received the payment during the years considered (Regione Piemonte, 2025). In addition, farms larger than 100 hectares were excluded from the analysis, as they are not eligible for CA payments. Including them would have led to a misclassification of their geographical location and distorted the estimation.

Based on this criterion, the final sample consists of an unbalanced panel dataset of 525 farms, resulting in a total of 3,171 observations, of which 36.14% are located in mountainous areas. Table 1 presents the distribution of the sample by FT, farm scale and geographic location. The majority of the sample comprises farms specialising in cattle, followed by those engaged in fruit production, and lastly, sheep and goat farming. Farms specialised in sheep and goats are the only group with a higher number of observations in mountainous areas compared to plains.

2.2. Analytical framework

The rationale behind the CA support measure assumes that farms located in mountainous areas face a significant income disparity compared to those in non-mountainous areas. The first step of our analysis aimed to empirically test whether this income disparity exists when excluding the effects of the CA. Subsequently, we assessed the extent to which the CA narrows the income gap between mountain and non-mountain farms.

To conduct this analysis, we used a pooled multivariate regression model. This model was selected because it allows for the simultaneous estimation of the effects of several explanatory variables on multiple dependent variables over time, making it particularly suitable for unbalanced panel data such as ours (Baltagi, 2008). The analysis was structured around two key dependent variables: net income (NI) per hectare of utilized agricultural area (UAA) excluding CA support, and overall NI per hectare of UAA. This distinction enabled us to isolate the specific contribution of CA payments in narrowing income disparities.

Looking at the descriptive statistics in Table 2, we observe that, on average, the NI excluding CA support is 41.16% lower for mountain farms compared to non mountain farms. However, when considering the overall NI, the income gap narrows to 37.76%.

Table 1. Sample size categorised by Farming Type, area and farm scale.

	Farm Scale	Cattle	Sheep and goats	Fruit	Total
Non mountain area	Small	364	60	546	970
	Large	853	21	181	1,055
Mountain area	Small	262	39	228	529
	Large	486	67	64	617
Total		1,965	187	1,019	3,171

Note: Small-scale = UAA < 20 ha; Large-scale = UAA between 20 and 100 ha.

For the independent variables, we included the farm's geographical location that distinguishes whether the farm is in a mountainous or non-mountainous area, as this is the primary focus of our study. Additionally, we considered several control variables, selected based on previous studies that identified key characteristics from the FADN database as significant determinants of farm income (Andrejovská & Glova, 2022; Kryszak et al., 2021; Ryś-Jurek, 2019; Średzińska, 2018; Strzelecka et al., 2018). These variables include a time variable to control for yearly trends, farm characteristics such as economic dimension (ED) of the farm, measured in terms of standard output, the number of farm labour units, the percentage of family labour, the hectares of UAA, the specific FT, the organic certification and some personal characteristics of the farmer such as age, gender and level of education (Table 3 and 4). An interaction term between FT, farm location and farm scale were included to capture any differential effects that may arise from the combination of these three factors. This approach enables us to consider how the limitations imposed by mountainous terrain may affect each FT and farm scale differently.

The regression model assumes that the error terms for the two dependent variables are identical, reflecting the premise that residual farm income, after controlling for the relevant variables, should behave similarly across the two income measures. Given that the same farms are observed across multiple years, we addressed the potential issue of autocorrelation by clustering the standard errors at the farm level. This adjustment corrects for any non-independence of observations within each farm over time, enhancing the robustness of our estimates.

Additionally, we addressed selection bias through inverse probability weighting (IPW). First, we defined the propensity score as $p(\mathbf{x}_i) = Pr(W_i = 1 \mid \mathbf{x}_i, \boldsymbol{\beta})$, where W_i is an indicator equal to 1 if a farm is a "Mountain farm" (i.e., receiving CA support) and 0 otherwise. The vector $\boldsymbol{\beta}$ represents the parameters, and $\mathbf{x}_i$ is a vector of observed covariates. The propensity score reflects the probability that a farm receives CA support and is modelled as $\mathbf{F}[H(\mathbf{x}_i)]$, where $\mathbf{F}$ is typically the logistic or normal cumulative distribution function (Guo & Fraser, 2010). In this study, the propensity scores were estimated using a logit model. Inverse probability weights were then computed by taking the reciprocal of the estimated probability of the observed treatment status. For a treated unit ("Mountain farm"), the weight is $1/p(\mathbf{x}_i)$, while for a control unit ("Non mountain farm") the weight is $1/(1 - p(\mathbf{x}_i))$. These weights adjust for differences in covariate distributions between the two groups. Finally, the computed weights were used in the multivariate regression (see Bellon et al., 2015) to estimate the effect of being in a mountainous area on net income. This weighted regression aims to balance the sample, mimicking a randomized experiment and providing less biased estimates (Guo & Fraser, 2010).

After estimating the regression models, we conducted pairwise comparisons to identify statistically sig-

Table 2. Descriptive statistics of dependent variables.

	Farm scale	NI excluding CA/ha				NI/ha			
		Non mountain		Mountain		Non mountain		Mountain	
		M (€)	*SD*	*M* (€)	*SD*	*M* (€)	*SD*	*M* (€)	*SD*
Cattle	Small	3,228	7,556	1,115	2,182	3,228	7,556	1,251	2,193
	Large	2,310	2,655	1,140	1,830	2,310	2,655	1,251	1,832
Sheep and goats	Small	2,079	9,849	1,006	3,124	2,079	9,849	1,142	3,132
	Large	355	356	793	1,016	355	356	908	1,047
Fruit	Small	4,421	4,826	4,344	3,985	4,421	4,826	4,488	3,992
	Large	5,129	5,594	3,878	3,350	5,129	5,594	4,016	3,365
Overall		3,265	5,120	1,906	2,925	3,265	5,120	2,032	2,936

Note: Small-scale = UAA < 20 ha; Large-scale = UAA between 20 and 100 ha.

nificant differences in NI between mountain and non-mountain farms across the various FT.

To further explore the specific role of the CA in reducing the income gap, we estimated the required financial magnitude of CA payment to effectively address income disparities between mountain and non-mountain farms. To achieve this, we conducted a pooled regression analysis, where the dependent variable was net income per hectare of UAA, and the independent variables included the CA payment per hectare of UAA, along with the same control variables used in the previous analysis. Using the model estimates, we calculated how the marginal increase in CA payment would affect the income of mountain farms, identifying the per-hectare payment needed to fully bridge the income gap with non-mountain farms.

2.3. Variables description

The description of the variables reveals that, on average, farms in the dataset employ slightly more than two workers, with an average of 2.07 labour units (LU), and rely predominantly on family labour, which represents approximately 92.2% of the total workforce. The average age of the farm managers is 53.9 years (Table 3).

Regarding ED, the majority of farms fall into the mid-range, with 40.24% of farms classified within the ED category, having a standard output between €100,000 and €500,000 per year. Farms with a standard output between €50,000 and €100,000 represent 24.38% of the dataset, while those with an output between €25,000 and €50,000 account for 17.85%, and 13.88% fall within the €8,000–€25,000 range. Only a small proportion of farms exceed €500,000 in standard output (3.66%). In terms of farm specialisation, 61.97% of farms focus on cattle farming, 32.13% specialise in fruit production, and 5.97% are dedicated to sheep and goat farming. The majority of farms (63.56%) are located in non-mountainous areas, while 36.14% operate in mountain regions.

For farm scale, farms are classified as *Small* (< 20 hectares) and *Large* (20 to 100 hectares). This classification reflects the structure of the compensatory allowance (CA), which is granted in full to farms under 20 hectares, while farms above this threshold receive a proportionally reduced payment. The sample is nearly evenly distributed, with 47.27% of farms classified as small and 52.73% as large.

In terms of farm management, 86.03% of the farm managers are male. Farm diversification is relatively limited, with only 18.46% of farms engaged in activities beyond primary agricultural production. Similarly, organic farming is a niche practice, with only 11.51% of farms certified as organic. Education levels vary among farm managers, with 62.37% having completed secondary school, and 22.31% holding a high school diploma. A smaller proportion has attained higher education, with 1.58% holding a bachelor's degree and 0.06% an associate degree, while 13.68% have primary or no formal education. The data spans multiple years, from 2012 to 2022, with a fairly balanced distribution of observations across these years (Table 4).

Table 3. Description of the continuous independent variables.

	Description	Unit of Measure	*M*	*SD*
LU	Farm's labour unit	n	2.07	1.96
FLU	Percentage of family labour	%	92.2	1.97
Age	Farmer's age	n	53.9	12.03

3. RESULTS

The findings from the IPW-adjusted multivariate regression model, as outlined in Table 5, show that the control variables are significant in the expected direction across the two equations. Specifically, an increase in the ED positively influences the dependent variables, as does a marginal increase of UAA. Moreover, farms specialised in fruit production scored higher on the dependent variables when compared to cattle farms. Focusing on the variable that distinguishes between farms located in mountainous areas and those not situated in mountainous areas, we observe that in the two cases the coefficient is significant and negative. This suggests that there is a gap in NI between farms located in mountainous areas and those not located in mountainous areas that the CA support is unable to bridge.

Post-hoc pairwise analyses indicate that, in the two regressions, the gap is not uniformly evident across all FTs and farm scales. From the first regression, which has NI excluding the amount of CA support received as the dependent variable, a negative income gap exists for small farms specialised in cattle and in sheep and goats, while large farms in these same categories and those specialised in fruit do not show a statistically significant gap. Focusing on small cattle farms, the estimated magnitude of the gap excluding CA support is -€1,319.44 per hectare, while the estimated NI gap is -€1,201.49 per hectare. For small farms specialised in sheep and goats, the estimated magnitude of the gap excluding CA support is -€2,384.19 per hectare, which decreases to -€2,258.49 when considering the estimated NI gap (Table 6).

Table 4. Description of the discrete allowance variables.

	Description	*n*	%
ED € of Standard Output	8,000 – 25,000	440	13.88
	25,000 – 50,000	566	17.85
	50,000 - 100,000	773	24.38
	100,000 – 500,000	1,276	40.24
	500,000 – 1,000,000	108	3.41
	> 1,000,000	8	0.25
Farm scale	Small (< 20 ha)	1,499	47.27
	Large (20 to 100 ha)	1,672	52.73
FT	Cattle	1.965	61.97
	Sheep and goats	187	5.97
	Fruit	1.019	32.13
Farm location	Non mountain area	2,025	63.56
	Mountain area	1,146	36.14
Gender	Woman	443	13.97
	Man	2,728	86.03
Diversification	Yes	588	18.46
	No	2,583	81.46
Organic	Yes	365	11.51
	No	2.806	88.49
Level of education	No formal education	70	2.22
	Primary school	362	11.46
	Secondary school	1,971	62.37
	High school diploma	705	22.31
	Associate degree	2	0.06
	Bachelor's degree	50	1.58
Year	2012	316	9.97
	2013	326	10.28
	2014	316	9.97
	2015	309	9.74
	2016	314	9.90
	2017	305	9.62
	2018	304	9.59
	2019	188	5.93
	2020	186	5.87
	2021	307	9.68
	2022	300	9.46

Our analysis further proceeded to determine the required financial magnitude of CA payment to effectively address income disparities between farms situated in mountainous and non-mountainous areas. The analysis was conducted exclusively on small farms specialising in cattle and sheep and goats, as these were the farming types where the income gap was found to be negative and statistically significant. As shown in Figure 1, mountain farms currently receive an average CA payment of around €135/ha. To fully close the income gap between farms in mountainous areas and those in non-mountainous areas, the CA payment would need to more than double, reaching approximately €340/ha.

4. DISCUSSION

The findings of this study provide a deeper understanding of the economic challenges faced by farms in Piedmont's mountainous areas, especially concerning income disparities when compared to farms in non-mountainous regions. In addition, the study highlights the role of public support in addressing these challenges, particularly evaluating the effectiveness of compensatory measures such as the CA.

Our results confirm the existence of an income gap between farms situated in mountainous and non-mountainous areas. This disparity is largely driven by socio-ecological challenges such as steep terrain, adverse climate conditions, and limited competitiveness, which collectively increase the risk of land abandonment in mountain regions (Dax, 2021). Additional challenges, including an ageing farming population, limited technical training, and the prevalence of low-input systems, further undermine the economic sustainability of agriculture in these areas (Giannakis & Bruggeman, 2015; Strijker, 2004). These vulnerabilities appear to be particularly pronounced in smaller farms, which tend to have fewer resources to adapt to structural constraints.

Moreover, our study demonstrates that this income gap is not uniformly distributed across different types of farming, confirming that distinct mountain farming types result in different economic outcomes (Papić Milojević & Bogdanov, 2023). The income gap was found to be statistically significant, and negative in small farms specialised in cattle and sheep and goats. Importantly, these differences are further influenced by farm scale: small-scale farms within these specialisations show a marked income disadvantage, whereas large farms within the same types often do not present a significant income gap. The reason for this phenomenon could be attributed to the high fixed costs borne by small farms specialized in animal breeding, which, combined with lower production volumes, result in a decrease in profitability (Kuhl et al., 2019). At the same time, the absence of a significant income gap for other FT raises important policy considerations. If certain sectors do not experience substantial economic disadvantages due to mountain constraints, this might suggest that CA support should not be uniformly distributed, but rather adjusted according to the specific needs of different FT and scales. Current eligibility rules already distinguish between small and large farms – granting full CA support only to those under 20

Table 5. Results of the IPW-adjusted multivariate regression model.

	NI excluding CA/ha		NI/ha	
	Coefficient	Robust SE	Coefficient	Robust SE
Location (Mountain)	-1319.44**	603.97	-1201.49**	605.79
FT (vs Cattle)				
Sheep & goats	1737.47*	1003.23	1741.02*	1005.25
Fruit	2419.50***	883.81	2421.13***	884.60
FT × Location × Farm scale				
Cattle × Mountain × Large	-2080.62**	821.62	-2065.50**	822.79
Cattle × Mountain × Small	-832.43*	481.14	-867.59*	483.10
Sheep & goats × Mount × Large	-4283.34***	944.87	-4282.66***	945.98
Sheep & goats × Mount × Small	-1064.76	1018.55	-1057.00	1022.25
Sheep & goats × Non M × Small	-2620.65***	996.31	-2662.57***	1001.69
Fruit × Mountain × Large	-2069.54**	801.21	-2063.17**	800.91
Fruit × Mountain × Small	-1513.35	939.55	-1513.56	947.54
Fruit × Non mountain × Small	86.07	927.07	91.64	930.49
LU	248.43**	116.99	247.35**	117.11
FLU	1179.13	1090.93	1161.00	1090.79
ED	1070.17***	260.69	1060.88***	260.84
Gender (Woman)	-298.93	299.37	-299.62	299.48
Diversification	-18.91	426.15	-22.89	426.63
Organic	39.21	475.92	57.18	477.77
Education	16.50	209.12	10.93	208.72
Age (years)	24.56**	12.35	24.28**	12.30
Year (vs 2012)				
2013	-66.35	353.20	-83.99	357.96
2014	145.63	405.84	141.99	405.14
2015	444.99	331.13	494.20	329.88
2016	1391.10**	690.63	1384.50**	690.78
2017	374.81	428.84	367.44	428.68
2018	1072.66**	490.55	1068.52**	487.95
2019	325.40	583.24	320.91	584.57
2020	520.55	555.68	499.98	554.84
2021	103.94	395.84	107.05	394.49
2022	-156.24	386.01	-150.14	384.57
Constant	-3252.46**	1416.46	-3188.35**	1413.39

Note: * p<0.10, ** p<0.05, *** p<0.01.

Table 6. Results of the post-hoc analyses.

	Scale	NI excluding CA		NI		χ^2	*P*-value
		Gap (€/ha)	Robust *SE*	Gap (€/ha)	Robust *SE*		
Cattle	Small	-1319.44 **	603.97	-1201.49**	605.79	159.88	< .0001
	Large	-71.24	305.14	-3.586	301.425	68.93	< .0001
Sheep & goats	Small	-2384.19 ***	867.49	-2258.49 ***	870.54	101.85	< .0001
	Large	343.25	386.87	418.60	397.00	9.31	0.002
Fruit	Small	-1233.37	754.99	-1109.84	757.62	147.01	< .0001
	Large	-763.25	946.99	653.55	953.66	0.48	0.486

Note: NI = Net income; CA = Compensatory allowance; Gap = estimate of the operating income difference between mountain and non-mountain farms; ** p < .05, *** p<0.01. The last two columns refer to the Wald test between the two estimated gaps, where H_0: NI excluding CA = NI.

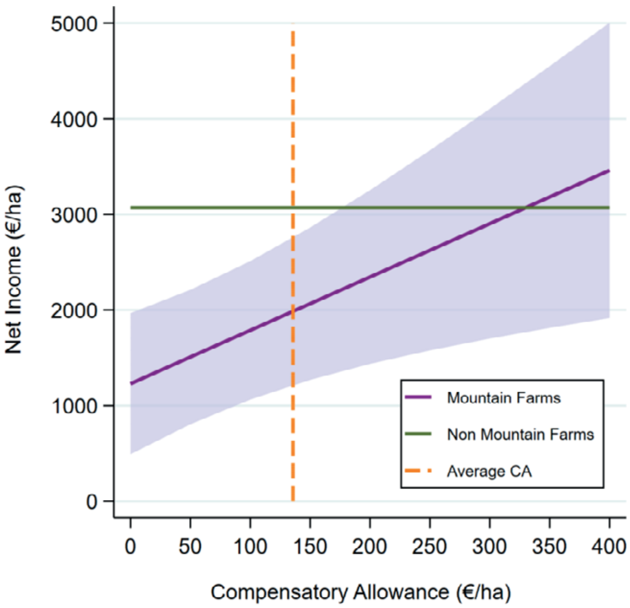

Figure 1. Estimated increase in CA required to bridge the net income gap between mountain and non-mountain farms. The shaded area represents a 95% confidence interval. The dashed line depicts the average CA received by mountain farms.

hectares – but our findings show that this differentiation, while appropriate in principle, does not go far enough in correcting income disparities.

Furthermore, our results indicate that the income gap in small farms specialized in animal breeding is only partially bridged by CA support, which covers only a small portion of this gap. This finding echoes previous concerns regarding the effectiveness of policies aimed at supporting mountain farms in Italy (Whitaker, 2024). However, CA support remains insufficient to fully close the gap. Previous studies have shown that the impact of ANC support is variable, depending on context (Namiotko et al., 2017). While some research aligns with our findings, demonstrating ANC supports' limited role in bolstering mountain farm income (Ferto et al., 2022; Wieliczko et al., 2018), other studies have highlighted its effectiveness in other agricultural types, such as cereals (Klima et al., 2021), or in boosting income for organic farms, especially small-scale (Veveris et al., 2014).

Even though current eligibility criteria consider factors such as the agricultural system, the level of land disadvantage, and farm scale (Regione Piemonte, 2016), they do not fully capture the economic heterogeneity across those factors and different FT. This limitation suggests that a more differentiated approach in the allocation of CA support could enhance its effectiveness. In particular, redistributing resources from less-affected sectors to those that bear the highest costs of mountain farming could provide a more targeted use of funds.

Notably, the current policy framework already recognises the importance of farm scale by modulating CA support, however our findings indicate that this differentiation is not sufficient to fully compensate for the income gap observed in small mountain farms.

To further reduce the income disparities, a multifaceted strategy should be considered. In addition to revising CA distribution, policies aimed at enhancing productivity and market access for mountain farms could be beneficial. Investments in infrastructure, technological innovation, and training programs tailored to the needs of mountain farmers could improve efficiency and economic resilience (Dax & Fischer, 2018; Pezzini, 2001). Furthermore, fostering cooperatives and producer organizations may strengthen the bargaining power of mountain farmers, enabling them to capture a larger share of market value and thereby reducing income disparities (Knickel et al., 2018).

Nonetheless, the income gap for farms specialised in animal breeding is not fully addressed by CA support, and achieving full compensation would require more than doubling the per-hectare payment. While increasing financial support could help, it is essential to evaluate its cost-effectiveness. A simple increase in payments may not be the most efficient approach, as it could lead to budgetary constraints without necessarily addressing structural inefficiencies. Instead, a combination of increased financial aid and complementary measures, such as targeted investments in modernization, innovation, and value-chain integration, could yield better long-term results. Future policy adjustments should consider the balance between financial sustainability and the actual impact of interventions on mountain farm incomes.

It is essential to consider a redistribution of support payments that reflects the varied economic outcomes across different mountain FT, underscoring the need for sectoral policies tailored to these differences (Papić Milojević & Bogdanov, 2023). A more tailored distribution of CA support, based not only on land characteristics but also on the specific economic challenges of different FT, could lead to a more equitable and effective support mechanism. In particular, an equitable distribution of CA support may be challenging to achieve with a flat per-hectare payment structure. Allocating contributions based on labour units rather than area could offer a more equitable approach, and presents a promising avenue for future research. Additionally, first-pillar direct payments could play a critical role in this redistribution by facilitating a convergence process that reallocates resources in favour of mountain areas (Tantari et al., 2017).

It is important to acknowledge a broader structural disadvantage that our analysis does not capture: the limited range of viable production options in LFAs. Mountain farms are often constrained not only by higher production costs but also by ecological and climatic factors that restrict crop and livestock choices, limiting their ability to diversify or switch to more profitable activities. This implies an additional layer of opportunity cost, which is not addressed through intra-sectoral profitability comparisons alone. Capturing such constraints would require integrating agronomic feasibility assessments and opportunity cost modeling into a broader analytical framework, an important, though currently out-of-scope, direction for future research. However, we believe recognizing this limitation is essential when designing compensation schemes and rural development strategies that aim to fully reflect the multi-dimensional nature of disadvantage in LFAs.

Beyond public support, narrowing the income gap between mountain and non-mountain farms might also require consumer recognition and willingness to pay a price premium for mountain-origin products. This added value would create a more sustainable revenue stream for mountain farms, helping to offset higher production costs and lower yields, and thus supporting the long-term viability of agriculture in these challenging areas (Cei et al., 2023; Staffolani et al., 2023; Mazzocchi & Sali, 2021).

It is important to acknowledge, however, that the empirical strategy employed in this study does not allow for causal inference. Although we apply statistical techniques to adjust for observable differences between farms, unobserved confounding factors may still influence the results. As such, the findings should be interpreted as associations rather than causal effects. Policy implications should be considered exploratory, offering indications rather than definitive prescriptions.

5. CONCLUSIONS

This study aimed to assess the effectiveness of RDP's measures to bridge the income gap between farms located in mountainous and non-mountainous areas in Piedmont. The results show that a statistically significant and negative income gap exists only in small farms specialized in cattle and sheep and goats. Net of the CA support provided through the RDP, the average shortfall amounts to €1,319.44 per hectare for cattle farms and €2,384.19 per hectare for sheep and goat farms. Compensatory allowance support helps reduce this gap by 8.93% for cattle farms and 5.28% for sheep and goat farms, though a substantial disparity remains.

While increasing compensatory allowances could help narrow income disparities in mountain areas, our findings suggest that this measure alone is neither financially sustainable nor sufficient to address the broader challenges these regions face. A more promising approach involves embedding CAs within integrated territorial development strategies that tackle structural and systemic constraints. For example, policy experiences in France during the early 2000s highlight the value of bundled interventions, whereby CAs were linked to participation in agri-environmental or organic farming schemes – promoting both economic viability and environmental stewardship. At the regional level, the Strategia per le Montagne del Piemonte (DGR 27/02/2023) offers a concrete illustration of how multi-sectoral action plans can support youth entrepreneurship, workforce training, and the valorization of ecosystem services alongside traditional income support (Regione Piemonte, 2022; 2023). Additionally, shifting from per-hectare to per-labor-unit payments could enhance the equity and effectiveness of support, better aligning aid with actual farm effort and viability – though this would require overcoming significant administrative and WTO-related hurdles. Ultimately, advancing the cost-effectiveness and legitimacy of rural policy in mountain areas calls for a transition from a logic of compensation to one of strategic investment, in line with the broader vision of the Strategia Nazionale per le Aree Interne, recognizing mountain farming as a cornerstone of territorial resilience and social cohesion

In general, the findings indicate that CA support does not fully bridge the income gap, even when supplemented by contributions from other RDP measures. To completely close this gap, CA support would need to more than double, increasing from €135/ha to €340/ha, which would require a substantial rise in allocated resources. Given the limited economic feasibility of this approach, a more viable solution would involve not only increasing contributions but, more importantly, redistributing them. All in all, mountainous areas constitute approximately 45% of Piedmont's total land area and 30% of its agricultural land, making them crucial for the region's economic and environmental sustainability. The study serves as an exploratory analysis, with the intention of expanding the research to additional Alpine regions in future studies.

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Do economic performance and innovation have a relationship? Evidence from Operational Groups in the Italian agri-food sector

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Abstract. This study aims to investigate the potential mutual interdependence between an environment that fosters and encourages innovation and the economic performance of agricultural businesses operating in the sector. Specifically, it seeks to determine whether the economic performance of farms in regions with established Operational Groups (OGs) is better than that of farms located in regions where OGs have not yet been implemented, using the European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI). We combine data on OGs collected from the Innovarurale website, with financial information from the ORBIS database for the period 2013-2022, to assess farm performance. Our estimation strategy employs three staggered difference-in-differences models and an event-study to validate the parallel trends assumption. The results show a positive association between the presence of OGs in a region and an improved economic performance. Our findings suggest that the diffusion of innovation tends to be related to the characteristics of the local economic environment, which should be a critical factor in future policy discussions.

Keywords: EIP-AGRI, staggered difference-in-differences model, Operational Groups, economic performance evaluation.

1. INTRODUCTION

A study on the 7th Italian Agricultural Census[1] (Henke and Sardone, 2022), reveals that the Italian agri-food sector is undergoing significant structural changes. Between 2010 and 2020, the number of farms declined drastically, with 380,000 out of 500,000 missing farms being smaller than 2 hectares. Meanwhile, larger farms expanded, with those over 100 hectares growing by 17% and those between 50-100 hectares increasing by 11%. Despite this consolidation, micro and small farms face challenges due to a lack of entrepreneurial skills, limiting their adaptability. Additionally, the expected generational transition has not materialized, raising concerns about the sustainability of small-scale farming in Italy. Innovation trends from the Census further highlight sectoral shifts. Over 50% of farms, particularly in the north, have

[1] https://www.istat.it/statistiche-per-temi/censimenti/agricoltura/7-censimento-generale/

adopted mechanization for planting, tillage, and irrigation, enhancing efficiency. Digitalization has risen sharply, with 15.8% of farms using IT compared to just 3.8% in 2010. However, diversification efforts remain limited, hindered by farm size and generational gaps. Regional disparities persist, with northern farms embracing technology more rapidly than those in the south. These findings indicate that while innovation is progressing, barriers to equitable and widespread adoption remain.

In the agri-food sector, according to Golubev et al. (2021), knowledge dissemination in agriculture could increase productivity, adapting to environmental and market changes, and improving decision-making. It helps farmers adopt innovative practices, manage resources efficiently, and make informed choices, boosting financial stability. It fosters continuous learning through shared experiences and provides access to resources like financial aid and training. Promoting sustainable farming practices ensures environmental conservation and long-term agricultural viability, contributing to food security and broader sustainable development goals for future generations.

To improve this aspect in the Italian agri-food sector, the EIP-AGRI[2] (European Innovation Partnership for Agricultural Productivity and Sustainability) has been implemented with the aim of improving agricultural productivity and sustainability through collaborative efforts among various stakeholders, including farmers, researchers, advisors, and sector representatives. The EIP-AGRI promotes a multi-actor and interactive approach, as a method of work, and this is applied in the implementation of OGs and of multi-actor research projects and thematic networks (under Horizon 2020, and Horizon Europe). This approach highlights the active participation of diverse stakeholders during the project, enhancing collaboration and integrating their knowledge into the innovation process. The interactive approach facilitates a reciprocal exchange of ideas, merging scientific knowledge with practical insights from stakeholders, thus expediting the implementation of new concepts. Knowledge sharing is central to this approach, encompassing both formal education and informal peer exchanges, which can improve learning outcomes and yield more effective solutions.

The main aim is to identify, develop, and implement innovative solutions tailored to the specific needs of farmers and rural communities (European Commission, 2014), and places emphasis on the importance of knowledge exchange and sharing as a practice among stakeholders to enhance the overall effectiveness of agricultural practices. This is achieved through various dissemination activities, including workshops, training sessions, and the use of digital platforms.

The European Commission study (2024) looks at the results and effects of EIP-AGRI support in order to get ready for the ex-post review scheduled for 2026. The study provides information on the effectiveness of OGs calls and possible areas for improvement by evaluating how Member States' answers to these calls have impacted the achievement of results. The parameters set by OGs calls have been shown to promote the co-generation of innovative solutions, indicating a collaborative approach to problem-solving. The results indicate that these calls have increased the likelihood that innovative ideas will be embraced more broadly, perhaps leading to improved stakeholder engagement and the development of new partnerships.

Arzeni et al. (2023) study the implementation of EIP-AGRI in Italy to analyse the effectiveness of Operational Groups (OGs). The authors conduct an online survey finding that the implementation of OGs has been effective in capturing the real issues faced by farmers and rural entrepreneurs. This effectiveness is attributed to the collaborative nature of the groups, which fosters relationships among partners and enhances the innovation process. The study identified also low levels of both internal and external communication within OGs, which hindered the dissemination of results and reduced overall effectiveness. As a result, the authors discuss how future OGs should focus on improving their capacity to address the needs of larger groups of farmers and enhance their communication strategies to better share innovative solutions.

The aim of this paper is to use the implementation of EIP-AGRI, combined with financial data, as a tool to identify the Italian regions that favour innovation through the financing of OGs and thus investigate the mutual interdependence between an environment that supports and encourages innovation and the economic performance of agricultural businesses operating in the sector. Using an estimation strategy suitable to analyse a policy characterised by a staggered implementation over time (staggered DID) we show that farms located in regions where OGs are present appear to experience a positive and significant increase in their economic performance.

In the first section there will be a review of the literature related to the topic discussed in this study; in the second section we examine the data and the main variables used in the analysis and in the third section we offer an overview of the methodological approach implemented in this study. Finally, we present the results (fourth section) and discuss the main implications (fifth section).

[2] https://ec.europa.eu/eip/agriculture/en/node.html

2. BACKGROUND

Innovation in the agrifood sector is often limited due to a combination of several factors. For example, Manning (2024) explains how farmers face challenges like socio-technical barriers, such as external factors (market dynamics, bureaucratic hurdles) and internal factors (employee relations, financial constraints). Moreover, both public and private sector investments in agrifood innovation have decreased, limiting research and development opportunities (Carlberg, 2024). Finally, a lack of awareness about food security and the benefits of digital innovations affects farmers' intentions to adopt new technologies (Aboagye-Darko and Mkhize, 2025).

The literature has emphasised that to foster innovation in the agrifood sector could be necessary several different strategies. To enhance innovation in the agrifood sector, it is essential to implement a diverse range of strategies tailored to different dimensions of the innovation ecosystem. A significant strategy is to engage stakeholders inclusively, ensuring that farmers, entrepreneurs, and researchers can collaborate meaningfully in digital co-innovation initiatives (Gouthon et al., 2024). Another strategy is to increase public investment in agricultural R&D, with the goal of allocating at least 0.10 percent of GDP to drive scientific advancement and technological progress (Carlberg, 2024). Furthermore, promoting sustainability-oriented innovation requires policies that support eco-innovation through environmental education, capacity building, and robust institutional frameworks (Chaparro-Banegas et al., 2024).

At the European level, innovation in the agrifood sector is supported through a combination of policies, strategic frameworks, and funding instruments. The EU research and innovation policy provides the overarching framework for initiatives such as Horizon Europe, a key funding programme that serves as an instrument to support research and technological development. Within Horizon Europe, Cluster 6 ("Food, Bioeconomy, Natural Resources, Agriculture and Environment") finances a wide range of projects related to sustainable agriculture, including but not limited to precision farming, agricultural robotics, biotechnology, circular bioeconomy, and climate-resilient farming systems.

Strategic documents such as the European Green Deal and the Farm to Fork Strategy guide the EU's long-term vision for sustainability and food system transformation. While not policies in themselves, these strategies shape legislative and funding priorities. They emphasize the reduction of pesticide and fertilizer use, support the development of sustainable business models, and promote innovative practices that enhance both environmental and economic performance in agriculture.

Crucially, the Common Agricultural Policy (CAP) remains the central EU policy for supporting agricultural innovation. Through mechanisms such as Operational Groups (OGs) under the European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI) and the strengthening of the Agricultural Knowledge and Innovation System (AKIS), the CAP facilitates knowledge exchange, co-creation, and the uptake of innovative solutions among farmers, researchers, advisors, and other stakeholders.

In this context, the EIP-AGRI also fits in, promoting collaboration between farmers, researchers and businesses to accelerate the adoption of innovations and financing operational groups to develop innovative solutions in the agricultural sector.

This paper uses EIP-AGRI as a tool to analyse the link between innovation and economic performance. This relationship is explored in literature from two perspectives: innovation as a driver of economic performance, and vice versa.

To examine which studies have found that innovation in the agri-food sector can lead to improved economic performance, we can mention Ponta et al. (2022) that describe a positive relationship between sustainability-oriented innovation outputs, production value growth and EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) growth in farms. Moreover, research across the EU-28 showed that countries with higher investment in R&D and agricultural education achieved better agricultural performance (Coca et al., 2017). Technological eco-innovation and R&D spending were identified as key conditions benefiting company performance in the Spanish agri-food sector (Rabadán et al., 2019). Additionally, regional clusters were found to play a role in spreading innovation among associated farms, particularly for small and medium-sized ones that face difficulties innovating individually (Finco et al., 2018). These studies collectively highlight the importance of innovation, sustainability-oriented practices, and collaborative efforts in driving economic growth and competitiveness in the agri-food sector.

The literature also proposes a cyclical pattern in which innovation might result in better economic performance, which in turn enables additional investment in innovation (Francois and Shi, 1999; Baláž et al., 2023; Lucchese and Pianta, 2011; Brusoni et al., 2006). The regional performance of the agri-food sector significantly influences new investment in innovation. Studies show that organizational factors, including management, strategy, structure, culture, climate, and market orientation help to achieve innovative performance in regional agri-food companies (Corchuelo Martínez-Azúa et al., 2020). Regional context affects both the capacity and nature of innovation, with marketing innovation in farms linked to prior ICT experience (Peón and Martínez-Filgueira, 2020). Small farms face challenges in achieving innovation individually, but regional clusters can help develop innovation strategies and increase competitiveness (Finco et al., 2018). Public funding can also support innovation, with regional funding being more accessible to agri-food companies compared to state funding (Alarcón and Arias, 2018). Therefore, creating an enabling environment could help stimulate for agricultural innovation.

To the best of our knowledge, no previous studies have examined this link using farm-level financial data and a European policy instrument, such as EIP-AGRI, as a tool to identify the farms that are located in an area where there are OGs promoting the dissemination of innovative knowledge in the sector. This paper aims to fill the gap in the literature using an estimation method that provides robust results when the policy is implemented at a staggered level.

3. DATA

We combine data from two different sources. We collected data on the year of first implementation, the duration of the project and the total number of OGs per region from the official Italian EIP-AGRI website (Innovarurale[3]) (Table 1). As can be seen there are some regions in our sample that do not yet have OGs (Abruzzo, Lazio, Molise, Sardegna, Valle d'Aosta). Some of these regions (Lazio and Molise) are currently in the selection phase. Others (Abruzzo and Sardegna) began forming their first OGs in 2023. Finally, Valle d'Aosta has not activated this measure.

The second dataset used is the ORBIS[4] database (Bureau van Dijk). ORBIS provides financial data on corporations for the past 10 years. The data are limited first of all to consider only active farms providing financial data in the period 2013-2022.

Then, according to the NACE classification code: limited to the following codes: 01 (Crop and animal production, hunting and related service activities); 02 (Forestry and logging); 03 (Fishing and aquaculture). From 2013 to 2022, we derive farm-level financial data to add the economic performance of the agri-food sector to our analysis. In Table 2 are summarized the descriptive statistics for the economic performance of selected variables.

[3] https://www.innovarurale.it/it/pei-agri/i-gruppi-operativi-italia
[4] https://login.bvdinfo.com/R0/Orbis

Table 1. Number of new OGs by Italian region and by year.

Region	2016	2017	2018	2019	2020	2021	2022	Total
Abruzzo	0	0	0	0	0	0	0	0
Basilicata	0	5	6	0	0	0	0	11
Calabria	0	0	0	0	0	2	2	4
Campania	0	0	0	34	6	11	0	51
Emilia-Romagna	51	37	5	44	43	33	0	213
Friuli V. G.	0	0	0	8	0	0	0	8
Lazio	0	0	0	0	0	0	0	0
Liguria	0	0	0	0	15	6	0	21
Lombardia	0	0	0	25	0	0	0	25
Marche	0	0	4	26	12	0	16	58
Molise	0	0	0	0	0	0	0	0
Piemonte	0	0	5	3	20	4	0	32
Puglia	0	0	0	0	47	1	0	48
Sardegna	0	0	0	0	0	0	0	0
Sicilia	0	0	0	5	45	4	7	61
Toscana	0	0	0	48	4	0	0	52
Trentino A. A.	3	8	4	0	2	0	0	17
Umbria	1	1	11	0	1	0	0	14
Valle d'Aosta	0	0	0	0	0	0	0	0
Veneto	0	3	19	39	0	0	0	61
Total	55	54	54	232	195	61	25	676

Note: The Italian OGs started to be formed in 2016.
Source: Authors' calculation using Innovarurale data.

Table 2. Descriptive Statistics of the economic performance variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
Operating Revenues	111779	1.986	5.947	0	44.716
Total Assets	111779	3.572	7.628	.006	52.254
Net Income	111773	.017	.191	-.727	1.118
Cash Flow	93241	.132	.392	-.479	2.653
Shareholders' Funds	111779	1.221	3.341	-.194	23.172
Solvency Ratio	110788	31.173	31.044	-34.992	99.268

Source: Authors' estimation from Orbis database.

4. ESTIMATION STRATEGY

We assign the farmers that are located in a region affected by the presence of OGs to a treatment group and those not affected by that to a control group. Therefore, a method that could be used to analyse this reform is the DID model, because it is appropriate to focus on the impact of the policy. As not all regions started to implement the OGs in the same year, there are more than two time periods and units are treated at different points in time. Roth et al. (2023) stated that using the 2X2 DID (2 groups, 2 periods) could lead to potential bias in the estimated result. As a result, a staggered DID model might be the best choice in this case.

We use three different recently developed estimation techniques.

Callaway and Sant'Anna (2021) develop a methodology characterized by the concept of "group-time average treatment effect", that is the average treatment effect for group *g* at time *t*, including information regarding the unit's first year of treatment:

$$ATT\,(g,t) = E[Y_{i,t}\,(g) - Y_{i,t}(\infty)\,|G_i = g] \tag{1}$$

The average treatment effect on the treated (ATT) can be interpreted as the difference between the potential outcome: the operating revenues (for example) of the *i* region in period *t* if there have been affected by OGs implementation at time *g*, and if there has not been influenced by time *t*. The difference between the expected change in operating revenues for group g between periods *g*-1 and *t* and the result for the control group that was not yet treated at period *t* is known as the ATT (Roth et al., 2023). The final estimation of ATT is:

$$\widehat{ATT}\,(g,t) = \frac{1}{N_g}\sum_{i:G_i=g}\left[Y_{i,t} - Y_{i,g-1}\right] - \frac{1}{N_{G_{comp}}}\sum_{i:G_i\epsilon comp}\left[Y_{i,t} - Y_{i,g-1}\right] \tag{2}$$

where N_g is the number of regions where there has been new OGs implementation at time *g*. $N_{G_{comp}}$ is the number of regions in the control group, not-yet-treated by time *t*. The difference in parentheses represents the difference between the dependent variable of the treated regions at year *t* and before the policy occurred (*g* – 1).

The main drawback of this approach is that the control period is limited to the period immediate prior the intervention. Consequently, to compute the ATT, we use also the imputation approach of Borusyak et al. (2024), that consider the entire pre-treatment period as the reference period. The authors start from a TWFE model:

$$Y_{i,t}(\infty) = \gamma_i + \delta_t + \varepsilon_{i,t} \tag{3}$$

Considering only regions that are not-yet treated during the periods. After that they use the predicted value from this regression to calculate the never-treated outcome for each treated region, to estimate the treatment effect for each treated unit and then aggregate them to compute the ATT.

Finally, the model proposed by de Chaisemartin and D'Haultfœuille (2020), with a binary treatment and two periods, consists of a weighted average of two DID estimators, the first one compares the evolution of the dependent variable between the "switchers in" observations (those transitioning from untreated to treated) and the never treated ones between period 1 and period 2, the second estimator compares the evolution of the dependent variable between the always treated observations and the "switchers out" (that go from treated to untreated) between period 1 to period 2. The final estimator, once derived from the previous calculations, could be applied also to analyse staggered policies with treatment occurring over more than two periods. The method is basically the same, but the comparison is for each pair of consecutive time periods and then computing the average of these estimators across time.

Furthermore, de Chaisemartin and D'Haultfœuille (2024) proposed another type of estimator that can deal with a non-binary treatment variable, that is suitable for analysing treatment intensity. In fact we will use this model to introduce in our study the number of OGs for each year and region as the treatment variable, instead of working with the binary variable considered in the other settings.

Since different parallel trends assumptions characterize each of these approaches (Marcus and Sant'Anna, 2021), we perform more than one estimation and, as Roth et al. (2023) recommend when there are multiple pre-treatment periods, we test for pre-trends using the event study plot developed by Borusyak (2023).

5. RESULTS

The total number of farms in our sample is 11496. The treatment group consist of 9607 farms, while 1889 are located in regions where OGs have not yet been implemented.

In order to verify the parallel trend assumptions needed for each of the three approaches we start by looking at the average trends of the dependent variables (Figure 1). Since 2016 is the first year that OGs start to form, we selected it as the graph's cut-off year. For any specification of the dependent variable, it is quite evident that the trends exhibit a parallel pattern prior to the policy's implementation (except for Solvency Ratio).

Using an event-study analysis in Figures 2, we offer a visual assessment of the pre-existing patterns in accordance with the pre-testing methodology (Roth et al., 2023). Since at least two models out of three shows not-significant pre-trend estimates (all of the intervals related to the pre-treatment include the zero value) the parallel trend assumption appears to be true and, consequently, we cannot reject the null hypothesis that the parallel trend was satisfied during the pre-treatment phase, confirming the validity of our design.

Having shown that the data support the parallel trend hypothesis, we can proceed to investigate in detail

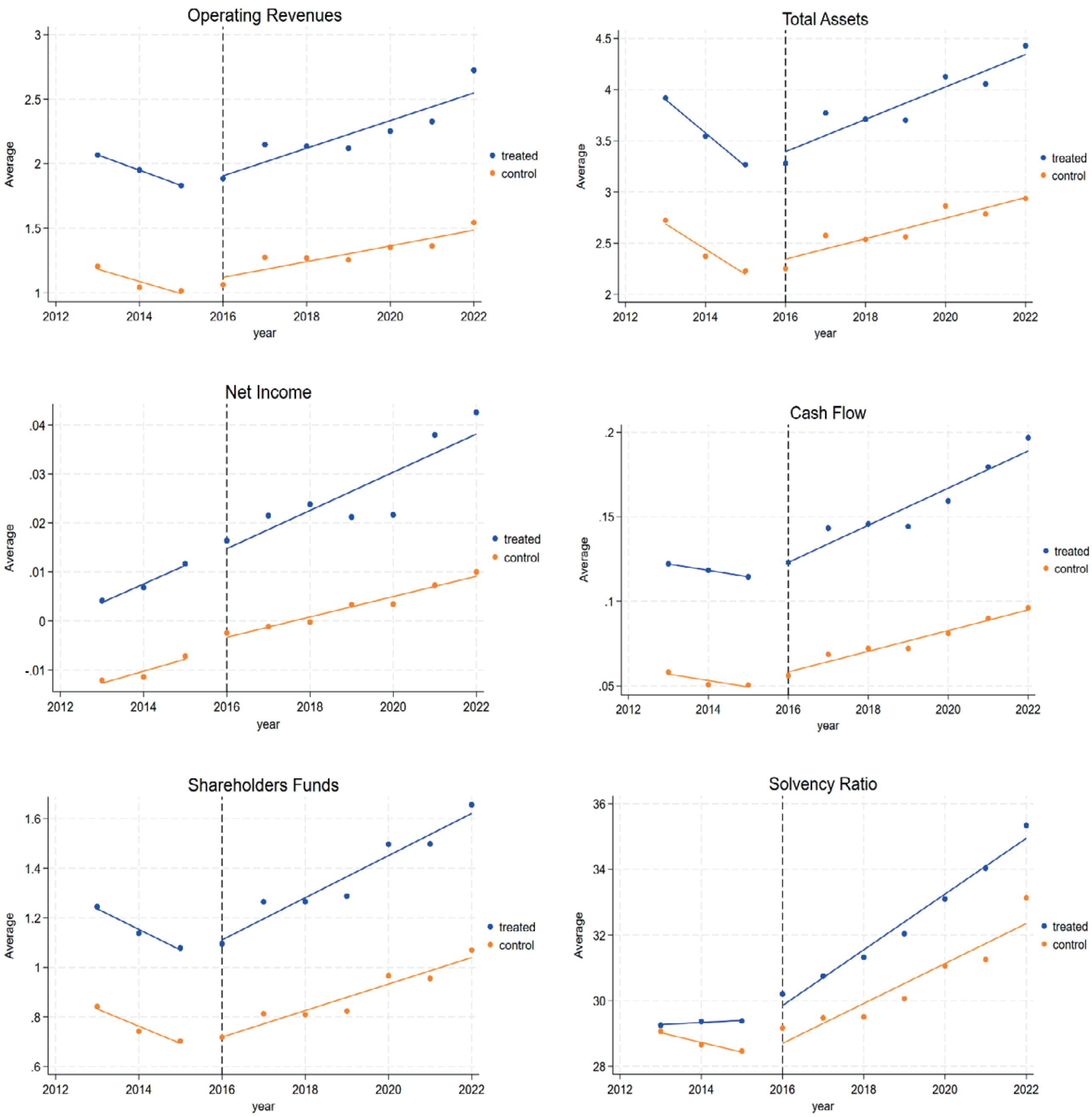

Figure 1. Average trends of the dependent variables in the treatment group and in the control group.

the differences between the two groups. Table 3 reports the Average Treatment Effects on the Treated (ATTs) estimated using the three staggered difference-in-differences (DID) models outlined in the previous section. The positive and statistically significant coefficients indicate that the farms located in the treated regions exhibit improved economic performance compared to those in regions where OGs was not yet implemented. Although the estimated effects vary in magnitude across the different model specifications, all results consistently point to a positive and statistically significant impact. These findings provide empirical evidence supporting the hypothesis that the presence of OGs is associated to an increase in economic performance.

Finally, we assess the effect of treatment intensity (measured by the number of OGs), on economic perfor-

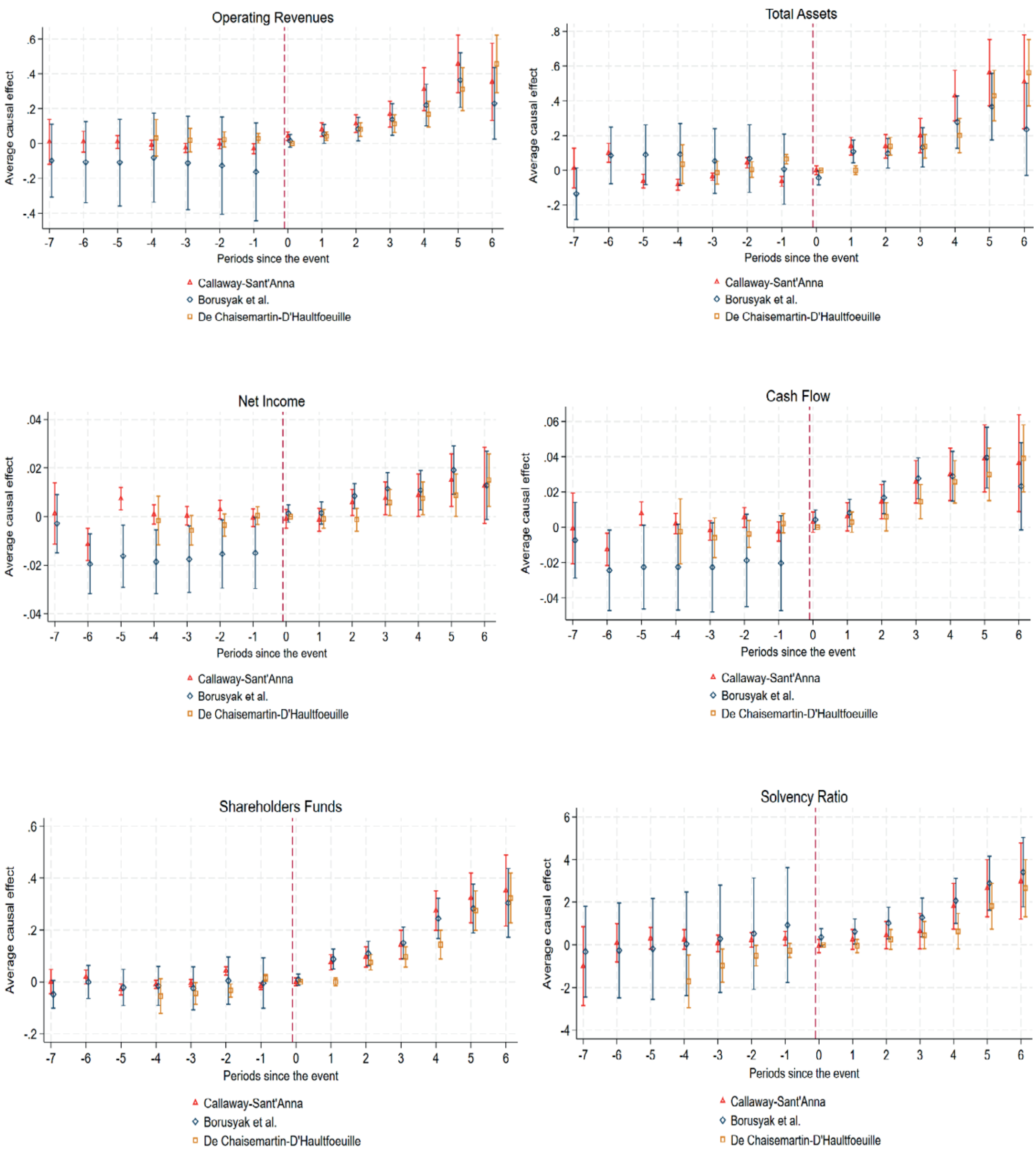

Figure 2. Comparison of the staggered DID estimators using the event-study plot.

mance, as reported in Table 4.

This analysis employs the estimator proposed by de Chaisemartin and D'Haultfoeuille (2024) as a robustness check, giving its suitability for handing non-binary treatment variables. The application of this model adds further depth to our empirical strategy. The results reinforce our previous findings: the positive and statistically significant coefficients suggest that a higher number

Table 3. Staggered DID estimation results (ATTs).

	Operating Revenues	Total Assets	Net Income	Cash Flow	Shareholders Funds	Solvency Ratio
Callaway and Sant'Anna (2021)	0.142***	0.176***	0.003*	0.015***	0.112***	0.639**
Borusyak et al. (2024)	0.102***	0.107***	0.006***	0.016***	0.115***	1.091***
De Chaisemartin and D'Haultfoeuille (2020)	0.135***	0.165***	0.003*	0.014***	0.104***	0.561**

Legend: * p<.1; ** p<.05; *** p<.01. Variables are expressed in millions (except for Solvency Ratio).

Table 4. Staggered DID estimation results (ATTs) using the intensity to treatment (number of OGs), according to De Chaisemartin and D'Haultfoeuille (2024).

	Operating Revenues	Total Assets	Net Income	Cash Flow	Shareholders Funds	Solvency Ratio
De Chaisemartin and D'Haultfoeuille (2024)	0.002***	0.003***	0.00007*	0.0002***	0.002***	0.011**

Legend: * p<.1; ** p<.05; *** p<.01. Variables are expressed in millions (except for Solvency Ratio).

of OGs in treated areas is associated with a significant improvement in farms' economic performance.

6. DISCUSSION

The results indicate the existence of a reciprocal relationship between farms' economic performance and an environment that encourages and supports innovation. This relationship emerges consistently across all three model specifications and when considering six different economic performance variables. Several possible interpretations may explain this finding.

One plausible explanation, supported by Finco et al. (2018), is that farms located in areas where OGs are active benefit from the diffusion of innovation fostered by the European Innovation Partnership (EIP), which provides funding and resources aimed at supporting innovation uptake. In this view, the presence of OGs encourages farms to adopt innovative practices, thereby improving their economic performance.

An alternative hypothesis, as suggested by Corchuelo Martínez-Azúa et al. (2020), asserts that certain Italian regions possess distinctive socioeconomic characteristics that both facilitate the emergence of OGs and provide a fertile ground for the development of innovative networks. These pre-existing regional conditions could, in turn, enhance the dissemination and effectiveness of innovation initiatives.

This study has two main limitations. First, our study does not constitute a formal impact evaluation of the EIP-AGRI, as it is not possible to precisely identify which of the farms in our sample are directly involved in OGs. Therefore, we are unable to attribute the observed effects to one explanatory theory over the other. Second, the Orbis database, while rich in financial information, is not fully representative of the Italian agri-food sector. In particular, it underrepresents SMEs, which are highly prevalent in the Italian context. Despite these constraints, our findings offer valuable insights into the dynamics of innovation support in agriculture and provide a preliminary understanding of how the OGs have been implemented within the Italian agri-food sector.

7. CONCLUSIONS

This study investigates the relationship between the economic performance of the Italian agri-food sector and the presence of an innovation-friendly environment. We apply an estimation strategy that compares three distinct staggered DID models employing recently developed methodological frameworks to assess this association. To the best of our knowledge, this is the first study to use the EIP-AGRI as an analytical tool to explore the relationship between regional economic performance in the agri-food sector and an innovation-friendly environment.

The main findings suggests that farms located in regions where OGs have been recently established show significantly better financial performance compared to those in regions without the presence of OGs. However, the data also reveal regional disparities in the effectiveness of this dynamic, specifically the expected virtuous circle of innovation, improved economic performance and increased regional investment in innovation, appears more evident in some regions than in others.

These findings could carry implications for policymakers. To promote the diffusion of innovation and improve local farm performance, targeted awareness campaigns and better-targeted incentive mechanisms may be necessary in regions where such dynamics are less evident.

Future research should focus on refining the identification of farms that are involved in the OGs, which would allow for the application of causal inference techniques to more precisely evaluate the impact of EIP-AGRI. Additionally, expanding the dataset to include non-corporate farms particularly SMEs would contribute to a more comprehensive analysis of the sector. Furthermore, understanding the temporal dimension of policy impacts, namely the lag between project completion and observable impacts could improve the evaluation of innovation policies.

This study offers an overview of the implementation of the EIP-AGRI across the Italian regions, providing insights into how the regional socioeconomic environment is connected with the diffusion of innovation and how the policy could be more consistently and effectively implemented nationwide.

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Towards digital farming: exploring technological integration in agricultural practices of a sample of italian livestock farms

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Abstract. Despite the rapid rise of digital technologies in agriculture, their application remains more prominent in crop farming than in the livestock sector. Recognizing this gap, our study explores the current state and determinants of digital technology adoption across Italian livestock farms, examining key factors and broader trends in the industry. Using national agricultural census, and national statistical programme data, we applied a logistic regression model to assess the likelihood of adoption of technology. Findings reveal that large ruminant farms, particularly dairy cattle and buffalo, are more likely to integrate digital tools like decision support systems, cloud services, and monitoring devices. In contrast, meat cattle, small ruminants, and pig farms lag. Key determinants include broadband connectivity, ownership structure, education, and age, with additional factors influencing specific technology categories. Our results establish a foundation for future policy and investment, underscoring the need to build digital infrastructure and promote an inclusive model.

Keywords: digital agriculture, livestock farming, technology adoption.

1. INTRODUCTION

The livestock industry has undergone significant transformations driven by evolving human needs, changes in consumption (Righi et al., 2023), and technological advancements (Subach & Shmeleva, 2022). Traditionally, livestock farming relied on subjective and less quantifiable but holistic approaches to animal welfare and management (Buller et al., 2020). However, a shift towards modern, data-driven processes characterized by interconnectivity and efficiency marks a significant change. Often referred to as digital farming, this shift includes concepts such as smart farming, precision agriculture, and Agriculture 4.0, rooted in the sustainability discourse and bolstered by advancements in information technology (Zhou et al., 2022). This shift is driven by concerns over food insecurity, economic factors, climate change, market dynamics and sustainability (Thornton et al., 2014).

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Digital technologies advance agricultural practices by enabling diagnosis, intelligent perception, decision-making, and improved production processes (Zhou et al., 2022; Finger, 2023). Applied along the entire value chain, they enhance resource management, trade promotion, operational efficiency, and knowledge exchange (Barnes et al., 2019; Elijah et al., 2018), promoting sustainability, resilience, and overall competitiveness (Finger, 2023). However, adoption challenges persist. Finger (2023) notes that technologies with more potential benefits are least profitable and less widely adopted by small scale farmers due to their high investment costs and limited returns. Large and capital-intensive farms tend to benefit disproportionately from these technologies, exacerbating existing inequalities (Hackfort, 2021). Additional challenges include data ownership and power distribution within the farming community (Morrone et al., 2022; Neethirajan & Kemp, 2021; Wolfert et al., 2017).

Despite the growing integration of digital technologies in agriculture, livestock farming remains one of the least digitalized sectors globally (Neethirajan & Kemp, 2021). Meanwhile, adoption is diverse and limited to basic aspects of livestock management (Guntoro et al., 2019). Barriers to adoption include social factors such as low levels of trust in new technologies, digital illiteracy, and resistance to change (Eastwood et al., 2021; FAO, 2022), as well as technological challenges like infrastructure limitations and system integration, compatibility, and interoperability (Abeni et al., 2019; Tuyttens et al., 2022). Economic factors include high cost of technology, uncertainty about the return on investment, and misaligned business models (Groher et al., 2020). Additionally, the complexity of agroecosystems, compounded by difficulties in collaboration among stakeholders, agreeing on common goals and farming practices represent barriers to successful digitalization (Grivins & Kilis, 2023). These combined factors create a complex environment that limits widespread adoption of digital technologies in livestock farming (Cui & Wang, 2023). Moreover, digital technology development is dominated by a small number of powerful multinational corporations, prioritizing digital innovations that support their market dominance, potentially misaligning with the practical needs of smaller farms (Hackfort 2021). Research related to digitalisation in the livestock sector has focused more on certain livestock species, particularly cattle, with less emphasis on small ruminants like sheep and goats (Morrone et al., 2022; Tzanidakis et al., 2023) and other livestock such as pigs and buffaloes. This disparity has implications for animal welfare, leading to species- or livestock- specific differences (Tuyttens et al., 2022). Therefore, it is crucial to comprehend the extent of digital technology usage in livestock production and management (Fuentes et al., 2022). In Italy, the livestock sector is vital not only economically but also for its cultural heritage (Pulina et al., 2017). Local breeds, adapted through selective breeding, support sustainable husbandry and rural communities. By leveraging breed diversity and innovative technologies, the sector can address challenges like greenhouse gas emissions and resource management, contributing to both productivity and sustainability.

The primary goal of this research is to explore the extent of digitalization among Italian livestock farms and identify the factors influencing digital technology adoption. This research contributes to existing literature in several ways. First, the study provides a comprehensive analysis across all livestock categories, including small ruminants and monogastric species, thereby addressing a critical gap in digitalization research within the livestock sector, predominantly focused on dairy cattle and large ruminants. Second, by leveraging a large-scale, nationally representative datasets, we offer robust empirical evidence on the determinants of digital technology adoption, moving beyond the commonly acknowledged availability of digital solutions to assess the actual uptake and utilization of these technologies at the farm level. Third, this study introduces a new economic dimension by examining the role of marketing channels and their influence on digital investments, shedding light on how different marketing sales strategies may either facilitate or hinder the adoption of technological innovations. The findings of this research provide valuable insights for policymakers, technology providers, and researchers seeking to foster a more inclusive and effective digital transformation in livestock farming. Specifically, it seeks to answer: What is the current extent of digital technology usage in livestock production and management? What factors influence the adoption these technologies? The paper goes on with a literature review on how digital technologies have been integrated into the livestock sector over time. In section 3, the material and methods are explained. The results of the analysis are presented and discussed in section 4. We conclude with reflections on policy implications and recommendations.

2. DIGITALIZATION IN THE LIVESTOCK SECTOR

Digitalization in the livestock sector encompasses a broad array of technological innovations reliant on digital infrastructures and networks. These components enhance the creation, storage, and exchange of data, improving the functionality of various digital tools. Initially, Information and Communication Technologies (ICT) were pivotal in precision agriculture (Cox, 2002), but today's digital solutions leverage the internet, big-data technology, cloud computing, and the internet of things (IoT) through sensors and wireless communication networks (Zhou et al., 2022).

Technologies in this digital shift, as recorded in the early 2000s, involve basic data management systems, including electronic identification systems such as Radio Frequency Identification (RFID) tags, tracking collars, and wearable biosensors, enabling farmers to monitor individual animal health, behaviours, and movement (Eastwood et al., 2021). These tools have improved animal welfare and productivity through early detection of health issues (Zhou et al., 2022). In Europe, Farm Management Information Systems (FMIS), barn cameras, and sensors are increasingly integrated into livestock management (Gabriel & Gandorfer, 2023). This phase also introduced simple automation for feeding, milking, and climate control systems.

Building on these early innovations, the mid-to-late 2000s saw the development of automated farm management technologies, increased development of robotic systems, and the integration of real-time data collection tools. These advancements laid the groundwork for further digitalization, allowing farms to transition from basic monitoring to more interactive, data-driven decision making.

In the last decade, digitalization advanced with integrated systems combining data analytics, real-time monitoring and advanced sensors to enhance precision and decision making (Wolfert et al., 2017; Chavan et al., 2024). Technologies at the forefront include Artificial Intelligence (AI)-driven analytics, IoT-based monitoring systems, blockchain technology, advanced automation, and robotics, which promise improvement in sustainability and traceability (Calcante et al., 2014; Alonso et al., 2020a; D'Agaro et al., 2021; Alshehri, 2023; Alipio & Villena, 2023). However, blockchain technology is in its early stage of development and requires further validation and adoption (Neethirajan & Kemp, 2021). Further innovations such as gene editing and advanced biometrics offer further potential for improving animal welfare and sustainability (Eastwood et al., 2021). As shown in Figure 1, these digital tools address species-specific challenges and benefits various livestock production systems - commodity based, nature-based, subsistence, and value-seeking systems (Kraft et al., 2022) and tailored technological solutions are necessary for each sys-

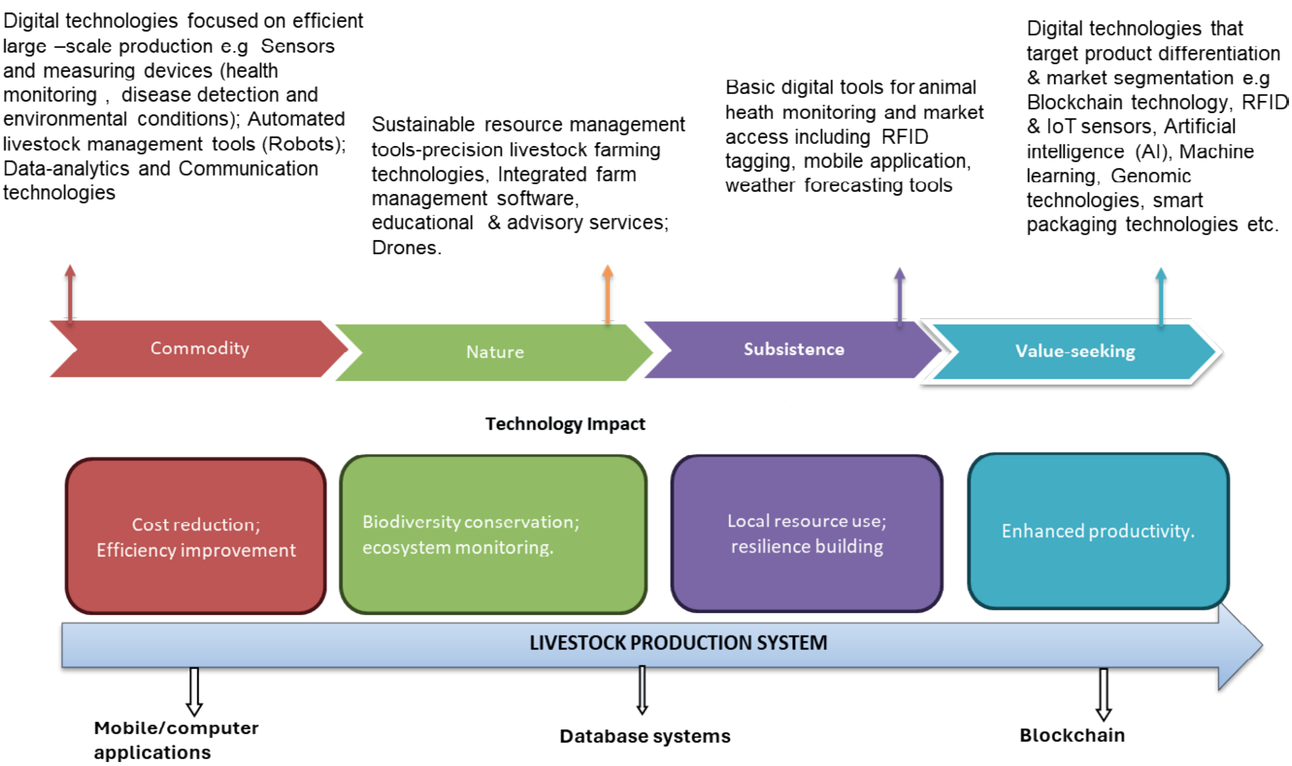

Figure 1. Livestock production systems: technologies and impacts. Adapted from Baker et al. (2022).

tem as they face unique challenges (Baker et al., 2022). For instance, a commodity-based system might struggle with regulatory issues, while a value-seeking system may face challenges related to skill shortages and data management. Despite these advancements, concerns remain that the focus on high-tech solutions may neglect simpler, more accessible innovations that could benefit a wider range of farmers, particularly small-scale operations (Barrett & Rose, 2022). To address issues of exclusion, Alonso et al. (2020b) suggest creating an integrated technology ecosystem – a coordinated network – where IoT, edge computing, AI, and blockchain technologies are bundled together. This approach is intended to lower the costs associated with adopting these technologies individually. However, while such an ecosystem could enhance accessibility, it may also introduce privacy and data ownership concerns that could limit widespread adoption. Promoting individual components of precision livestock farming technologies can be unsustainable (Banhazi et al., 2012).

Digitalization presents both optimistic prospects and contentious challenges. Precision livestock farming technologies can enhance animal welfare monitoring, but increased automation risks detaching farmers from direct animal care (Buller et al., 2020; Tuyttens et al., 2022), and technologies like drones may also cause stress to animals (Alanezi et al., 2022). Ethical concerns persist around factory farming practices and environmental impacts (Neethirajan & Kemp, 2021). Meanwhile the prioritization of economic efficiency could undermine broader sustainability goals (MacPherson et al., 2022). While these tools can drive sustainability, their deployment must prioritize ethical standards and resource efficiency.

Moreover, digitalization is reshaping farm business models, facilitating direct marketing and mitigating price effects and risks. However, it also alters farm operations, work content, and interactions among value chain stakeholders (Weber et al., 2022), requiring support for farmers as they navigate these complexities. While the adoption of digital technologies is inevitable, particularly as they become more affordable, akin to the widespread adoption of smartphones (Morrone et al., 2022), farmers adoption decisions are influenced by socio-demographic, institutional, and economic factors, which complicate the process (Vecchio et al., 2020).

The future of digital technologies in livestock farming requires a balanced approach that recognizes current capabilities while learning from past lessons. Stakeholders must integrate digital advancements with practical applications and ethical considerations to build a sustainable and competitive future (Eastwood et al., 2021).

3. MATERIAL AND METHODS

3.1. Data

This study utilized secondary data from two sources: the 7th General Census on Agriculture conducted by the National Institute of Statistics (Istituto Nazionale di Statistica-ISTAT) for the agricultural year 2019-2020, specifically covering the period from November 1st, 2019, to October 31st, 2020. The reference date for farm herd size in this dataset was December 1st, 2020. This census provided structural data on farms at national, regional, provincial, and municipal levels. The ISTAT survey was structured into sections covering general farm information, land use, consistency of farms, farm management methods, related activities and company managers, labor, and additional information on product destination, revenues/subsidies, marketing, investment in innovations, and memberships in associations or organizations. This dataset contributed to most of the socio-demographic variables used for this study. The target population comprised Italian farms, with at least 20 Ares (2,000 m^2) of Utilized Agricultural Area (UAA).

The National Statistical Programme (IST-00173) survey (NSP) aimed to survey the number of cattle, buffaloes, pigs and sheep and goats owned on June 1st and December 1st of each calendar year. In the December 2020 edition, additional questions were introduced to survey the diffusion of technologies in livestock holdings. The livestock farms are selected by stratified random sampling; the stratification is by region and livestock classes, based on the total number of animals owned on the farm. Both datasets were collected via online questionnaire and telephone interviews.

The datasets initially included 246,161 observations from ISTAT and 7,587 from the NSP survey. After merging based on identification number and cleaning the datasets, the sample size was reduced to 4,133 livestock farms. The following exclusion criteria were further applied, that is, farms raising multiple types of livestock (due to the ambiguity of digital technology application), and those raising only horses, rabbits, ostriches, or poultry. The final sample size was 2,412 observations. The variables used in the analysis, summarized in Table 1, were categorized based on their relevance to technology adoption, as highlighted in the existing literature.

3.2. Methodology

The study draws on various explanatory variables established in the literature to explore the adoption of digital technologies in livestock farming. Tey & Brindal, (2012)

Table 1. Variables selected from the datasets.

Variable	Type	Description
SOCIO-DEMOGRAPHIC CHARACTERISTICS		
Age	Continuous	Individual age; Min. age: 21 & Max. age: 94
Gender	Categorical	1: Male; 2: Female
Education	Categorical	1: No educational qualification. 2: Primary school leaving certificate/ Certificate of final assessment. 3: Secondary or vocational school-leaving certificate (obtained no later than the year 1965) /Secondary education diploma. 4: Professional education/training qualification related to agriculture that does not permit enrolment in university. 5: Professional education/training qualification not related to agriculture that does not permit enrolment in university. 6: Upper secondary education related to agriculture that allows enrolment in university. 7: Upper secondary education not related to agriculture that allows enrolment in university. 8: Bachelors/master's or equivalent qualification in agriculture. 9: Bachelors/master's or equivalent qualification not in agriculture.
Area	Categorical	1: Central; 2: Northeast; 3; Northwest; 4: South.
FARM OPERATIONS & ENDOWNMENT		
Labor	Continuous	Total number of employees on the farm.
Livestock unit (UBA)	Continuous	Sum of each livestock unit.
Total agricultural area (SAT)	Continuous	Total area in hectares
Type of ownership (Legal form)	Categorical	1: Entrepreneur or sole proprietorship or family business. 2: Partnerships 3: Capital companies 4: Cooperative Societies 5: State Administration or Public Body. 6: Other private entities 7: Collective ownership 8: Consortia
Production system	Categorical	Organic=1, conventional=2
Type of livestock (Dairy cattle, meat cattle, Buffaloes, Sheep, Goat, Pig)	Categorical	1: large ruminants; 2: Small ruminants; 3: Monogastric
Number of livestock	Continuous	Total number of each livestock in the farm.
Membership of association	Binary	0: No association; 1: Yes association Association with producer organization Association with network of enterprises Association with other organization/companies
Public subsidies (%)	Continuous	The amount of subsidy received in percentage of the farms total gross revenues.
Marketing channels for animal products	Binary	0: No sales on this marketing channel. 1: Yes, sales in this marketing channel. Direct sales on the farm Off-farm direct sales Sales to other farms Sales to industrial companies in Free Market Sales to industrial companies with multi-annual agreements Sales to commercial enterprises in Free Market Sales to commercial enterprises with multi-annual agreements Sales or contribution to association bodies
Other Remunerative activities	Binary	0: No other activities, 1: Yes, Other activities
BEHAVIOURAL ATTRIBUTE		
Agricultural training (Learning orientation)	Binary	0: Never attended agricultural training. 1: Attended agricultural training.

(Continued)

Table 1. (Continued).

Variable	Type	Description
REGIONAL INFRASTRUCTURES		
Fixed broadband connectivity	Binary	1: Yes, the farm uses at least one fixed broadband internet connection, 0: No
DIGITALIZATION		
.	Binary	0: No, I do not use this technology. 1: Yes, I use this technology. Decision support software Data Cloud computing Digital devices for animal monitoring Social network/website Precision animal husbandry system/machinery

classify factors influencing adoption into six categories: socio-economic, agro-ecological, institutional, informational, perceptual, and technological. Based on these, a tailored set of variables were selected for this research.

The analysis categorized livestock into large ruminants, small ruminants and monogastric animals because they have distinct management requirements, economic values and level of environmental impacts that shape the development of digital technology. Variations in the availability and adoption of digital technologies across different livestock categories have been documented in the literature (Thomann et al., 2023). Research on digital technologies has predominantly focused on dairy cattle reflecting their intensive management systems and economic importance (Marino et al., 2023). Similarly, buffalo farming follows specialized intensive management strategies, particularly in regions where it plays a significant economic role, such as Italy, due to the high demand for Mozzarella di Bufala Campana PDO (Trapanese et al., 2024). While digitalization efforts often focus on ruminants due to their large land use and contributions to greenhouse gas (GHG) emissions (Pulina et al., 2017), this study considers adoption across all livestock categories to assess variation.

In assessing the status of digitalization in farms, the study considered the data utilization (meteorological, satellite, and drone-collected data), websites and social networks, cloud computing, Decision Support Systems (DSS), digital devices for individual animal monitoring, and precision husbandry systems or machinery. The percentage frequency of digital technology adoption was then calculated for each livestock category.

To ensure robustness and comparability across livestock categories in analyzing the determinants of technology adoption, the study further identified specific tools within digital devices for animal monitoring and precision animal husbandry systems/machinery. These technologies were analyzed as individual tools, rather than being grouped under broader categories. Only technologies applicable to all livestock types were retained in the analysis. Species-specific technologies, such as milking robots and milking parlors equipped with online milk quality measurement systems (which are exclusively used in dairy farming), were excluded to maintain consistency and enable cross-category comparisons. Similarly, social networks and websites were not considered core digital tools, as they do not serve a direct farm management function. Technologies were classified into three categories: highly adopted (adopted by at least 15% of sampled farms), somewhat adopted (adopted by less than 15% of sampled farms) and no digital technologies. Accordingly, livestock farms were grouped into farms using highly adopted digital technologies, farms using somewhat adopted digital technologies, and farms using no digital technology. This classification enabled a detailed assessment of digital technology adoption across farms by capturing variations in uptake. Including the 'somewhat adopted' category allowed us to distinguish farms with low but notable level of adoption, enabling a more focused analysis of the factors influencing digital technology adoption. This approach helped identify specific drivers or barriers associated with each category. This categorization formed the dependent variable in the econometric analysis, where the outcome variable Y_i was binary, taking a value of 1 if the farm adopted any form of digital technology (highly or somewhat adopted) and 0 if no digital technology was adopted.

3.2.1. Model specification

A binary choice framework was used to model the decision to adopt digital technologies. A logistic regression model was employed to estimate the probability of adoption based on a set of independent variables. This approach, estimated via the maximum likelihood estimation (MLE), is preferred over multinomial logistic regression, as the categorization of digital technology use is not based on a distinct choice between unordered categories, but rather a binary decision of adoption. The logistic regression model is specified as:

$$\log\left(\frac{(\Pr(Y_i=1))}{1-\Pr(Y_i=1)}\right) = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n \quad (1)$$

where: $\Pr(Y_i = 1)$ represents the probability that farm i adopts at least one digital technology within each category. $X_1, \ldots, X_n$ are the independent variables hypothesized to influence adoption. β_0 is the intercept, and β_n (for each n) are the estimated coefficients indicating the change in log-odds with a unit change in each variable. The independent variables include, total area of holding, state aid subsidy received, livestock unit (UBA), age, labour, total number of livestock, fixed broadband connectivity, area, type of livestock, type of ownership (legal form), production system, other remunerative activities, gender, education, agricultural training, membership of association, and marketing channels.

3.2.2. Marginal Effects

Marginal effects were calculated to provide an intuitive understanding of how each variable impacts the likelihood of adopting digital technologies. These effects translate the logistic regression coefficients into changes in the probability of adoption.

The marginal effect of each variable X_j on the probability of adoption $Pr(Y = 1|X)$ is given by:

$$\frac{\partial \Pr(Y=1|X)}{\partial X_j} = Pr(Y = 1|X) \,.\, (1 - Pr(Y = 1|X)) \,.\, \beta_j \quad (2)$$

where:
$\frac{\partial \Pr(Y=1|X)}{\partial X_j}$ is the marginal effect of variable X_j on adopting probability.
$Pr(Y = 1|X)$ is the predictive probability of adoption.
$1 - Pr(Y = 1|X)$ is the probability of non-adoption.
β_j is the estimated coefficient of X_j.

Marginal effects were computed for both highly adopted and somewhat adopted technologies to observe differential impacts across varying levels of adoption.

4. RESULTS AND DISCUSSIONS

4.1. Descriptive results

Table 2 presents the descriptive analysis of the sampled livestock farms. The average age varied across livestock types, ranging from an average of 47 years for buffalo farmers to an average of 56 years for pig farmers, with an overall average age of 53 years. This reflects the typical demographic trend of middle-aged individuals managing farms. Gender distribution shows a predominance of male farm managers (85%), consistent with traditional gender roles in agriculture.

Labor input, measured as the number of permanent employees, also varied across livestock categories, with buffalo farms requiring the highest average labor (4.6 employees), while other types, such as meat cattle and sheep farms, operated with fewer workers. The scale of operations, measured in livestock units, showed significant variation, with buffalo farms having the largest average livestock units per farm (321.8), indicating a high scale of operations that requires more labor force. There are also variations in the total area of holdings (SAT).

Public subsidies, an essential component of agricultural support, varied across livestock types. These variations could be attributed to policy priorities or the socio-economic focus of subsidies. Ownership structures leaned heavily towards sole proprietorship and family-owned businesses, which likely offer flexibility in decision-making processes that are less bureaucratic than other ownership forms. In terms of education, 41.3% of farmers had secondary education diplomas, and only 17% had formal higher education in agriculture. However, 64.9% of farmers participated in agricultural training programs, indicating a reliance on non-formal education to compensate for the lower levels of formal education.

Conventional farming remained the most predominant type of production system (95.2%), while organic farming remained relatively limited (5%). The limited adoption of organic methods may be due to the challenges of organic livestock production, as farmers rely on organic crops and avoid conventional feed additives, hormones, and medicines, making organic farming both costly and complex. Engagement in other remunerative activities varied by livestock type, with goat farmers (34.52%) participating more frequently in these activities compared to other livestock types. A suggestion that income diversification may be a crucial strategy for economic resilience. Marketing channels for final products were influenced by farm scale and final products (processed vs. non-processed), and 45.4% of respondents were affiliated with companies or organizations, with 28.2% participating in producer associations, reflecting a differentiated approach to market engagement.

4.2. Extent of digital technology adoption

Table 3 illustrates significant variation in digital technology adoption across livestock types, revealing distinct trends within the Italian livestock sector. Deci-

Table 2. Descriptive statistics of socio-economic characteristics across various livestock types.

	Dairy Cattle (n=1091)	Meat Cattle (n=435)	Buffalo (n=49)	Goat (n=84)	Sheep (n=329)	Pig (n=424)	Total (n=2412)
Age (mean & SD)	54 (13.4)	53 (14.2)	47 (13.2)	49.6 (15.5)	48.6 (14.4)	55.7 (14.0)	53.0 (14.0)
Gender							
Male	987	355	43	62	266	350	2063
Female	104	80	6	22	63	74	349
Labour (mean & SD)	3.2 (3.7)	1.6 (2.4)	4.6 (3.7)	1.6 (2.1)	1.9 (5.6)	2.5 (5.5)	2.6 (4.2)
Type of ownership (legal form)							
Entrepreneur or sole proprietorship or family business	525	356	30	70	259	273	1513
Partnerships	543	69	12	11	63	132	830
Capital companies	17	7	7	2	4	16	53
Cooperative Societies	6	3	-	1	3	3	16
State Administration or Public Body	-	-	-	-	-	-	-
Other private entities	-	-	-	-	-	-	-
Collective ownership	-	-	-	-	-	-	-
Consortia	-	-	-	-	-	-	-
Education							
No educational qualification	4	5	-	-	5	4	18
Primary school leaving certificate/ Certificate of final assessment	90	67	-	9	35	65	266
Secondary education diploma	458	183	16	39	145	155	996
Professional education/training qualification related to agriculture	77	14	-	1	9	14	115
Professional education/training qualification not related to agriculture	57	18	2	3	10	26	116
Upper secondary education related to agriculture	156	44	6	13	31	45	295
Upper secondary education not related to agriculture	167	63	19	11	73	79	412
Bachelor's/master's or equivalent qualification in agriculture	41	12	1	1	9	15	79
Bachelor's/master's or equivalent qualification not in agriculture	41	29	5	7	12	21	115
Livestock unit (UBA) (mean & SD)	196.0 (231.9)	81.4 (247.6)	321.8 (250.9)	20.1 (30.8)	44.6 (50.5)	248.9 (697.2)	160.4 (358.3)
Production system							
Organic	33	45	4	4	19	10	115
Conventional	1058	390	45	80	310	414	2297
Total No of livestock (mean & SD)	128.5 (155.2)	66.0 (295.7)	342.6 (262.0)	115.1 (194.3)	398.8 (480.2)	868.9 (2236.2)	288.2 (1010.2)
Total area of holding (SAT) ha. (mean & SD)	68.9 (80.1)	84.9 (169.8)	45.3 (50.6)	35.3 (52.4)	81.6 (160.2)	50.4 (229.8)	68.7 (145.5)
Membership of association							
Producer association	398	99	16	19	54	93	679
Network of enterprises	45	11	5	3	12	15	91
Association with companies/organization	579	160	22	23	130	181	1095
Public subsidies (%)	13.2 (17.3)	225.1 (24.5)	8.0 (12.0)	18.0 (26.9)	30.2 (28.8)	13.3 (20.4)	17.7 (22.4)
Marketing channels							
Direct sales on the farm	135	776	10	18	60	112	411
Off-farm direct sales	59	32	4	4	31	43	173
Sales to other farms	65	78	1	10	19	32	205

(Continued)

Table 1. (Continued).

	Dairy Cattle (n=1091)	Meat Cattle (n=435)	Buffalo (n=49)	Goat (n=84)	Sheep (n=329)	Pig (n=424)	Total (n=2412)
Sales to industrial companies in Free Market	220	39	14	11	69	59	412
Sales to industrial companies with multi-annual agreements	75	11	1	2	9	9	107
Sales to commercial enterprises in Free Market	328	179	12	14	91	91	715
Sales to commercial enterprises with multi-annual agreements	33	7	3	1	0	3	47
Sales or contribution to association bodies	398	31	6	8	48	17	508
Remunerative activities	215	62	8	29	44	132	490
Agricultural Trainings (Learning orientation)	827	231	36	40	173	258	1565
Regional Infrastructures							
Fixed broadband connectivity (%)	64.5	37.5	63.3	45.2	28.9	51.2	51.7

Source: own elaboration.

sion Support Systems (DSS) are adopted by 28.32% of farms, indicating their role in optimizing farm management and decision-making. Similarly, cloud computing services are utilized by 26.16% of farms, with the highest adoption rates observed among buffalo (48.98%) and dairy cattle farms (33.09%), emphasizing their role in managing complex, large-scale operations. In contrast, meat cattle, sheep, goat, and pig farms display relatively lower adoption rates. The limited uptake in these sectors may reflect a low perceived value of investment in digital technologies, as these farms may not require the same level of operational complexity as dairy or buffalo farms.

However, pig farms (24.06%) report a higher adoption of cloud services compared to meat cattle (17.47%), suggesting a moderate level of digitalization in this sector. Among small ruminants, goat farms (23.81%) exhibit a higher adoption rate of cloud services compared to sheep farms (14.59%).

In the sample, 29.98% of the farms use any type of digital devices, particularly sensors for individual animal monitoring that is widely adopted among dairy (37.21%) and buffalo farms (28.57%), where real-time tracking of animal production and health is essential in high-output dairy operations. In contrast, meat cattle (20.69%), sheep (19.15%), and goat farms (17.86%) show moderate adoption, while pig farms report the lowest uptake (9.91%). Detectors for individual animal production are primarily employed in buffalo (16.33%) and dairy cattle farms (15.12%), whereas behavior image analyzers show minimal adoption across all species (3.69%).

Precision animal husbandry systems remain underutilized, with an overall adoption rate of 1.78%. Their adoption is virtually nonexistent among small ruminants, with no recorded uptake in goat and sheep farms. Among large ruminants, dairy cattle (2.84%) and buffalo farms (2.04%) report some adoption, while meat cattle and pig farms have minimal use (1.38% and 1.18%, respectively). According to Bucci et al., (2019), Italy continues to lag behind other EU countries in the adoption of Precision Agriculture Technologies (PATS). Additional precision systems, such as information management tools (0.95%), machines with online food quality analysis (0.12%), remote animal identification (0.54%), and robotic systems for ration management and stable cleaning (0.21%), remain rare across all livestock categories. The limited use of Precision Livestock Farming (PLF) technologies in small ruminants and pig farms suggests significant untapped potential for digital transformation in these sectors. Studies by Abeni et al., (2019) and Vaintrub et al., (2021) indicate that advanced management tools are predominantly adopted in dairy-intensive regions, where they enhance operational efficiency and reduce labor costs, although this trend remains less prevalent in the Italian livestock sector.

The adoption of meteorological and satellite data follows a similar pattern, with dairy cattle farms (26.58%) being the primary users, followed by meat cattle (18.39%) and buffalo farms (14.29%). Small ruminant and pig farms demonstrate relatively low adoption rates, indicating a reduced reliance on environmental data for operational decision-making. Large, commercially oriented farms tend to perceive greater value in meteorological data, whereas smaller-scale and traditional operations may not prioritize these digital tools.

Social networks and websites, which are frequently used for marketing and supply chain engagement, show the highest adoption rates among goat (27.38%) and buffalo farms (26.53%). In contrast, dairy cattle (12.37%), meat cattle (7.36%), sheep (8.51%), and pig farms (19.34%) exhibit lower engagement on these platforms, which may reflect sector-specific market structures and differences in digital literacy.

In summary, the results reveal clear disparities in digital technology adoption across livestock sectors. Dairy cattle and buffalo farms lead in the adoption of DSS (43.26% and 44.90%, respectively) and cloud computing (33.09% and 48.98%, respectively), indicating higher levels of digital transformation in these intensive production systems. Conversely, meat cattle, small ruminants, and pig farms demonstrate limited digital engagement, highlighting areas of untapped potential and the need for targeted strategies to promote digital technology adoption.

4.3. Determinants of digital technology adoption in livestock production

The logistic regression model was used to examine factors influencing the likelihood of adopting digital innovations among livestock farms. It explicitly distinguishes between farms with highly adopted and somewhat adopted digital innovations. The output of the marginal effects analysis is summarized in Table 4.

Fixed broadband connectivity significantly impacts both highly and somewhat adopted digital innovations. Sozzi et al. (2021) agree that poor internet coverage impacts adopting digital agriculture (DA) tools, particularly in Italy's marginal and hilly agricultural areas. Thus, targeted investments in rural internet infrastructure are critical to advancing agricultural modernization. The variable *Area* captures regional effects on digital innovation adoption, and it is significant only for highly adopted digital innovations. Compared to the Central region, the *Northeast* region and *Northwest* region have a 9% and 8% likelihood of adoption of digital technology, respectively. This regional disparity mirrors findings by Altamore et al., (2024), who suggest that policy support and socio-economic differences shape diverse regional practices. Just as structural characteristics such as governance and historical influences drive varying agricultural practices across northern and southern Italy, similar regional factors may influence digital innovation adoption in our context. This suggests that adoption patterns may be shaped by

Table 3. Adoption of digital tools across different livestock types in percentages.

Digital tools	Dairy Cattle (n=1091)	Meat Cattle (n=435)	Buffalo (n=49)	Goat (n=84)	Sheep (n=329)	Pig (n=424)	Total (n=2412)
Decision support system	43.26	16.55	44.90	11.90	9.12	18.16	28.32
Use of Data	26.58	18.39	14.29	11.90	12.46	13.44	20.11
Cloud services	33.09	17.47	48.98	23.81	14.59	24.06	26.16
Social network/website	12.37	7.36	26.53	27.38	8.51	19.34	12.98
Digital devices	41.61	23.45	40.82	17.86	23.40	12.97	29.98
Specific digital devices common to various livestock types							
Sensors on the limbs neck or ear tags	37.21	20.69	28.57	17.86	19.15	9.91	26.12
Detectors of individual production	15.12	1.84	16.33	2.38	0.61	1.89	8.00
Behavior image analyzers	7.15	0.92	4.08	0.00	0.91	0.47	3.69
Others	1.01	2.76	6.12	0.00	8.21	0.71	2.32
Precision animal husbandry system	2.84	1.38	2.04	0.00	0.00	1.18	1.78
Specific precision animal husbandry system/machinery common to various Livestock types							
Information system for livestock management	1.92	0.46	0.00	0.00	0.00	0.00	0.95
Machines equipped with online analysis of food quality	0.18	0.23	0.00	0.00	0.00	0.00	0.12
Milking robots	0.37	0.00	2.04	0.00	0.00	0.00	0.21
Milking parlor equipped with online milk quality measurement system	0.73	0.00	2.04	0.00	0.00	0.00	0.37
Remote animal identification management systems	0.92	0.23	2.04	0.00	0.00	0.24	0.54
Sensors for detecting the productive and reproductive activity of the live-stock	1.83	0.46	0.00	0.00	0.00	0.24	0.95
Robotic systems for ration management and stable cleaning	0.09	0.23	0.00	0.00	0.00	0.71	0.21
Others	0.18	0.00	0.00	0.00	0.00	0.71	0.21

Source. Authors own elaboration.

present-day policies and longstanding regional characteristics that impact economic and social development. Similarly, for the highly adopted digital innovations, the *Type of livestock* variable shows that farmers managing *monogastric animals* are less likely (by approximately 14%) to adopt digital technologies. Additionally, managing *small ruminants* is associated with a reduced likelihood (by 8%) of digital technologies adoption compared to the *large ruminant animals*. The implication is that the digital technologies available may be more applicable to certain livestock systems than others and reflect specific technological needs or economic considerations in different livestock types. The *type of ownership (legal form)* positively influences high and somewhat adopted digital innovations, with a probability of 10% and 5% respectively, particularly within family-owned enterprises, where streamlined decision-making processes support the adoption of new technologies. Meanwhile, for somewhat adopted digital innovations, *Other Remunerative Activities* significantly increase the likelihood of adoption by 14%, suggesting that farmers with additional income streams may be more inclined to explore these digital solutions, as diversified income streams provide additional financial flexibility. However, these activities have no significant effect on highly adopted innovations, indicating that diversified income streams do not necessarily impact the adoption of broader farm management systems like DSS or cloud services. This provides evidence that although technology adoption is widespread, it is often limited to basic aspects of livestock management, with more sophisticated systems concentrated in specialized sectors. *Education* is a significant predictor for high and somewhat adopted digital innovations, with each additional year of schooling increasing the likelihood of adopting digital innovations by 1% in each case. Educated farmers are expected to be more receptive to technological advancements, given potential improvements in understanding and implementing new digital tools. *Agricultural training* positively impacts highly adopted digital innovations (5% increase), highlighting the role that Agricultural Knowledge and Innovation Systems (AKIS) play in facilitating digital transformation. In Italy, the coordination of knowledge exchange and training initiatives falls under the jurisdiction of the regional authorities (Birke et al., 2022). This decentralized approach allows AKIS to tailor training and knowledge-sharing programs for different regions' specific needs and contexts. Such regionalized systems align with the Common Agricultural Policy's cross cutting objective of modernizing agriculture by fostering knowledge sharing, innovation and digitalization through specialized training programs (An, 2024). *State aid subsidies received* show a negative impact on somewhat adopted digital innovations. Altamore et al., (2024) argues that Italian farms primarily use subsidies to supplement income. For instance, in southern regions of Italy where subsidies makeup a substantial portion of farm revenue, farms may prioritize essential operational costs over technology investment. While some EU aid targets agricultural innovation, the lack of subsidies specifically for digital technology suggests that generalized aid does not effectively drive digital adoption, underscoring a need for targeted incentives. Being part of a *Producer association* is positively associated with highly adopted digital innovations, increasing the likelihood of adoption by 6%. This supports the notion that community networks facilitate knowledge exchange and collective learning, making innovation adoption easy. A structured network encourages technology use more than independent farms by fostering a focus on product quality and accountability (Chen et al., 2021). The amount of *Livestock unit (UBA)* has a strong positive effect on highly adopted digital innovations, particularly for large farms where technologies such as DSS and cloud services offer benefits for streamlining operations and managing complex farm activities. This effect aligns with findings in literature, where herd size is often linked to greater investment in management tools that support efficiency at scale (Abeni et al., 2019). *Age* has an inverse relationship with highly and somewhat adopted digital innovations. Younger farmers are generally more likely to adopt digital innovations, possibly because they tend to have higher digital literacy and a longer-term outlook, giving them more time to benefit from these technologies. This trend is consistent with findings in the technology adoption literature (Barnes et al., 2019; Michels et al., 2020). *Labor* shows a positive impact on somewhat adopted digital innovations, with each additional worker associated with a 2% increase in the likelihood of adopting these technologies like precision animal husbandry systems and digital devices (e.g., behavior analyzers and production detectors, etc.), which require continuous monitoring and data interpretation. Conversely, highly adopted digital technologies like DSS and cloud services, designed to automate tasks and reduce labor dependency post-implementation, may appeal more to farms with fewer employees. Marketing channels play a critical role in shaping digital technology adoption. Direct on-farm sales have been found to positively influence somewhat adopted digital innovations, while sales through association bodies are more strongly linked to highly adopted innovations. However, the structure of the supply chain affects the

Table 4. Determinants of digital innovation adoption in the livestock sector: Marginal effects analysis.

Variables	Marginal effects (Highly adopted digital innovations)	Marginal effects (Some-what adopted digital innovations)
Fixed broadband connectivity	0.16*** (0.02)	0.14*** (0.02)
Area		
Northeast	0.09** (0.04)	0.02 (0.03)
Northwest	0.08* (0.04)	-0.01(0.03)
South	-0.01(0.04)	-0.04 (0.03)
Type of livestock		
Monogastric	-0.14*** (0.03)	-0.01 (0.02)
Small ruminants	-0.08** (0.04)	0.03 (0.03)
Type of ownership (Legal form)	0.10*** (0.02)	0.05*** (0.02)
Total area of holding (ha)	-0.00 (0.00)	-0.00 (0.00)
Production system		
Conventional	-0.05 (0.05)	-0.06(0.04)
Other Remunerative activities	0.01 (0.03)	0.14*** (0.02)
Gender		
Female	0.03 (0.03)	-0.00 (0.02)
Education	0.01** (0.01)	0.01*** (0.00)
Agricultural training	0.05* (0.02)	0.03 (0.02)
State aid Subsidy received	-0.00 (0.00)	-0.00* (0.00)
Membership of association		
Producer association	0.06** (0.03)	0.01(0.02)
Network of enterprises	0.09 (0.07)	0.02(0.04)
Association with companies/organization	-0.00 (0.02)	0.02(0.02)
Livestock unit (UBA)	0.00*** (0.00)	-0.00 (0.00)
Age	-0.00*** (0.00)	-0.00** (0.00)
Labor	0.00 (0.00)	0.02*** (0.00)
Total No. of livestock	-2.69e-06 (0.00)	-9.57e-06 (0.00)
Marketing Channels		
Direct sales on the farm	-0.02 (0.03)	0.04* (0.02)
Off-farm direct sales	0.00 (0.04)	0.01(0.03)
Sales to other farms	-0.02 (0.04)	0.00 (0.03)
Sales to industrial companies in Free Market	0.05 (0.03)	-0.03 (0.02)
Sales to industrial companies with multi-annual agreements	0.04 (0.06)	0.03(0.04)
Sales to commercial enterprises in Free Market	0.03 (0.03)	-0.01(0.02)
Sales to commercial enterprises with multi-annual agreements	-0.07 (0.08)	0.06 (0.05)
Sale or contribution to association bodies	0.09***(0.03)	0.02 (0.02)

Source: own elaboration. Standard error values are inside parentheses, *p<0.10, **p<0.05, ***p<0.01.

extent to which producers benefit from price fluctuations and market stability, which in turn influences their ability to invest in digital technologies. Empirical evidence suggests that farmers represent a weak link in the value chain, meaning that increases in retail market prices often do not translate into significant financial benefits for producers (Goodwin et al., 2024). This price asymmetry may limit farmers' financial capacity to adopt digital tools, particularly when market uncertainty discourages long-term investments.

5. CONCLUSION

This study highlights the variations in the adoption of digital technologies in livestock farming across Italy, with dairy and buffalo farms leading in digital engagement, while meat cattle, sheep, goat, and pig farms are lagging. This disparity in digital adoption is shaped by differences in operational scale and economic structure, which collectively impact animal welfare across species. Key socio-economic determinants, such as broadband connectivity, farm ownership structure, education, and age, significantly influence digital technology. Younger farmers and those with higher education levels are generally more inclined toward technology adoption, suggesting that digital literacy and training could potentially bridge adoption gaps for other farm demographics. Additionally, fostering a bottom-up, participatory co-design approach in the development of digital tools can play a crucial role in aligning technology with farmers' specific needs and contexts. Engaging farmers actively in the co-design process allows for the tailoring of digital tools to address practical challenges, usability concerns, and operational requirements from the perspective of end-users. This approach not only enhances relevance but also promotes a sense of ownership and empowerment among farmers. By incorporating feedback from farmers into the design of digital tools, technology providers and developers can ensure that these innovations are accessible, adaptable, and directly responsive to the needs of those who will implement them in the field.

Highly adopted digital innovations are influenced by the location, livestock type, participation in agricultural training, livestock unit size, membership in producer associations, and engagement in sale or contributions to association bodies. In contrast, somewhat adopted innovations are driven by engagement in other income-generating activities, state aid subsidies received, labor availability, and involvement in direct sales marketing. Improving broadband infrastructure remains crucial to fostering widespread digital adoption, and targeting younger, digitally literate farmers is key. Integrating digital literacy into agricultural training programs can further ensure broad and effective engagement. The gap between traditional agricultural education and the skills needed for digital farming highlights the need for modernized curricula to align with evolving demands of the industry.

The Common Agricultural Policy (CAP) presents an opportunity to promote digital transformation by providing targeted funding for rural broadband infrastructure and digital literacy training. Future CAP reforms could focus on promoting digital technologies that enhance sustainability and efficiency, with a particular focus on small and mid-sized farms. Addressing disparities in access is essential to ensure that the benefits of digital agriculture extend to farms of all sizes and types.

These economic constraints with regards to the market structure reinforce the need for targeted policies that support both digital innovation and income stabilization measures. Ensuring that farmers have more predictable market conditions and access to stable contracts may enhance their ability to invest in digital technologies, fostering greater digital transformation in the livestock sector.

Looking ahead, further research should explore the long-term effects of digital technologies on farm productivity, economic outcomes, and sustainability. Additionally, it is important to examine the specific barriers faced by small and medium-sized farms in adopting digital tools and assess how policies such as the CAP can promote digital inclusion across the sector. Understanding the adaptation of digital solutions to different farm sizes and livestock species is essential for advancing precision livestock farming and ensuring technological advancements benefit the entire sector, not just a select few.

Broader implications for the livestock sector were also noted, particularly in underrepresented areas such as PLF for small ruminants and pigs. Reducing barriers to adoption in these areas is critical for fully realizing the potential of digital technologies across all livestock types. Collaborative efforts among technology providers, agricultural organizations, and policymakers are essential to fostering a sustainable and equitable transformation in livestock farming, benefiting a diverse range of farm types and sizes.

In summary, this study provides valuable insights into the current state of digital adoption in Italian livestock farming, yet limitations such as unaccounted regional differences that may affect the generalizability of the findings and the dataset, which was collected up until 2021, needs to be updated to reflect more recent developments, suggest avenues for ongoing research. Bridging the digital divide in livestock farming will require targeted, well-informed strategies to achieve a comprehensive digital transformation across the sector, equipping farmers with the tools needed to thrive in an increasingly digital agricultural landscape.

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Assessing the social impacts of Digital Agriculture Technology Solutions: a practical tool

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Abstract. Digital Agriculture Technology Solutions (DATSs) can improve the sustainability of the agricultural sector. While most of the research on the impacts of DATSs is focused on the economic and environmental dimensions of sustainability, this work aims to understand the social benefits that DATSs have on farmers. Integrating top-down and bottom-up approaches, a Social Sustainability Assessment Framework for DATSs adoption was developed and subsequently applied in the form of a Social Self-Evaluation Tool, a questionnaire tested on 60 farmers across 20 European countries, with a heterogeneous composition in terms of sector, types of DATSs, agronomical context, and socio-economic background. The Framework and the Social Self-Evaluation Tool allowed for a deep investigation of the social impacts of DATSs in terms of labour evolution, education and learning, and generational change. The results demonstrated the positive effects of DATSs on the social sphere of sustainability, as well as the importance of integrating this type of social analysis in the evaluation of digital technologies in agriculture.

Keywords: social sustainability, social framework, agriculture 4.0, digital agriculture.

1. INTRODUCTION

Agriculture faces significant economic, environmental, and social challenges and a range of megatrends – including climate change, environmental degradation, geopolitical instability, demographic dynamics, changing supply chains and evolving consumer demand – are increasingly putting pressure on the sector at both local and global levels. According to FAO (2025), between 638 and 720 million people may have faced hunger in 2024 (7.8-8.8% of the global population), with projections indicating that 512 million people will be chronically undernourished by 2030. The global population is expected to reach 9.7 billion by 2050, demanding increased agricultural productivity while preserving natural resources, ecosystems, and biodiversity (UN, 2022). Climate change is adversely affecting agriculture, leading to significant economic and productivity losses, complicating efforts to meet human needs (IPCC, 2022). In this scenario, digital technologies can play a pivotal role in increasing the sustainability, productivity, and resilience of agriculture (European Commission, 2023a). It has already been extensively highlighted how technologies like Internet of Things (IoT), Data Analytics and Cloud Computing, Artificial Intelligence (AI) and Machine Learning (ML), Satellites, Geographic Information Systems (GIS), Drones and Robots, could enable a wide range of Digital Agriculture Technology Solutions (DATSs) with the potential to transform agriculture, increasing productivity while reducing impacts on natural resources and alleviating the labour-intensive work of farmers (Papadopoulos et al., 2024; Maffezzoli et al., 2022; Balafoutis et al., 2020).

While a lot of work has been done to assess and prove the environmental and economic sustainability of DATSs, there is a lack of studies in the literature focusing on the social impacts of digital innovation in agriculture. The research presented in this paper stems from the need to deeply investigate the social impacts of DATSs adoption on farmers. Therefore, this paper aims to present the development, application, and testing of a framework to analyse the benefits and impacts of DATSs on farmers from a social perspective.

This paper is structured as follows. Section 2 will briefly introduce the concept of social sustainability and describe its relationship with DATSs, setting out the background and the objectives of the present work. Section 3 will explain the research methodology that led to the Framework presented in Section 4. A discussion on results is presented in Section 5. Lastly, Section 6 will offer a general assessment of the findings, along with the limitations of the current study and potential future developments.

2. THEORETICAL BACKGROUND AND OBJECTIVES

2.1. Social Sustainability and DATSs

Despite its frequent use in academic literature and public discourse, the concept of "social sustainability" lacks a universally accepted definition (McGuinn et al., 2020), as most attention is often focused on economic and environmental sustainability (Janker & Mann, 2020). The 2030 Agenda for Sustainable Development frames social sustainability as a multidimensional objective encompassing social equality, poverty eradication, and decent living standards for all (UN, 2015). According to the World Bank, "*Social sustainability increases when more people feel part of the development process and believe that they and their descendants will benefit from it*", but the concept remains elusive due to complex socio-cultural factors that are difficult to analyse empirically (Barron et al., 2023). The social sustainability of agriculture is increasingly gaining relevance in scientific discussions as well as within institutional and agribusiness sectors, despite the research focus on farming sustainability having been predominantly centred on environmental aspects so far (European Commission, 2023; Nowak et al., 2019; McGrath et al., 2023). In agriculture, social sustainability mainly refers to the possibility of maintaining or improving farmers' lives and working conditions (Trivino-Tarradas et al., 2019), encompassing various aspects such as fair income, social inclusion, decent living standards, and physical and emotional well-being (Zanin et al., 2020). Jenker et al. (2019), applying Maslow's hierarchy of needs, define social sustainability in agriculture as improving farmers' satisfaction with their physiological, security, social, esteem, and self-actualisation needs. Latruffe et al. (2016) distinguish social sustainability at two levels: the farm community level, focusing on farmers' well-being, working conditions, education, and quality of life; and the society level, involving rural development, employment, ecosystem services, quality products, intergenerational continuity, and acceptable agricultural practices.

Since the 1990s, concepts such as Precision Farming, Digital Agriculture, Smart Agriculture, and, more recently, Agriculture 4.0 have emerged, with digitalisation increasingly recognised as a key driver in addressing global and local agricultural challenges, promoting sustainable, inclusive, and equitable agricultural development (Bertoglio et al., 2021; Schroeder et al., 2021; Hernandez et al., 2024). Agriculture 4.0, defined as the evolution of Precision Farming through automated data collection, integration, and analysis from various sources, aims to transform traditional farming systems into digitalised ones, enhancing benefits, reducing costs, and promoting environmental and social sustainability (Maffezzoli et al., 2022). The adoption of DATSs can also improve social sustainability at both the farm and society levels. However, understanding the interactions between technologies, people, and society, along with their associated risks and impacts, remains difficult yet essential (Gardezi et al., 2022). Policy and strategic EU documents and frameworks, such as the European Union's Farm to Fork Strategy, the Green Deal, the CAP, the EU Food2030 and the EU Vision for Agriculture and Food, all recognize digitalisation and digital connectivity as crucial factors to promote social sustainability, improving quality of life and economic prosperity in rural areas (European Commission, 2023a, b, c; European Commission, 2025). However, digital innovation in agriculture has lagged due to several interrelated factors such as solutions complexity, limited scalability, and structural barriers such as education, technological proficiency, and connectivity (Dutta et al., 2019). Moreover, farmers often lack clear evidence of the tangible benefits these technologies provide, as well as their actual return on investment, making it difficult to justify their adoption, especially on smaller farms, while larger farms are more likely to adopt DATSs due to the economies of scale they can leverage (Castle et al., 2015). This highlights the need for a thorough investigation of the benefits of DATSs, particularly in the understudied social dimension. The social impacts, benefits, and risks resulting from digitalisation can be various, depending on the type of DATSs, the productive sector, the agronomic, cultural, and socio-economic context, and the way each specific technology solution is used and integrated within farm management. Among the most immediate and relevant benefits of implementing DATSs are the reduction of farmers' workloads and working hours, and the substantial increase in work productivity and flexibility (Khanna & Kaur, 2019; Sri Heera et al., 2019; Tsouros et al., 2019), as well as the reduction in heavy labour activities, injuries, and accident rates (Balafoutis et al., 2020). A reduction in workload and more flexible working hours could mean a better work-life balance for farmers, allowing for more time with family, friends, or leisure activities (McGrath et al., 2023). This, combined with the support that DATSs provide in decision-making, management, monitoring, and labour-intensive tasks, can result in lower work-related stress. However, the use of DATSs may also generate stress, particularly during the initial phase of technology adoption, due to the steep associated learning curve (Gaber et al., 2024), the need to change traditional farm management (Butler & Holloway, 2016; Driessen & Heutinck, 2015), and issues related to information processing and technology calibration or malfunctioning (Balafoutis et al., 2020).

Naturally, there are also areas of impact that extend beyond the personal realm of individual farmers and concern labour rights, women's empowerment, gender gaps, social interactions, rural communities, territorial development, youth engagement in farming, and many others (Rolandi et al., 2021; Ali et al., 2016). The technical knowledge, hard skills and training required to implement DATSs in farms could also impact the local and regional labour market, leading to a higher demand for qualified workers with ICT and digital skills, leading to possible digital skills gaps, especially in certain socio-economic contexts (Pogorelskaia and Várallyai, 2020). When farmers cannot acquire the appropriate technical knowledge and fail to update their skills, a digital divide can arise between those who can take advantage of the benefits of technology and those who cannot, a process further exacerbated by factors such as age, gender, language, or socio-economic background (Trendov et al., 2019). This digital divide can play not only locally but also globally, accentuating socio-economic differences (FAO, 2023) or enhancing power disparities among food systems actors (Gardezi et al., 2022). According to FAO (2023), DATSs have proven to be capable of reducing the gender gap in agriculture, strengthening women's livelihoods and empowerment, but only if women's access to education, financial services, decision-making power and technologies is ensured, all things for which women still lag behind men, particularly in low- and middle-income countries (Rodgers and Akram-Lodhi, 2019; Ali et al., 2016). DATSs can also radically change the role and social identity of the farmer, undermining his traditional agronomic techniques and knowledge, and shifting their work from the field to the office, to the extent that a future of farms without farmers can be envisaged (Gardezi et al., 2022). As already happened in the history of agriculture with the introduction of disruptive technologies (e.g. the tractor, the combine harvester, chemical pesticides, new genetically modified varieties), the adoption of DATSs seems to evoke the fear that technology might reduce human labour in both manual and intellectual tasks and lead to a decline of workers in the fields and farms (Rotz et al., 2019). On the contrary, DATSs can solve the problem of labour shortage in agriculture, particularly in agricultural systems where matching labour supply and demand is difficult, such as in Western and Southern Europe, the US, and Canada. These regions are heavily reliant on seasonal migrant workers, and exploitative and illegal labour practices are frequently reported in both media and academia (Caxaj et al., 2023). In this context, DATSs can be a valuable tool to reduce the reliance on exploited workers, increase supply chain transparency, improve working conditions, and ensure respect for workers' rights. DATSs could also create new job opportunities and drive the creation of new professional roles and actors involved in the digital transformation of food supply chains (Bampasidou et al., 2024).

The multiplicity of social aspects, risk factors, and critical issues related to the use of DATSs makes it necessary to thoroughly investigate how DATSs change, for better or worse, the lives of farmers, and requires that such assessments are integrated into every analysis on the benefits and costs of digitisation. The assessment of social sustainability in agriculture encompasses various levels of analysis and can be approached through multiple methodologies, often derived from social sciences and based on interviews and surveys for farmers (Packer & Zanasi, 2023). However, the multidimensional and qualitative nature of social sustainability makes its assessment in farming systems more challenging compared to the economic and environmental dimensions (Latruffe et al., 2016). Through this work, we aim to close this gap and explore the social impacts of DATSs on farmers, seeking to better understand the benefits, but also the risks, that digital technologies bring to the social sphere of sustainability.

2.2. Research objectives

The objective of this study is to provide a framework for assessing the social sustainability of DATSs: the Social Sustainability Assessment Framework. This Framework will serve as the basis for the development of a practical tool – the Social Self-Evaluation Tool – to enable a comprehensive assessment of the social implications of DATSs adoption by farmers. This objective arises from the recognition that commonly proposed frameworks and indicators in the literature, which often focus on the economic and environmental domains of sustainability, are insufficient to fully examine the social impacts of DATSs. Additionally, the study illustrates a first application of the Social Self-Evaluation Tool to a sample of farmers adopting DATSs in order to assess the practical relevance of the Framework. However, the utility and applicability of the developed Framework and Tool extend beyond the scope of this research, offering potential for broader use in future studies and practical applications. The approach and structure underlying the conception and development of the Social Sustainability Assessment Framework and the Social Self-Evaluation Tool will enable their adaptation to other agricultural contexts and facilitate their use in future practical applications, making them a valuable resource for assessing the social sustainability of digital innovation in various farming systems.

3. RESEARCH METHODOLOGY

The research is conducted within the Horizon Europe QuantiFarm project, which aims to support the development and adoption of DATSs across EU countries as a key element for improving the sustainability performance of the agricultural sector. The QuantiFarm project encompasses 30 Test Cases (TCs), each involving one or more farmers who have adopted DATSs on their commercial farms and other stakeholders, such as agronomists and technology providers. As shown in Figure 1, the research methodology that led to the development of the Social Sustainability Assessment Framework and the Social Self-Evaluation Tool integrated a top-down approach – through a literature review aimed at examining existing frameworks for the assessment of social aspects in agriculture, particularly those applicable to the impact of digital technologies – with a more bottom-up perspective. To this end, semi-structured

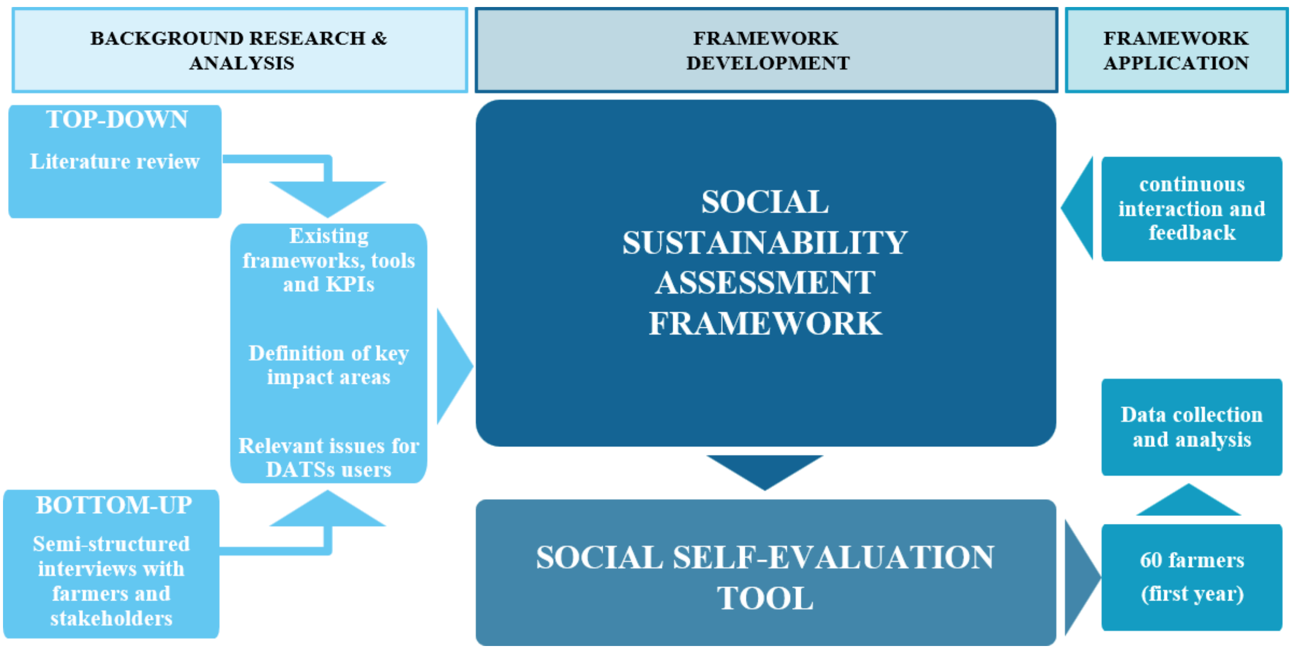

Figure 1. An overview of the methodology for the development of the Framework and the Tool.

interviews were conducted with the TCs to incorporate into the Framework the most relevant impact areas and social issues related to the implementation of digital solutions on farms. The feedback collected through ongoing interaction with farmers and other stakeholders served to refine, improve and validate the Framework for its application. This integrated approach led to the development of the Social Sustainability Assessment Framework, which was then translated into a questionnaire for farmers, the Social Self-Evaluation Tool. The first application of the Tool was conducted with the sample of farmers who adopted digital solutions within the TCs of the QuantiFarm project. The experience gained from this first application, combined with the feedback collected through ongoing interaction with the TCs, served to test the future applicability of the Framework and the Tool in other agricultural contexts.

3.1. Literature review

A literature review was conducted to explore the application of the social sustainability concept in agriculture, particularly in relation to the digital innovation process and the use of Agriculture 4.0 technologies. More specifically, the goal of the literature review was the identification of the main areas of impact of DATSs on social sustainability, thanks to the analysis of existing frameworks, tools and KPIs for assessing the social impacts in farming. The review provided a deeper understanding of how digital technologies interact with the social aspects of farmers' lives and daily work activities, including work-life balance, working conditions, skills development, farm management, workplace culture, and workforce development. Given the predominantly practical outcomes of the research – namely, the development of a framework that could be easily used with farmers – a pragmatic approach took precedence over a purely theoretical literature review. Therefore, a balance was sought between narrowing the research focus to the main areas of impact and maintaining the ability to account for all the nuances and types of influence that the technology could exert on farmers. Consequently, rather than a systematic review, our work more aligns with the concept of scoping/mapping review (Paré et al. 2015), or integrative review, defined by Torraco (2005) as: "*…a form of research that reviews, critiques, and synthesizes representative literature on a topic in an integrated way such that new frameworks and perspectives on the topic are generated.*" As underlined by Elsbach & Knippenberg (2020), an integrative review could consolidate evidence but also generate new insights to advance a specific field of study.

For the literature review, the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines were followed, as described in Figure 2 (Page et al., 2021). This approach allowed for a transparent and structured identification, selection, and evaluation of relevant studies, ensuring the reliability and validity of the review process. Thus, a four-step review methodology was followed, consisting of: 1) the definition of an appropriate search strategy, including keywords and databases, 2) the delineation of boundaries and inclusion and exclusion criteria, 3) a first screening and selection of papers, and 4) the full-text analysis of papers and extraction of relevant information.

Based on the authors' expertise and previous literature analysis, a set of keywords related to digital technologies in agriculture was selected. The keyword "Agriculture 4.0", which refers to a wide array of digital technologies and solutions used in agriculture (Maffezzoli et al. 2022), has been complemented by other keywords frequently used as synonymous terms in academia and industry: "Precision Farming", "Precision Agriculture", "Smart Farming", "Smart Agriculture" and "Digital Agriculture". This allowed for the inclusion of studies published before the widespread adoption of the Agriculture 4.0 concept, encompassing digital agricultural technologies not explicitly categorised under the Agriculture 4.0 paradigm by the authors. The selected keywords were combined with the keyword "Social": "Agriculture 4.0" AND "Social", "Precision Farming" AND "Social", "Precision Agriculture" AND "Social", "Smart Farming" AND "Social", "Smart Agriculture" AND "Social", "Digital Agriculture" AND "Social". These queries were considered sufficient to allow the retrieval of research articles relevant to our objective, enabling a thorough investigation of the main areas of social impact of DATSs.

The literature search was undertaken through Scopus, the largest abstract and citation database, selected for its international recognition, multidisciplinary coverage, and comprehensiveness. The database search was carried out using each query individually. To narrow the scope of the analysis and ensure that the papers retrieved from Scopus were relevant to the most recent digital technologies – falling under the umbrella of Agriculture 4.0 – the search was limited to publications from the last ten years, i.e., from 2013 onwards. Moreover, since a preliminary analysis of the papers found in Scopus using the first two queries, "Agriculture 4.0" AND "Social" and "Precision Farming" AND "Social", returned many articles without a clear focus on the social dimension, the search strategy for the subsequent queries was refined by applying a "Subject area" filter in Scopus, limiting results to those in the "Social Sciences" domain.

After the elimination of duplicated papers – that is, those retrieved in Scopus by more than one query – the screening process involved the analysis of the title, keywords and abstract of each paper. This led to the exclusion of the articles that did not have a clear and substantive focus on the social impacts of digital technologies on farmers. The number of papers identified for each query is shown in Figure 2, along with the total number of papers subjected to full-text analysis after excluding duplicates and those not aligned with the research objectives.

From a total of 857 publications found on Scopus, 15 were excluded because they were duplicates, while 687 were excluded because they addressed the topic of social impacts only superficially or failed to provide impact areas, indicators, or tools related to the social aspects of digital technologies in agriculture. A total of 155 papers were included in an in-depth analysis to extract relevant information, such as existing frameworks, tools and KPIs on social impacts of DATSs. Each paper was thoroughly reviewed, and those demonstrating a direct relationship with social impacts on farming were entered into an Excel database, where key information and insights were systematically recorded.

The analysis of the scientific literature was complemented by grey literature, specifically focusing on reports from government agencies, NGOs, international institutions (e.g. World Bank), UN Agencies (e.g. FAO, IFAD), and industry associations working on the social aspects of sustainability in farming. These sources were carefully reviewed and cross-referenced with the scientific literature. Including grey literature allowed us to capture a broader range of perspectives, enriching the evidence beyond what is available in peer-reviewed journals. This approach also made it possible to integrate context-specific insights and practical knowledge from

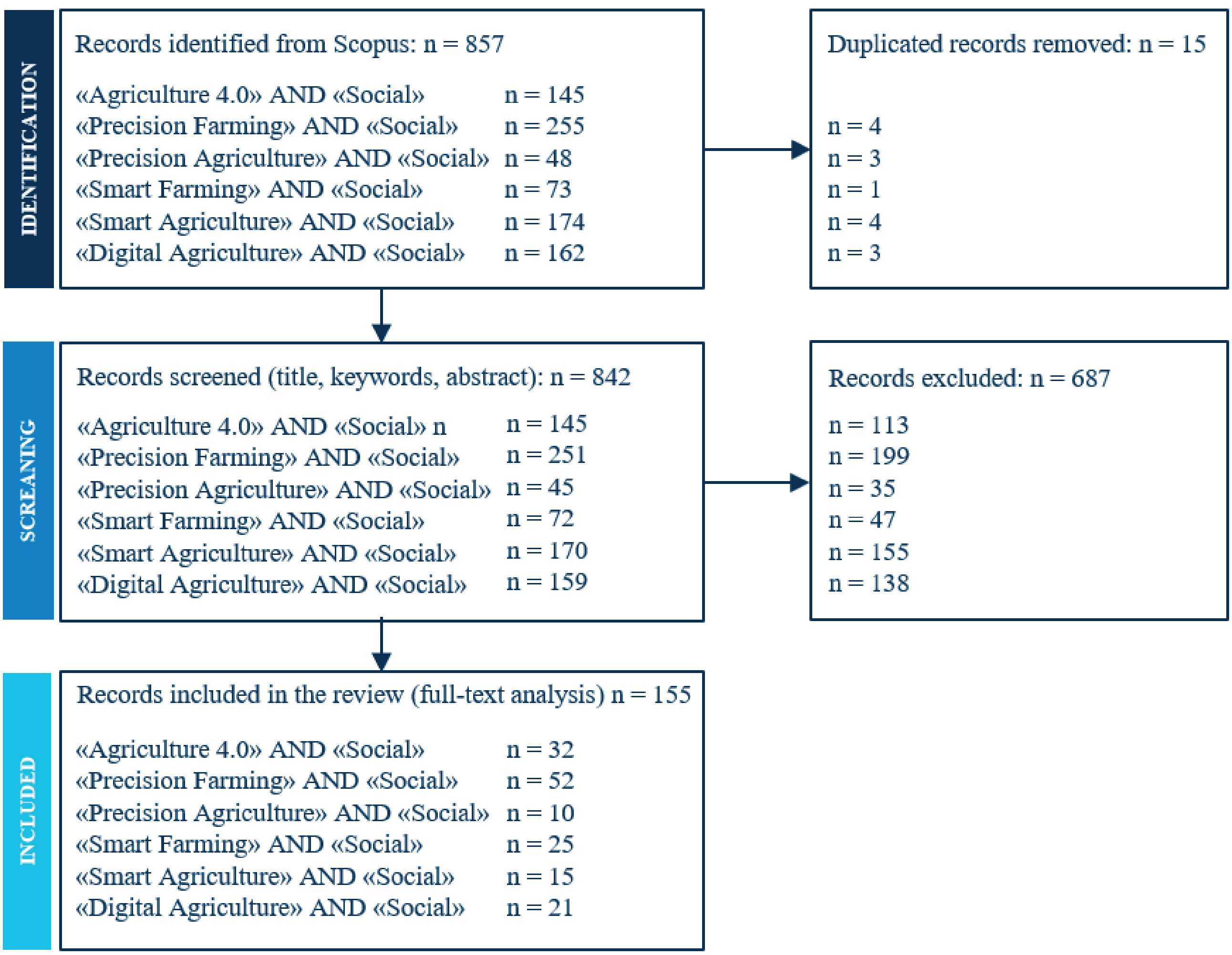

Figure 2. Flow diagram of literature review (adapted by the authors based on PRISMA 2020)

real-world applications, leading to a more holistic understanding of the social implications of DATSs adoption.

3.2. Integration of a bottom-up approach

Given the practical goal of the research, the top-down literature review was complemented with a bottom-up approach. The importance of combining top-down and bottom-up methods in social science and social sustainability assessment is increasingly recognised (Ochsner et al., 2017), not only to improve the comprehensiveness of analyses but also to ensure a more holistic understanding of complex societal dynamics and the inclusion in the assessment process of all the issues that truly matter on the ground (Magee et al., 2013). As highlighted in Yin's seminal work on Case Studies (Yin, 2017), the value of interviews lies in their ability to provide direct and context-specific insights into complex situations, allowing for the collection of detailed information about the experiences of the interviewees. Interviews not only offer an immediate understanding of social dynamics but also enrich the analysis and offer a deeper understanding of the phenomenon under study (Yin, 2017). Thus, 30 semi-structured interviews were organised with the Test Cases (1 interview for each TC), involving farmers using DATSs, but also agronomists and technology providers engaged in each TC. All the interviews were conducted remotely through the Microsoft Teams platform and lasted approximately one hour each. While the focus of the interviews was on farmers, agronomists and technology providers were also involved, as they served as contact points between the farmers and the project and played a crucial role in facilitating communication, as many of the farmers did not speak English, the language of the interviews. Moreover, agronomists and technology providers gave valuable insights into the social implications of DATSs, offering a complementary perspective to that of the farmers. A semi-structured set of open-ended questions was used to conduct the interview in order to balance consistency with the research objectives, but also to ensure enough flexibility for participants to elaborate on their experiences and perspectives. The question addressed: 1) the business and agronomical context of the farms involved in the TC; 2) the reasons behind the DATSs adoption; 3) the main impacts of DATs in terms of agronomic practices and farm management; 4) the barriers, problems and limitations to DATSs use; 5) the main benefits of DATs; 6) the impacts that DATSs had on the social dimension, including the implication the digitalisation process had on farmers lives and farm management. Each interview has been recorded and the audio transcribed to ensure accurate capturing of all information. The transcriptions of all the interviews were analysed using a "manual approach", due to the relatively small scale of the sample and the need to maintain a more flexible, nuanced understanding of the social impacts and issues mentioned by each stakeholder. As underlined by Mattimoe et al. (2021), a manual approach "*can facilitate a closeness to the qualitative data*" and "*facilitate the identification of themes in an organic manner*". Also, Maher et al. (2018) suggest that a manual approach "encourages more meaningful interaction with the data, compared to a technological approach". Recurring themes, issues and concepts regarding the social impacts of DATSs were extracted from the text and collected to be compared and integrated with the outputs of the literature analysis. By doing so, the bottom-up process enriched the top-down analysis (literature review), offering direct and concrete insights into the social implications of DATSs, specifically from the perspectives of farmers and relevant stakeholders involved in field activities. This approach not only ensured that real-world context was incorporated in the research but also helped identify the key aspects around which to structure the framework, focusing on the issues that most directly affect farmers in their daily work and lives.

3.3. Framework application to Test Cases

To test and apply the Framework and the Tool, we used the sample of 30 Test Cases involved in the QuantiFarm project, comprising commercial farms operating in 20 European countries, and 7 agricultural sectors, including 20 different crops and animals. Each TC includes one or more farmers who have recently adopted one or more categories of DATSs, providing a valuable sample for the application and testing of the Framework and Tool. In Table 1, the sector of each Test Case is reported, together with the type of crop or animal production, the category of DATSs implemented in the farm, the country, the total production managed through technology (expressed in terms of ha or total number of animals), and the number of farmers using DATSs. The categories of DATSs adopted across the 30 TCs are:

- Decision Support Systems (DSS)
- Farm Management Systems
- Variable Rate Technologies (VRT)
- Precision Irrigation Systems
- Digital Pest Control Systems
- Automated Greenhouses
- Feeding robots
- Milking robots
- Sensors for quality assessment (for the aquaculture sector)

– Automated monitoring, activity sensors, heat and calving detectors (for the meat and dairy sector)

The final sample consists of 60 farmers, as some TCs involved more than one farmer. While the sample size may seem limited, the heterogeneity in agronomic, socio-economic contexts, and technological settings represents a strength of this research, allowing for a more comprehensive investigation of the social impacts of DATSs across diverse backgrounds and environments. Moreover, this sample of farmers enabled the evaluation of the Framework's and Tool's applicability in various agronomic and socio-economic settings, thus paving the way for future applications in different contexts.

4. RESULTS

4.1. The Social Sustainability Assessment Framework and the Social Self-Evaluation Tool

Based on the findings from the literature analysis (section 3) and the semi-structured interviews with the Test Cases (section 3.2), the areas of the social dimension most impacted by the adoption of DATSs were identified. Despite the widespread use and established nature of some questionnaires and indicators for social impacts and working conditions assessment found in literature, such as those proposed by Eurofound (2016) or Horodnic et al. (2019), there is a notable scarcity of question-

Table 1. Overview of the Test Cases (TC) to which the framework was applied.

TC	Sector	Production	DATSs category	Country	DATSs management	n. of farmers using DATSs
1	Arable	Potatoes	DSS	Greece	0.85 ha	2
2	Arable	Corn	Precision Irrigation system, VRT	Portugal	29.2 ha	2
3	Arable	Barley, Wheat	DSS	Spain	30.6 ha	1
4	Arable	Cotton	VRT	Greece	5.1 ha	3
5	Arable	Wheat	DSS	Turkey	105 ha	8
6	Arable	Wheat, Onion, Potatoes	DSS	Netherlands	3.5 ha	1
7	Arable	Potatoes	DSS	Poland	98 ha	2
8	Arable	Wheat, Rapeseed, Rye, Barley	DSS	Latvia	1 silo	1
9	Arable	Corn, Wheat	DSS	Slovenia	17 ha	1
10	Arable	Wheat	DSS	Romania	553 ha	1
11	Horticulture	Olives	DSS	Greece	8.6 ha	5
12	Horticulture	Apples	DSS; Digital pest control System	Poland	1 ha	1
13	Horticulture	Grapevine	DSS	Italy	1.1 ha	1
14	Horticulture – Indoor farming	Strawberries and Blueberries	DSS	Serbia	3.4 ha	3
15	Horticulture	Olives	DSS	Cyprus	5.1 ha	5
16	Horticulture	Apples	DSS; Digital pest control System	Netherlands	1 ha	1
17	Horticulture	Grapevine	DSS	Romania	14 ha	1
18	Horticulture	Tomatoes	DSS	Italy	60.5 ha	9
19	Horticulture – Indoor farming	Tomatoes	Automated Greenhouses	Netherlands	6 ha	1
20	Horticulture	Bananas	Precision Irrigation System	Spain	2.2 ha	1
21	Horticulture – Indoor farming	Tomatoes	Automated Greenhouses	Finland	1.2 ha	1
22	Meat	Poultry	Farm management system	UK	64,000 birds	1
23	Meat	Cows	Feeding robot; Heat and calving detectors	France	302 cows	1
24	Meat	Pigs	Farm management system	Belgium	682 pigs	1
25	Dairy	Cows	Feeding robotics + Activity Sensors	France	207 cows	1
26	Dairy	Cows	Milking Robot	Ireland	180 cows	1
27	Dairy	Cows	Automated monitoring	Germany	250 cows	1
28	Dairy	Cows	Milking Robot; Feeding robotics	Romania	803 cows	1
29	Apiculture	Bees	Automated Monitoring	Lithuania	10 beehives	1
30	Aquaculture	Oysters	Sensors for quality assessment	Croatia	5,000.0 m^2	1

Table 2. Key social impact areas of DATSs.

Social impact area	Definition	Some references
Data	Every aspect related to data collection, usage, ownership, sharing and privacy	Rotz et al., 2019; McGrath et al., 2023; Wisemana et al., 2019
Food Quality/Safety	The influence of DATSs on the quality and safety of food delivered to consumers, including traceability and transparency issues	Guruswamy et al., 2022;
Food Availability	The influence of DATSs on the productivity of farms and the consequent availability of food in local, regional and global contexts	Benfica et al., 2023
Labour Evolution	Every aspect related to the farmers' activities and farm management impacted by DATSs	Rotz et al., 2019; Salvia, 2019
Inclusive Growth	The influence of DATSs in creating equitable opportunities for all individuals	Hernandez et al., 2024
Education and Learning	All the aspects concerning skills, education, and technical competences required to adopt and use DATSs, but also the impacts that new technologies can have on reskilling processes and learning opportunities for farmers	Lundström et al., 2018; Gardezi et al., 2022
Gender Equality	The impacts that DATSs could have on the creation of opportunities for women to gain power and leadership in the sector, but also the possible digital and economic divide that new technologies can create	Ofisi & Lukamba, 2020; Abdulai 2022; Huyer, 2016; Hernandez et al., 2024
Ruralisation	All those processes concerning the revitalisation of rural areas and the impacts that DATSs could have on the creation of new job opportunities for young people outside urban areas	European Commission, 2023; Rolandi et al., 2021
Generational Change	The role of young farmers in innovation, the attractiveness of farming for young people and the generational change within farm companies	Kabadzhova, 2022; Afere et al., 2019

naires tailored to the primary sector and, more specifically, focused on the adoption of innovative technologies by farmers, failing to incorporate certain social indicators that are significantly impacted by the implementation of DATSs. Thus, the first result of this work has been the identification of the 9 key social impact areas associated with DATSs adoption, listed in Table 2.

Although the adoption of digital technologies has both positive and negative effects on farmers across all the identified social areas, the focus of the Framework was placed on those areas that, according to the literature and the information gathered directly from the Test Cases, can be considered the most directly impacted: Labour Evolution, Education and Learning, Generational Change, and Gender Equality. Food Safety is more closely related to analyses involving downstream actors in the food value chain and was not included in the Framework. Similarly, since the areas related to Food Security, Inclusive Growth and Ruralisation go beyond impact assessments at the individual farm level and require territorial or regional approaches, they were excluded from the Framework. The area of Data Concerns was also excluded from the Framework, as it is more closely related to technical issues rather than social ones.

Labour evolution is a central topic in the literature on the social impact of DATSs, representing the area most directly affected by digitalisation and the one in which farmers experience the greatest impact from the transformative role of digital technologies (Rotz et al., 2019). A substantial part of the Framework's development focused on this area of impact, within which three specific sub-areas were identified: Work Dynamics and Activities, Work-related Stress, and Work-life Balance.

Work Dynamics and Activities refer to the role that DATSs play in transforming the day-to-day work of farmers in terms of monitoring, automation, decision-making, resource optimisation and farm management (McGrath et al., 2023; Rotz et al., 2019). In this regard, it is relevant to understand whether DATSs help the farmer in his daily activities and how his tasks and workload change.

Work-related Stress embeds the physiological, psychological, and behavioural responses that individuals may experience when the demands of their job exceed their ability to cope effectively (Michie, 2002). Nevertheless, the impact of DATSs on work-related stress remains uncertain according to the scrutinised papers. On one hand, the solutions have the potential to reduce farmers' workload, thereby providing them with more relaxed working schedules. On the other hand, the adoption of new technologies may introduce additional stress and intensify work demands as individuals strive to familiarise themselves with the technology (Smith & Carayon, 1995).

Work-life Balance does not imply only an equal distribution of time between work and personal life but rather entails the ability to effectively manage and harmonise these two domains, ultimately enhancing both the quality of life and work outcomes. When successfully achieved, work-life balance can generate positive spillover effects, benefiting not only the individuals directly involved but also all other stakeholders. In this regard, the adoption of digital solutions has shown promise in facilitating this delicate equilibrium by enabling more efficient task completion and promoting conscious utilisation of data (Wolor, 2020; Esguerra, 2020; Čehovin & Kohont, 2017).

Education and Learning are a prerequisite for the dissemination of DATSs, but at the same time, can be promoted by their adoption. Agriculture 4.0 technologies require hard skills and technical competencies to fully exploit their potential. This means that a certain learning effort and re-skilling processes are often required from farmers. Therefore, it is important to analyse the effort that farmers had to exert to use a new technology, the difficulties related to understanding how it works and the possible stress generated by the learning process.

Generational Change refers to the attractiveness of the agricultural sector for young people and the impacts that new digital technologies could have on the business succession to the new generation of farmers. Understanding the perceptions of young individuals regarding agriculture as a viable and appealing career choice is essential for addressing the challenges associated with attracting and retaining young talent and promoting economic development and employment in rural areas. Historically, agriculture has struggled to attract young individuals, largely due to perceived factors such as low prestige, manual labour, and limited opportunities for growth and innovation (Kabadzhova, 2022; Afere et al., 2019). Our goal is to investigate whether the integration of digital solutions and the resulting increased entrepreneurial opportunities make the sector more attractive to young people and farmers' sons.

Gender Equality and the issues related to the gender gap in agriculture encompass the disparities and unequal treatment experienced by men and women within the agricultural sector (OECD, 2018). This gap is apparent in multiple dimensions of agriculture, such as land ownership and tenure, availability of credit and financial services, control over productive assets, involvement in decision-making processes, access to education and training, and representation within agricultural organisations and institutions (Fremstad & Paul, 2020). Various social, cultural, economic, and institutional factors contribute to the perpetuation of the gender gap in agriculture (Ali et al., 2016). While several studies have examined the impact of gender on technology adoption in agriculture, there remains a lack of research exploring the influence of digital solutions on the gender gap. Despite this being a central topic in today's debate, especially in a traditionally male-dominated sector like agriculture, the issue will be explored in more depth during the second year of the project, and it is not included in the framework presented below.

Building on the identified key social impact areas, the Social Sustainability Assessment Framework was developed, as illustrated in Figure 3. For each key social impact area, a set of relevant themes and indicators was identified to be included in the Framework, the evaluation of which is essential for assessing the real social impact of DATSs. Several studies in the literature (e.g. Eurofound 2016; Horodnic et al., 2019; Boxal & Macky, 2014) have provided a robust foundation, having undergone rigorous testing and demonstrating efficacy in identifying relevant social indicators. However, these studies were not specifically designed to assess the impacts of DATSs. To address this gap and ensure a comprehensive examination of the distinctive aspects of the agricultural sector, the Social Self-Evaluation Framework incorporates certain indicators already present in the literature with novel indicators focusing on work-life balance (Wiradendi Wolor, 2020; Esguerra, 2020), work-related stress (Persechino et al., 2013), and the attractiveness of the sector for young individuals (Afere et al., 2019).

Building on the Social Sustainability Assessment Framework, the Social Self-Evaluation Tool was developed as a questionnaire consisting of 23 rating scale items to be administered to farmers. The rating scale system is used to measure the respondent's opinion and attitude towards each item. Rating scales are frequently employed in the social sciences to measure attitudes. One commonly used instrument is the Likert-type scale (Tanujaya et al. 2022). Likert scales assess respondents' attitudes by asking them to indicate their level of agreement or disagreement with a series of statements related to a specific topic (Croasmun & Ostrum, 2011). Some researchers argue that increasing the number of points makes the scale more representative and closer to a universal system. However, others believe that increasing the number of items beyond the minimum needed does not significantly improve reliability, and more response options can decrease response quality and consistency due to increased mental effort (Croasmun & Ostrom, 2011). Some research indicates that answer quality declines with more than eleven options and that there are no additional psychometric benefits beyond six options, with the optimal number being between four and six (Tanujaya et al., 2022).

A Likert-type scale was therefore used for the Social Self-Evaluation Tool with an ordinal data type and five answer choices for each question: strongly disagree (SD), disagree (D), neither agree nor disagree (N), agree (A), and strongly agree (SA). The questions are divided as follows:

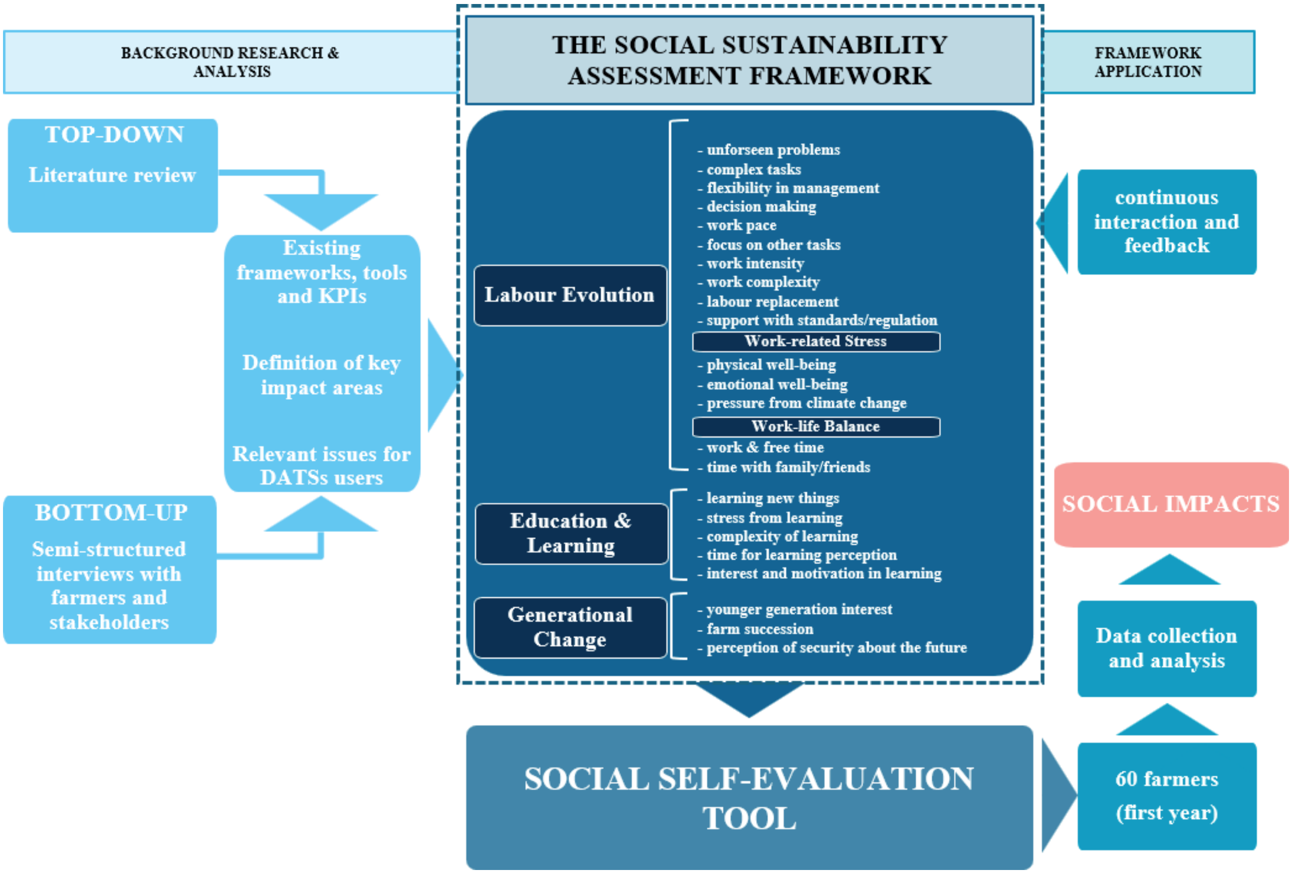

Figure 3. The Social Sustainability Assessment Framework.

- 15 questions on Labour Evolution – 10 on Work Dynamics and Activities, 3 on Work-related Stress and 2 on Work-life Balance
- 5 questions on Education and Learning
- 3 questions on Generational Change

The Social Self-Evaluation Tool was distributed to the sample of farmers for completion, with the data being collected and returned through the contact points of each TC. These contact points facilitated communication and ensured the farmers' participation in the process, allowing for a systematic collection of the social impact data generated through the application of the tool.

4.2. First application of the Social Self-Evaluation Tool

The analysis of the data collected through the Social Self-Evaluation Tool administered to the farmers shows that digital solutions seem to contribute positively to the social sustainability of farming in line with what has been found on economic and environmental aspects by other researchers (Papadopoulos et al., 2024). Indeed, considering the responses obtained from farmers from the first application of the Tool, it appears that DATSs positively impact social aspects concerning all three key impact areas identified within the Framework: Labour Evolution, Education and Learning, and Generational Change. The overall farmers' perception of DATSs seems to be quite positive, even in cases where the technology has been adopted quite recently and farmers are still getting accustomed to it.

In Figures 4, 5, 6 and 7, the results obtained from the Tool application are shown for each item. To facilitate an immediate interpretation of results, data are expressed in terms of the percentage of all the responses for each Likert class. Concerning the dimension of "Labour Evolution", specifically the "Work Dynamics and Activities" in Figure 5, the most evident positive impact is the enhanced ability to make decisions more consciously and efficiently, a factor observed in over 90% of cases, considering the sum of the farmers who strongly agree and those who agree with that sentence. This aligns with the fact that more than half of the implemented DATSs fall into the DSS category,

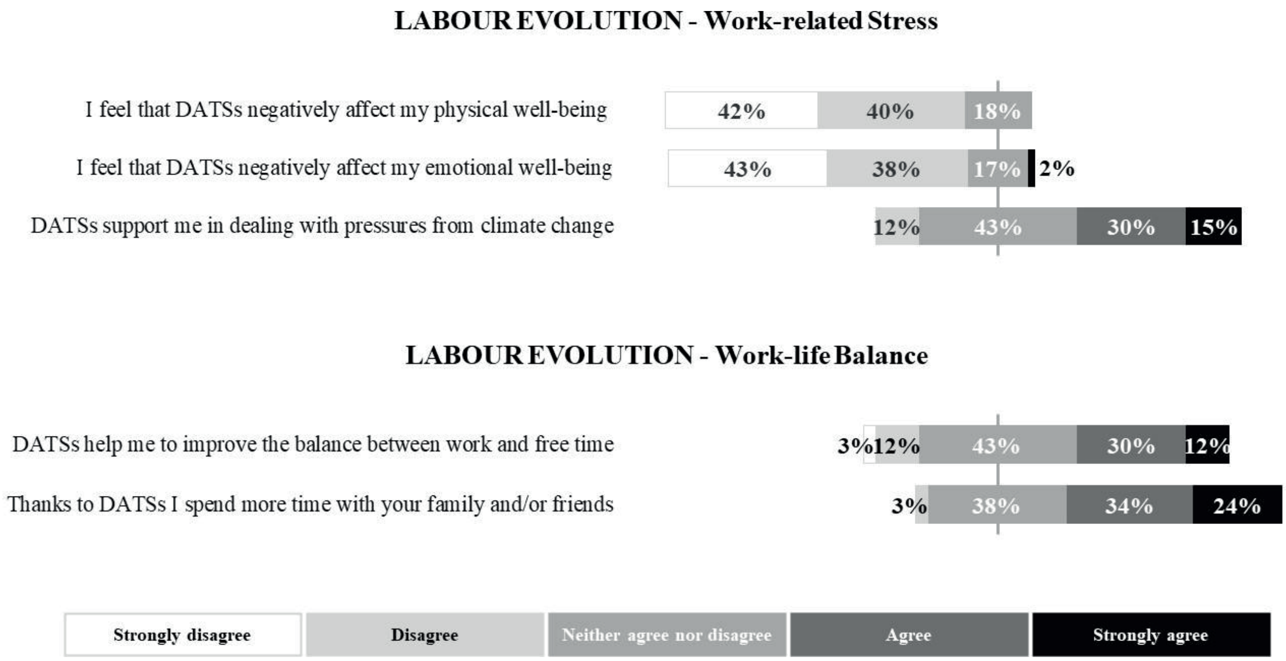

Figure 4. Impacts of DATSs on Work-related Stress and Work-life Balance. Values represent the percentage of respondents in each class for each item (sample: 60 farmers).

hence solutions that are specifically designed to support the decision-making process of farmers. Moreover, most of the other technologies incorporate sensors, IoT and monitoring systems that can valorise the large amount of data generated in fields, stables or greenhouses and support day-to-day farm management. DATSs also appear to contribute significantly to tackling complex tasks and addressing unforeseen problems, with 72% and 64% of respondents agreeing or strongly agreeing, respectively. The implementation of new digital technologies in farms has allowed more than half of the farmers to have more time to focus on other tasks, likely due to a reduction in the workload in areas where DATSs can assist. In nearly half of the cases, farmers perceive that DATSs reduce the intensity and complexity of work activities, improve their planning, and allow them to better calibrate the speed of execution. Despite the occasional perception that digital technologies might replace farmers and their managerial and decision-making roles, only a small portion of respondents (12%) feel that their role is being "replaced" by DATSs.

Currently, the perceived contribution of DATSs to certification and compliance with production standards remains limited. However, this perception is likely to evolve in the coming years, given the increasing importance of certifications related to sustainability, provenance, and traceability for both consumers and food companies. Digitalisation has the potential to significantly enhance third-party certification processes, thereby increasing the relevance and utility of DATSs in this domain.

Adopting new digital technologies demands that farmers acquire new skills to operate and maintain innovative solutions they are not used to. In addition, steep learning curves and the time required to achieve proficiency with these new technologies can be daunting, particularly for farmers less accustomed to technology and more tied to "traditional" management. This could lead to work-related stress, which in turn can reduce the acceptance of DATSs and curb their adoption. Despite these considerations, it can be seen in Figure 4 that most farmers are not affected by stressful factors, from a physical and emotional point of view. Instead, for 45% of respondents DATSs appear to mitigate stress stemming from external factors like climate change.

A key component to consider in assessing farmers' well-being in terms of their work and their quality of life, and consequently the impact that DATSs can have on these areas, is Work-life Balance (Herrera Sabillòn et al., 2021). Our analysis suggests that farmers perceive DATSs as increasing their available free time, providing more opportunities to spend quality time with family and friends. These results stem not only from having more free time but also more regular working hours, better aligned with those of other types of employment.

It is well recognised how technical knowledge and skills, both soft and hard, are essential to facilitate the

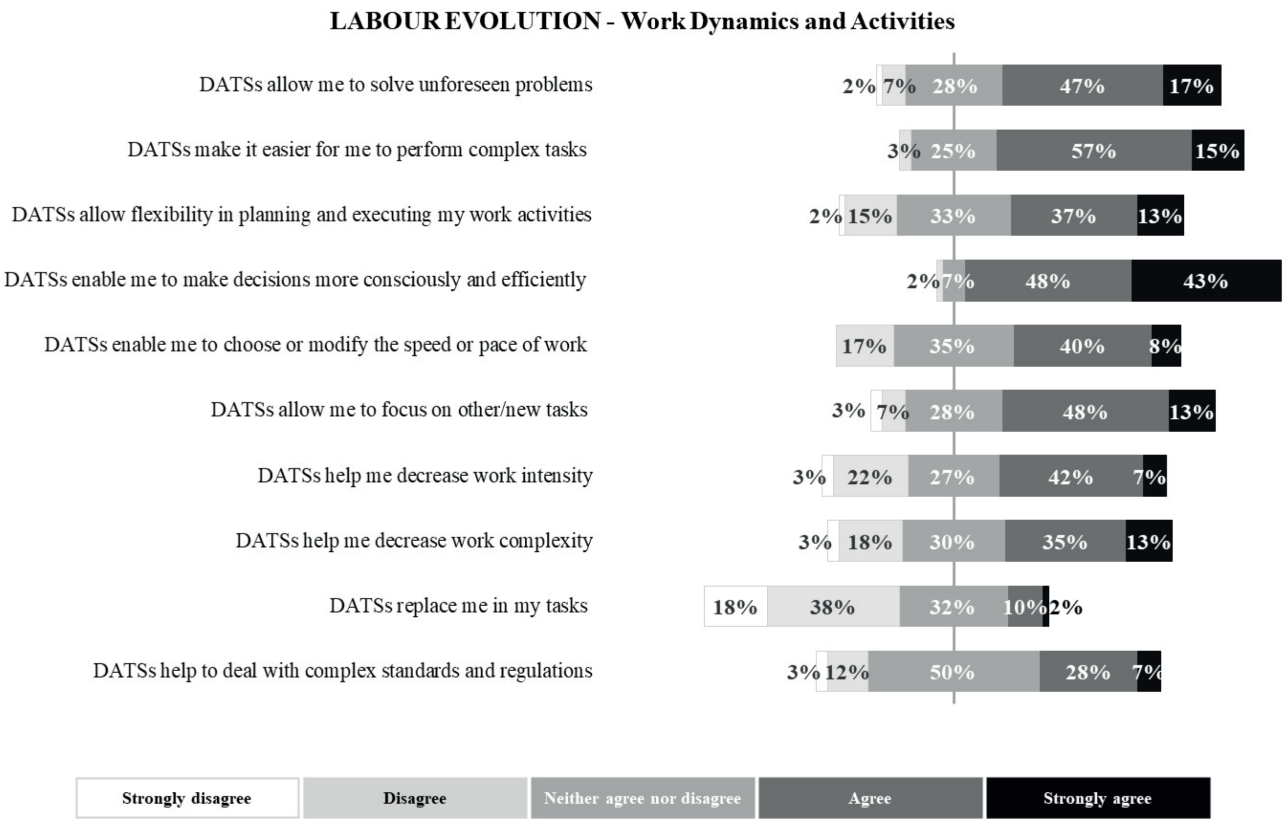

Figure 5. Impacts of DATSs on Work Dynamics and Activities. Values represent the percentage of respondents in each class for each item (sample: 60 farmers).

adoption of DATSs (Geng et al., 2024) and can limit their successful use and resulting benefits (Trendov et al., 2019). As can be seen in Figure 6, more than 4 out of 5 farmers had to learn new things to use DATSs. Nevertheless, farmers perceive that they have engaged in an interesting and motivating learning and upskilling process, and so, for more than 90% of respondents, the need to acquire new knowledge is viewed entirely positively and not as a burden on their work. Contrary to common assumptions, the learning process is not experienced as time-consuming, nor is it regarded as complicated or stressful.

Digitalisation should not be regarded solely as a consequence of generational renewal in agriculture; rather, it ought to be recognised also as a catalyst for this process. By making the sector more appealing to younger generations, digital innovations can actively facilitate and accelerate generational turnover within agricultural enterprises. (Farrell et al., 2021; Borda et al., 2023). This is also what the farmers involved in this work perceive, as can be seen in Figure 7: 65% of them believe that DATSs are capturing the interest of younger people in working on the farm or in the agricultural sector, thereby facilitating the transition in company management (47% of respondents). All of this helps half of the farmers become less uncertain about the future of their business.

5. DISCUSSION

The main contribution of this work lies in the development of a Framework for the analysis of social sustainability impacts of digital agriculture solutions. This Framework identifies the key areas of social impact and, within each area, delineates specific indicators for assessing social outcomes.. The Framework was designed to be operationally usable for assessments and self-assessments, providing a structured approach, simple yet effective, to evaluate the social implications of DATSs adoption by farmers. To test its practical usability, we developed and implemented a first pilot application in the form of a Social Self-Evaluation Tool, which enabled the collection and assessment of social impacts experienced by farmers following the implementation of digital solutions in their farms. Existing frameworks and indicators in the literature on social sustainability in agriculture do not specifically focus on the effects of digitalisation, which is a

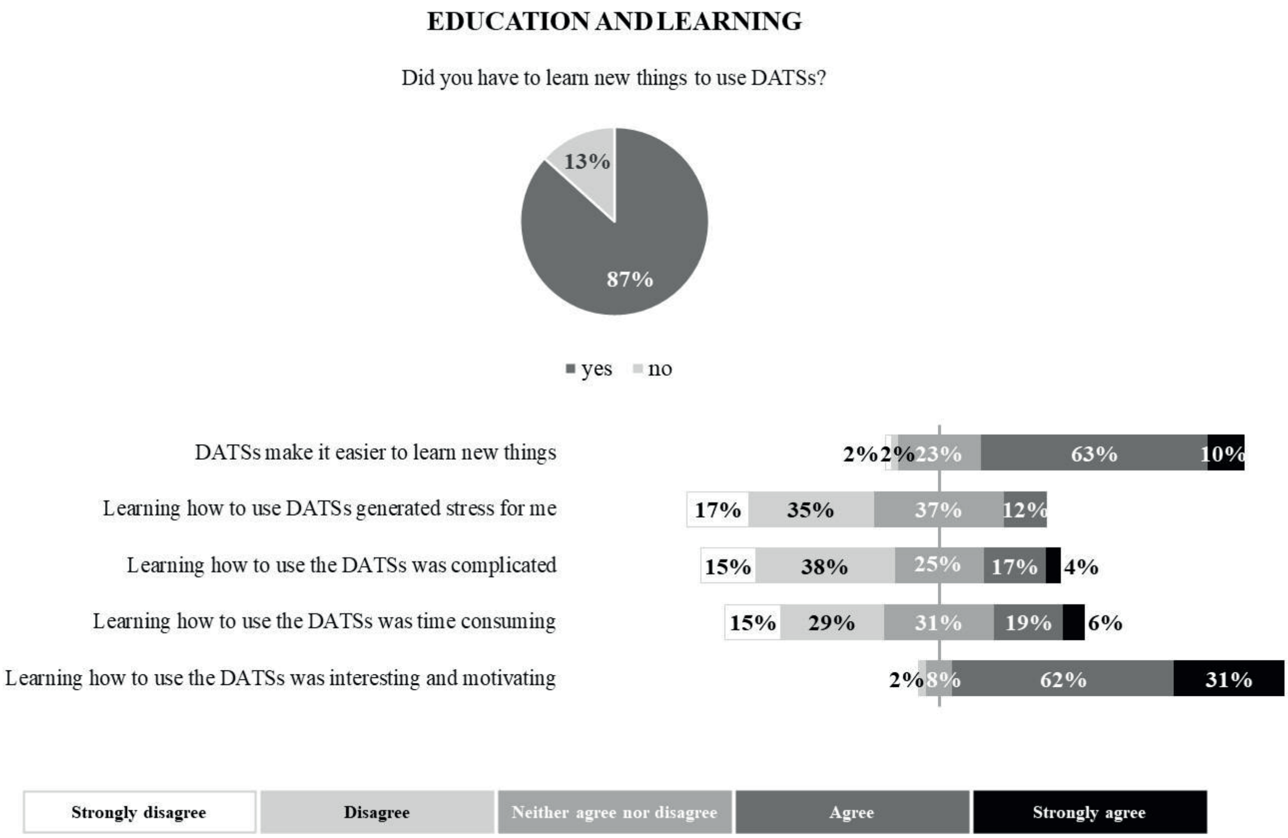

Figure 6. Impacts of DATSs on Education and Learning. Values represent the percentage of respondents in each class for each item (sample: 60 farmers).

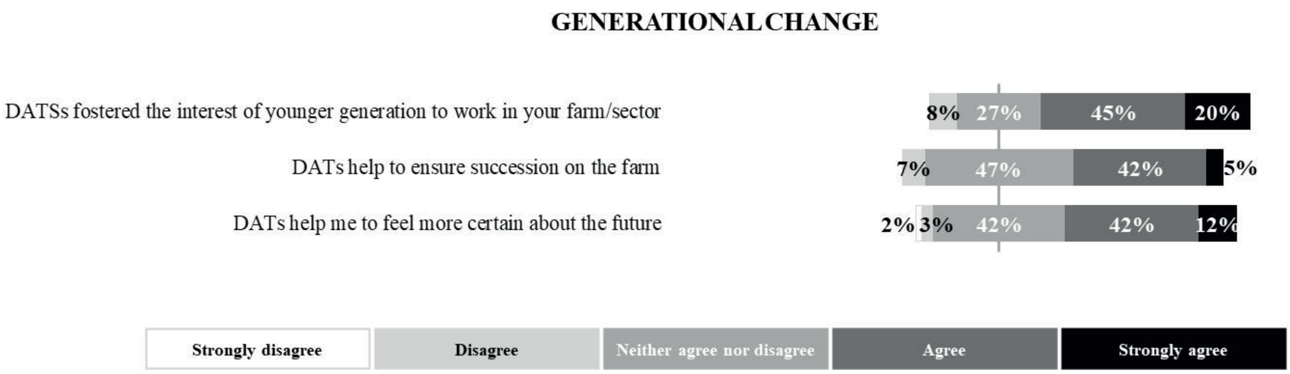

Figure 7. Impacts of DATSs on Generational Change. Values represent the percentage of respondents in each class for each item (sample: 60 farmers).

growing area of interest within the primary sector. Moreover, among the papers reviewed in the literature analysis that address the social impacts of DATSs, a lack of structured frameworks emerges for understanding the positive and negative repercussions of digital solution adoption by farmers. Some existing frameworks for analysing the social aspects of digitalisation in agriculture, despite their significant scientific and theoretical value, are often distant from the perspective of the individual farmer. These frameworks address important issues, but they focus on broader societal impacts, which are not aligned with the primary objective of this study: to understand the effects of digitalisation on the social sphere more directly related to farmers' daily lives and work.

The Framework and the corresponding Tool were tested on a sample of 60 farmers who adopted different types of DATSs. This allowed for an assessment of its usefulness and applicability, as well as the collection of valuable insights about the group of farmers involved in the project. The analysis of the results from the first application of the Framework has revealed a generally positive perception of DATSs, with several beneficial impacts identified. DATSs were found to be effective in reducing workload, increasing work productivity, and simplifying complex tasks. Although limited hard skills and technical knowledge are recognised as common barriers to the widespread adoption of DATSs, farmers were not deterred by the necessity for learning and did not perceive the required training as stressful. Conversely, the process of learning to utilise DATSs was regarded as engaging and intellectually stimulating. Furthermore, in most cases, farmers observed that the introduction of digital solutions heightened the interest of younger generations in agriculture, reinforcing the notion that digital innovations can facilitate the generational transition and ensure the continuity of the agricultural sector. The present work attempted to define a tool for assessing the social impacts of DATSs in real farming conditions, leading to good relevance of the collected data, but posing some challenges. Indeed, the practical and time-related requirements of the project have necessitated a compromise between the amount of information that could have been asked from the farmers and the ability to thoroughly investigate and rigorously explain all the social issues related to the adoption of DATSs. The research methodology, therefore, was focused on reviewing existing literature on the social impacts of DATSs and subsequently developing a framework that could have been easily interpreted by farmers. Since the Framework collected responses from DATSs adopters involved in the QuantiFarm project, the total number of respondents was only 60, whereas a larger sample size would have allowed for greater robustness. However, it is important to highlight the geographical scope and the internal diversity of this sample. This heterogeneous group of farmers, albeit seemingly not sizable, allowed us to assess the framework in different agronomical contexts, sectors (i.e. arable, horticulture, livestock, apiculture, aquaculture), socio-economic, and technological backgrounds, ensuring a more comprehensive understanding of the social impacts of DATSs in agriculture. To obtain a more statistically robust analysis of the social impacts of DATSs, the Social Self-Evaluation Framework will be applied throughout the remaining two years of the project. This longitudinal approach will enable an examination of the evolution of social impacts over time, while also allowing farmers to adapt to the technologies, become familiar with their usage, and more accurately assess the perceived experiences and benefits resulting from their adoption. This will lead to a more robust evaluation of the social impacts of DATSs. Furthermore, a tool like the Social Self-Evaluation Framework could be applied in other contexts with a higher number of potential respondents, such as the annual research on Agriculture 4.0 conducted by our research group, the Smart AgriFood Observatory of the Politecnico di Milano, which involves the participation of hundreds of farmers every year.

The TCs and farmers' active involvement with a bottom-up approach facilitated the successful development of the Framework and contributed to a robust and inclusive data collection process. This bottom-up approach has allowed for the validation of the questionnaire's robustness and the identification of potential responses to impacts not yet analysed in the literature. Additionally, through the continuous interaction with farmers, TCs and other stakeholders involved in the project, the Social Self-Evaluation Framework will be integrated with new indicators, primarily focusing on the Gender Gap and the role of DATSs in improving the condition of women in agriculture. The qualitative nature of social indicators and the challenge of attributing impacts solely to digital solutions underscore the need for a process of "data normalisation" in subsequent data collection rounds. This normalisation aims to refine the analysis by excluding contingencies and external factors, providing a more accurate view of the true impact of digital technologies on social dimensions.

6. CONCLUSIONS

This work addressed a critical gap in the existing literature by developing a Framework, specifically tailored to the primary sector, to assess the impacts of digitalisation on a diverse range of social aspects. Indeed, despite the existence of frameworks in scientific literature focusing on assessing social sustainability and working conditions in companies, there is a lack of social frameworks tailored to the primary sector and specifically focused on DATSs adoption. For these reasons, the Social Sustainability Assessment Framework has been developed to offer an operational tool to evaluate the social implications of DATSs adoption by farmers.

The approach followed to develop the Social Sustainability Assessment Framework, with the integration of a literature analysis and a bottom-up process with semi-structured interviews with farmers and other relevant stakeholders, has proven to be effective in identifying the most relevant social issues related to DATSs adoption. The developed Framework offers an opportunity for further exploration of critical aspects that can be impacted by the digital innovation process, such as the evolution of work, generational change, and gender equality in the agricultural sector. In this way, the Social Sustainability Assessment Framework not only offers a valuable initial contribution to the social sustainability assessment of DATSs, but also lays the groundwork for future research aiming to develop robust methodologies for assessing and addressing the social impacts of digital innovations in the agricultural sector.

In order to test the practical applicability of the Social Sustainability Assessment Framework, we developed and implemented a Social Self-Evaluation Tool, which enabled the collection and assessment of social impacts experienced by a sample of 60 farmers following the implementation of digital solutions in their farms. The overall results of the first year demonstrated the real benefits that the adoption of DATSs could have on farmers and farm management, not only in terms of economic and environmental sustainability (broadly demonstrated by other researchers), but also regarding social impacts. Even more importantly, the application of the Framework allowed us to demonstrate both its utility and its simplicity in use with farmers in assessing the social sustainability of DATSs.

It is increasingly evident that the need to consider social sustainability arises whenever discussing and working on the digitalisation of agriculture. The social impact areas and issues identified in our Social Sustainability Assessment Framework, along with the data collected through the Social Self-Evaluation Tool, demonstrate that policymakers, technology providers, agribusinesses, agronomists, and all stakeholders involved in the digital innovation of the primary sector could benefit from using frameworks and tools like the one developed in this study to guide the adoption of digital solutions in agriculture. By focusing on the social impact areas and issues identified in this work, policies can help ensure that the digital transformation in agriculture not only drives economic and environmental sustainability but also promotes social benefits, such as inclusive growth and improvements in working conditions on farms. The adoption of such frameworks can be instrumental in the design of targeted policy interventions aimed at addressing social issues in rural areas, ensuring that technological advancements benefit all members of the farming community. From the perspective of technology providers, it is equally crucial to consider the social implications of DATSs that could be linked to the technical aspects of their development. The usability, ease of use, and reliability of digital tools play a significant role in determining farmers' willingness to adopt and effectively implement these technologies. By integrating social sustainability into the design and development of their solutions, technology providers can ensure that their products promote inclusivity, equity, and social benefits, without causing stress or introducing additional complications to farm management. This includes making sure that digital solutions are accessible to a wide range of farmers, including those with limited digital literacy or technical skills, and that these solutions foster work-life balance, flexibility, better decision-making processes, and simplify the overall management of their farms.

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Impacts of heat waves on agricultural workers: An analysis of adaptation measures

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Abstract. This study evaluates the effectiveness of different farm-level adaptation measures aimed at mitigating the adverse impacts of heat waves on labour productivity. Despite the increasing frequency of heat waves, existing literature on occupational heat stress primarily relies on modelled estimates. To address this gap, exploratory interviews and structured questionnaires were employed to identify key challenges posed by heat waves, as well as the perceived benefits and limitations of different adaptation strategies. Data were collected from nine farms located in Emilia-Romagna (Northeast Italy), all of which were characterized by a long-standing commitment to improving working conditions. The Analytic Hierarchy Process was used to evaluate the perceived effectiveness of adaptation measures according to three criteria: acceptability, flexibility, and timeliness. Findings indicate that, in the absence of adaptation strategies, productivity losses may reach up to 30%. Among the measures assessed, shifting work hours was identified as the most effective strategy. The study underscores the need for structured thermal risk assessment protocols and provides recommendations to inform sustainable and worker-centered adaptation policies in the agricultural sector.

Keywords: heat waves, adaptation measures, agricultural workers, productivity loss, Analytic Hierarchy Process (AHP).

1. INTRODUCTION

Worldwide, climate change scenarios point to an intensification of extreme heat events across all regions with growing implications for outdoor workers (IPCC AR6 WGI, 2021). According to the World Meteorological Organisation (WMO), a heat wave is defined as a period of at least six consecutive days during which the maximum daily temperature exceeds the 90th percentile based on the climatological reference period (1981-2010 or if available 1991-2020). Studies, such as de Sario et al. (2023), have shown that heat waves have significant economic impacts on society, including increasing healthcare costs (Martínez-Solanas et al., 2018), and costs for the social security system, that must compensate workers for heat-related injuries (Ma et al.,

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2019). In addition to these social costs, several studies have reported economic costs linked to a reduced worker productivity resulting from high temperature exposure in working environments (Morabito et al., 2021; Kjellstrom et al., 2009). In sectors such as agriculture, where most activities, are carried out outdoors, heat waves significantly increase the risk of work-related injuries and work productivity reductions (Di Blasi et al., 2023).

Thus, in recent years, the necessity to introduce acceptable preventive measures able to reduce the risk of outdoor work-related injuries and excessive heat exposure has become pressing. For instance, in recent years, countries such as Italy have introduced regional regulations to improve the working conditions during heat waves. Specifically, these regulations limit the working time between 12:30 and 16:00 for specific sectors such as agriculture and construction during the summer months and in case of heat waves. In 2021, these measures were implemented in three southern Italian regions (Puglia, Calabria and Basilicata). In 2024, similar regulations were adopted by 15 of the 21 Italian regions.

Economic effects linked to heat waves can be classified as direct and indirect impacts. Workers' productivity loss (PL) involves a direct output loss for farms. This can entail relevant indirect effects because of the interdependencies along the value chain, and at a macroeconomic level on household consumption, national output, etc. (Zhao et al., 2021). These aspects related to climate changes are often neglected, but the magnitude of their potential impact on workers' health and productivity underlines the need for case studies providing information on PL in different contexts and activities, and for different economic sectors (Kjellstrom et al., 2009). Indeed, current knowledge is scarce about the economy-wide effects of heat waves on the productivity of diversified economic sectors that range from outdoor to indoor activities and feature a heterogeneous structure and production orientation, such as agriculture (Day et al., 2019).

One approach to quantifying heat-related productivity loss is the use of the Wet Bulb Globe Temperature (WBGT) index and ISO 7243 standards. Kjellstrom et al. (2018) developed risk functions based on these metrics to estimate reductions in work capacity under different levels of heat stress. These functions assume that workers self-regulate their workload to avoid severe health consequences, such as heat stroke. Accordingly, these models can estimate productivity loss (PL) as a function of heat exposure and work intensity.

Individuals and firms can reduce the heat-stress implementing specific adaptation strategies able to cope with heat conditions (Kjellstrom, Holmer et al., 2009). A range of adaptation options are available and these offer different solutions that can fit to different working conditions and contexts cost-effectively. In general, behavioural adaptations such as the anticipation of working hours to avoid heat peaks, and passive adaptation options such as frequent drink breaks, together with technical equipment are indicated as valuable options for outdoor workers (Day et al., 2019). However, the identification of the adaptation measures strictly depends on local contexts and the type of activities. This warns against a generic identification of adaptation solutions and highlights a particular need for economic sectors such as agriculture, for an evaluation carried out at the farm level and able to consider the complexity of adaptation decision-making (Day et al., 2019).

The effectiveness of the available adaptation measures in reducing the impact of heat waves has a specific relevance to evaluate their soundness as tools to be included in regulations targeting the adaptation of working environments to climate risks. For instance, building on the work of Kjellstrom et al. (2018), Morabito et al. (2021) applied different heat risk functions to estimate the effectiveness of simple adaptation measures. In this study, WBGT and typical working hours data were combined to compare PL and economic costs related to farming activities in an Italian region with and without the adoption of adaptation measures. Using the modelled functions, Morabito and colleagues estimated a significant effect of the adaptation measures, and thus highlighted a potential positive impact for firms and workers engaged in intensive activities during heat waves, such as agricultural workers.

While model-based approaches provide valuable insights, evaluating the perceived effectiveness of adaptation measures and understanding workers' and managers' perceptions of climate risks are equally important. Risk perception is a critical factor influencing adaptive behavior (Madhuri and Sharma, 2020), and a range of psychological, economic, and contextual factors may shape the willingness to adopt preventive strategies (D'Alberto et al., 2024). Despite a robust body of literature focused on modeled projections of productivity loss under heat stress (e.g., Orlov et al., 2019; Kjellstrom et al., 2009; Morabito et al., 2021), empirical data on the perception of heat waves from both the individuals directly affected and those responsible for managing and organizing outdoor working activities during these events are currently limited.

Moreover, research on the operational feasibility and perceived efficacy of various adaptation strategies is still limited. In particular, studies investigating the views of land managers on the implementation and effectiveness of such measures are, to our knowledge, lacking. Yet, understanding these perspectives is important, as land managers are ultimately responsible for adopting and enforcing adaptation strategies at the farm level. The lack of empirical data on the perceived utility and impact of adaptation measures impedes the development of evidence-based policies that ensure worker safety and productivity during heat events. Without such insights, efforts to identify and promote tailored, context-specific adaptation measures risk being ineffective or unsustainable (Final Scientific Report of the WORKLIMATE Project, https://www.worklimate.it/).

This study aims to address this research gap by investigating how farm managers in Emilia-Romagna perceive and evaluate various adaptation measures designed to mitigate the impacts of heat waves on outdoor agricultural workers. The work contribution to the existing literature is twofold: (1) it provides an in-depth analysis of the challenges posed by heat waves within a specific agricultural context; and (2) it evaluates the perceived effectiveness of adaptation strategies based on empirical data collected from nine farms in the region. Specifically, the research explores land managers' assessments of the impacts of heat waves on different types of workers, their evaluation of the advantages and disadvantages of various adaptation strategies, and their perceptions of these strategies' effectiveness in reducing productivity losses.

2. METHODOLOGY

2.1. Analytical approach

In this analysis, the analytic hierarchy process (AHP) method was employed (Saaty, 2013). AHP was developed to support decision-making by structuring complex problem into a hierarchical framework. AHP organises decision problems into a hierarchy of factors that can be easily interpreted by an expert, thereby facilitating complex judgments and enabling a structured evaluation of multiple alternatives across different criteria. Originally developed by mathematician Thomas Saaty in the 1970s (Saaty, 1977), AHP is a widely used multi-criteria decision analysis (MCDA) technique. At the core of AHP lies the pairwise comparison approach, which evaluates decision elements in pairs, allowing for a more nuanced assessment of their relative importance. The hierarchy itself takes the form of a tree structure with successive levels representing broader decision criteria, specific subcriteria, and eventually alternatives. These elements are compared pairwise at each level of the hierarchy, from the lowest level (typically comprising the alternatives or specific actions under evaluation) up to the highest-level criterion (Saaty, 1987). In this study, the objective was to identify the most effective adaptation measures to mitigate the impacts of heat waves. The AHP process involves assigning numerical values to each pairwise comparisons using a 1-to-9 scale, where 1 indicates equal importance and/or relevance of the two elements on the control element and 9 represents extreme importance of one element over another (Saaty, 2008) (Tab. 1). These comparisons are recorded in pairwise comparison matrices that reflect the relationships between criteria and adaptation measures. After completing the pairwise comparisons, the relative weights (or priority) for each criterion are calculated using specific procedures, particularly the eigenvalue method. This priority is defined as a vector representing the influence (or weight) of each single element within that level of the hierarchy (Duke & Aull-Hyde, 2002). The process entails calculating the normalized values for each matrix to derive weights that reflect the relative importance of each criterion, by means of the eigenvector method and a process of averaging over the normalised columns of the matrix (Meade & Sarkis, 1999; Saaty, 2008). For further details on the calculation of the priority by means of different matrix multiplication methods see in particular Villanueva et al. (2015). Subsequent consistency checks are then carried out to ensure the reliability of comparisons. The Consistency Ratio (CR) is utilised to assess consistency, by comparing the consistency index of the judgments to a random index. A CR value below 0.1 is generally considered acceptable, indicating a reasonable level of consistency in the decisions made during pairwise comparisons. Finally, the calculated weights are aggregated to determine the overall priorities of the adaptation measures (Liu et al., 2025).

However, one of the main limitations of this methodology is that the quality of results heavily depends on the expertise and understanding of the respondents. Biases may be introduced if participants are not sufficiently knowledgeable about the subject matter (Villanueva et al., 2015). Furthermore, AHP does not rely on assumptions regarding known probability distributions (Duke & Aull-Hyde, 2002). As a result, the method is not statistical in nature and typically involves a relatively small number of expert respondents, due to the in-depth knowledge required to complete the questionnaires accurately.

2.2. Identification of target participants

As illustrated in Figure 1, the survey was organized in three main phases. The first step involved identifying the target group of participants.

Table 1. Saaty's fundamental scale for pairwise comparison judgments.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
2	Weak or slight	Experience and judgment slightly favor one activity over another.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
4	Moderate plus	Experience and judgment strongly favor one activity over another.
5	Strong importance	Experience and judgment strongly favor one activity over another.
6	Strong plus	An activity is favored very strongly over another.
7	Very strong or demonstrated importance	An activity is favored very strongly over another.
8	Very, very strong	The evidence favoring one activity over another is of the highest possible order of affirmation.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.

Source: Saaty, 2013.

For our study, the target participants were farm managers of large, well-structured farms with a significant number of workers. Given the exploratory nature of the research, we considered appropriate to begin by involving farm managers operating within the same geographical area (Emilia Romagna). This choice allowed for greater homogeneity and consistency in the data collected, thereby minimising the influence of contextual and structural difference across regions. In light of the limited number of studies investigating the impact of heatwaves on farm management and the scarcity of empirical data on this issue, the survey specifically targeted farms with a demonstrated commitment to workers' welfare. Indeed, the selected farm managers had already been implementing strategies and measures to mitigate the effects of heat waves on their employees over several years. Such an analysis enabled an in-depth analysis of the current implementation status of various adaptation measures. The first part of the survey focused on the Cooperative Agricole Braccianti (CABs) in the province of Ravenna. Later, the survey was extended to include other large farms in the region with the help of trade associations.

Collectively, these cooperatives manage approximately 11,500 hectares of utilised agricultural area (UAA). Their production is primarily oriented towards fruit trees, vegetables and cereal crops, although some also operate in the livestock and nursery sectors. These cooperatives were of particular interest due to their organisational structure: workers are also cooperative members and are involved in the decision-making process. Being directly exposed to the working conditions, the worker-members have developed a deeper awareness of the impacts of heat waves, including suggestions and proposals to more effective prevention and protection measures.

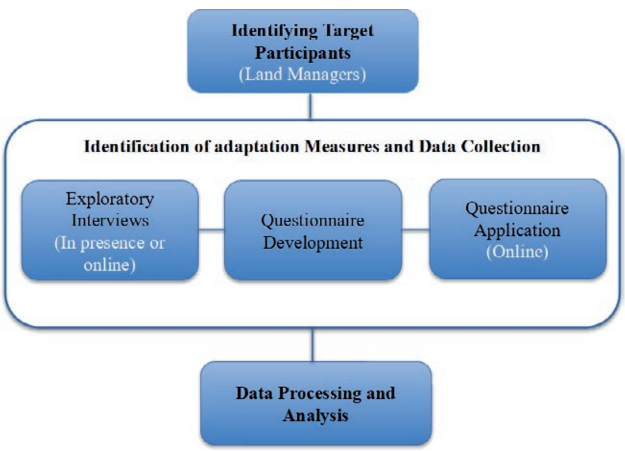

Figure 1. A flow diagram of the research process.

2.3. Identification of adaptation measures and data collection

We conducted a literature review to identify the adaptation measures able to reduce the impacts of heat waves on agricultural workers. Four adaptation measures were identified through a literature review (Day et al., 2019; Habibi et al., 2023; Kjellstrom et al., 2009; Marinaccio et al., 2022; Morabito et al., 2021; Spector et al., 2019; Zhao et al., 2021):

- shifting/anticipating work hours;
- setting up shaded areas;
- increasing the frequency of work breaks with facilitation of the availability of water;

– special equipment (ventilated jackets, clothing in technical, breathable fabric).

These measures represent different management options for the organisation of outdoor labour that can improve workers' resilience to heat stress and aim to maintain a safe work environment. Therefore, the adoption of the measures also allows to enhance significantly worker performance, productivity, and company profits (Habibi et al., 2023).

The second phase involved the data collection (Figure 1). We started with exploratory interviews with the CAB farm managers, aimed at collecting preliminary information on the phenomenon of heat waves and identifying pros and cons related to the potential implementation of adaptation measures at farm level and productivity-related issues or operational problems observed during the last heat wave events. Five exploratory interviews were conducted with the managers of the seven CABs in the province of Ravenna. Each interview lasted on average 40 minutes and was conducted either online or in person. The interview was divided into two main sections: The first section focused on framing the problem and identifying the work problems already encountered during the last heatwaves (summer 2022-2023). The second section assessed the advantages and disadvantages and the respondents' perceptions of the four selected adaptation measures. Then, based on the information gathered in the exploratory interviews, a questionnaire was designed to collect quantitative data on the adaptation measures and assess their effectiveness in reducing the impact of heatwaves on agricultural workers.

The questionnaire included 34 questions, and it was implemented on the Qualtrics^{XM} (2024) platform (Provo, Utah, USA, https://www.qualtrics.com).

The questionnaire was structured in three main sections: the first section included general information about the respondents and the farms, such as their role, main crops, farm size, the main symptoms observed in workers during the heat waves of the summers of 2022-2023, the activities most affected by the heat waves, and the adaptation measures adopted in these circumstances.

The second part of the questionnaire dealt with the assessment of the effectiveness of adaptation measures. In order to assess the effectiveness of the identified heat wave protection measures, we included four questions to collect data using the AHP method (Fig. 2). Three of these questions focused on specific criteria for assessing the effectiveness of each adaptation measure, namely:

1. Worker acceptability, i.e. the expected willingness of outdoor agricultural workers to adopt the measures.
2. Timeliness of implementation, i.e. the time needed to implement the measure after a heat wave forecast.
3. Flexibility of application, i.e. the possibility to adopt the measure in different types of farms.

In addition, a further question concerned the comparison between the selected criteria. These criteria were derived from those identified by Day et al. (2019) and subsequently adapted based on the information gathered during the exploratory interviews.

This set of questions included four matrices comparing adaptation measures according to each of the criteria listed above using the AHP 1-9 scale.

As an example, we report two of the submitted questions for the two assessment levels:

– (Q11) - *With respect to the criterion acceptability by workers, which of the following pairs of factors do you think is the preferred adaptation measure by workers? (Shifting of working hours VS Setting up shaded areas; Shifting of working hours VS Increased frequency of breaks… etc.) For each pair, express your preference on a scale of 1 to 9, where 1 indicates that the measures are equally preferred and 9 indicates that one measure is extremely more accepted than the other.*
– (Q13) - *Which criterion, among the following pairs of criteria, do you think is most important for an effective reduction of workers' productivity loss?* (*Acceptability by the workers VS Timeliness of implementation; Acceptability by the worker VS Flexibility of application…etc) For each pair, express your preference on a scale of 1 to 9, where 1 indicates that the criteria are of equal importance and 9 indicates that one criterion is extremely more important than the other for reducing productivity loss.*

The final part of the survey focused on estimating the productivity loss of agricultural workers. In the land manager survey, respondents were asked to report any adaptation measures implemented to cope with heat wave events. Respondents were then asked to estimate productivity loss in the following ranges in the absence of adaptation measures: 0-10%, 10-20%, 20-30%, and more than 30%. Specifically, the questionnaire asked respondents to provide an estimate of the percentage of daily productivity loss estimated for general workers and specialised workers during heat waves and in the absence of adaptation measures.

The questionnaire was distributed in June and July, and it was initially distributed to the CABs and to the main regional farmers' associations, who then distributed it to the agricultural land managers in Emilia-Romagna. The distribution of the questionnaires to Emilia-Romagna was motivated by the need to obtain data that were as homogeneous as possible. This strategy helped to reduce the variability linked to geographical and struc-

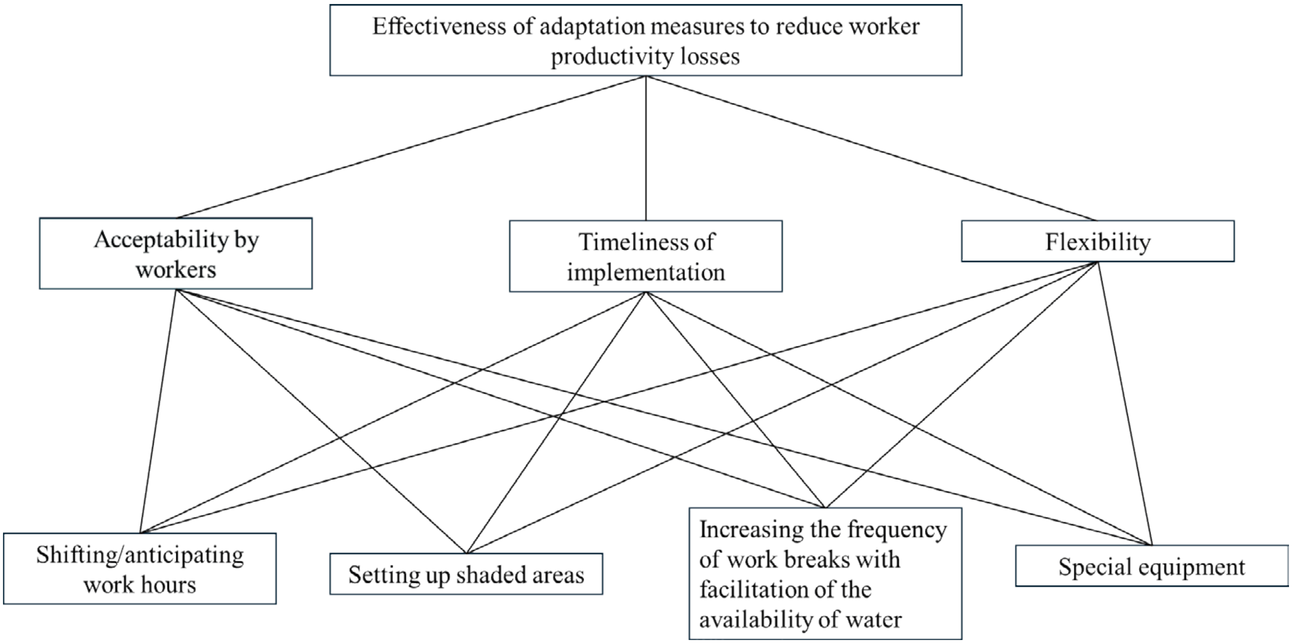

Figure 2. Hierarchical decision-making structure for selecting the most effective heat wave adaptation measures.

tural factors, ensuring greater consistency in the results and facilitating comparisons between the different farm realities analysed.

2.4. Data processing and analysis

The survey collected a total of 15 responses from land managers in Emilia-Romagna. Only 9 questionnaires were completed in all parts and included in the analysis. For the AHP questions, we normalised the comparison matrix data and determined the priorities for each level of the hierarchy. Elaborations were performed with R 4.4.1 (2024) (RStudio: Integrated Development for R. RStudio, PBC, Boston, MA, http://www.rstudio.com/). The priority calculation was used to compare the relative contribution of the elements at each level of the hierarchy with an element in the adjacent higher level. We conducted a synthesis of the priorities to calculate a composite weight for each alternative, based on the preferences guided by the comparison matrix. After calculating the composite weight, the relative priority of each adaptation measure was obtained, and a final ranking was developed to identify the best adaptation alternative through the calculation of the average of all the overall priorities that were calculated for each questionnaire (Veisi et al., 2022).

Finally, the consistency ratio (CR) was calculated to verify the consistency of the judgments expressed by the respondents. The CR is suggested as a valid indicator of the cognitive stress of respondents, i.e. a high CR indicates a high complexity level of the questions and thus higher efforts required in the judgement process.

3. RESULTS

3.1. Results of the exploratory interviews

We conducted five interviews with CAB farm managers to get an initial overview of the impacts of the heatwaves, the benefits and challenges of the adaptation measures selected.

It emerged that all farms observed issues related to heat waves during the summers of 2022-2023, particularly in orchards during the harvesting of peaches and apricots: "*The issue of heat waves is primarily felt in the orchard*". One farm also encountered difficulties in nurseries and in organic fields: "*Heat waves are also felt in open fields across the 1,200 hectares of organic farmland, which requires frequent tilling to eliminate weeds*". Additionally, all managers reported that in the orchards, due to heat waves combined with high levels of humidity, the presence of nets and rows of trees themselves limit air circulation, workers experience signs of fatigue, tiredness, and breathing problems. The farm managers also stated that the productivity of workers decreased during heat waves: *"During the hot-*

test hours, fewer kilograms are harvested and in general during heat waves, yields decrease because workers are slower", "From eleven o'clock onwards, employee performance drops by about 30 per cent".

The interviewed farm managers stated that, to avoid extreme heat during the central hours of the day, they adjust the work schedule. In fact, field workers (who are mostly women) finish their workday by noon and, depending on daylight, they start working about an hour earlier, around 5 a.m. The shifting/anticipating of working hours was implemented by 5 out of 5 farms. For greater clarity, we provide the interviewee's response as follows: "*During the summer, it became necessary to start the workday an hour to an hour and a half earlier (depending on daylight) or to leave an hour earlier (by 12 p.m.)*". The anticipation of the working time also contributed to mitigate operational problems related to harvesting and storing the product. Indeed, excessive heat also affects the quality of the harvest, especially if it remains under the sun and is not delivered immediately to storage or processing centres.

Regarding the adaptation measures already implemented by the interviewed farms, in addition to adjusting work hours, five out of five farms also indicated the use of shaded areas represented by break rooms, warehouses, or shelters near the orchards. Other shaded areas included seminatural elements like hedges and groves established for instance with the support of agro-environmental measures in the past. The interviewees reported that most employees rely on own water supply. In the five farms however, the interviewees reported that supervisors are always supplied with drinking water as well as with a first aid kit. The availability of water supplies at the farm centre was also indicated by the five interviewed farm managers. Regarding the use of special equipment, the purchase of technical clothing to promote better breathability was reported in one interview: "*In the summer of 2023, the farm purchased technical fabric shirts that allow workers to work more comfortably. The request originated from the workers*".

Table 2. Characteristics of respondents.*

	Frequency	%
Respondent type		
Entrepreneur	2	22.22%
Director/Manager	5	55.56%
Technician/Foreman	2	22.22%
Farming system		
Cereal farming	7	77.78%
Horticultural	4	44.44%
Viticultural	5	55.56%
Fruit farming	4	44.44%
Zootechnical	3	33.33%
Other	2	22.22%
Symptoms observed during heat waves		
Tiredness	9	100.00%
Pressure drops	1	11.11%
Muscle cramps	1	11.11%
Intense sweating	8	88.89%
Activities affected by heat waves		
Fruit and vegetable harvesting	6	66.67%
Field operations	4	44.44%
Other (manual weeding)	3	33.33%
Measures against heat waves		
Shifting/anticipating work hours	8	88.89%
Setting up shaded areas	6	66.67%
Increasing the frequency of work breaks with facilitation of the availability of water	9	100.00%
Special equipment	2	22.22%
Other (e.g. umbrellas)	1	11.11%

* Each participant had the opportunity to select more than one answer, so the total number of answers may exceed the number of participants.

3.2. Results of the questionnaires

The main characteristics of the sample are presented in Table 2. The results of the questionnaire indicate that heat waves have a notable impact on farm workers' health. Respondents reported significant physical symptoms among workers, including intense fatigue, excessive sweating, drops in blood pressure, muscle cramps, and dehydration. These symptoms typically occur during labor-intensive tasks such as fruit and vegetable harvesting, field operations, and manual activities like weed removal.

To mitigate the effects of heat waves, most farms have already implemented various adaptation measures. All respondents reported increasing the frequency of breaks and improving access to drinking water. Additionally, more than half of the farms have either shifted the start time of work to earlier hours, shortened the duration of work shifts, or established shaded rest areas near the fields. Fewer than a quarter of respondents reported the use of specialized equipment during heat waves. Among the additional adaptation measures mentioned, several farms have introduced portable shading structures, such as umbrellas, to protect workers during fruit harvesting.

The average of the assigned priorities allowed for the development of a ranking of the most effective adap-

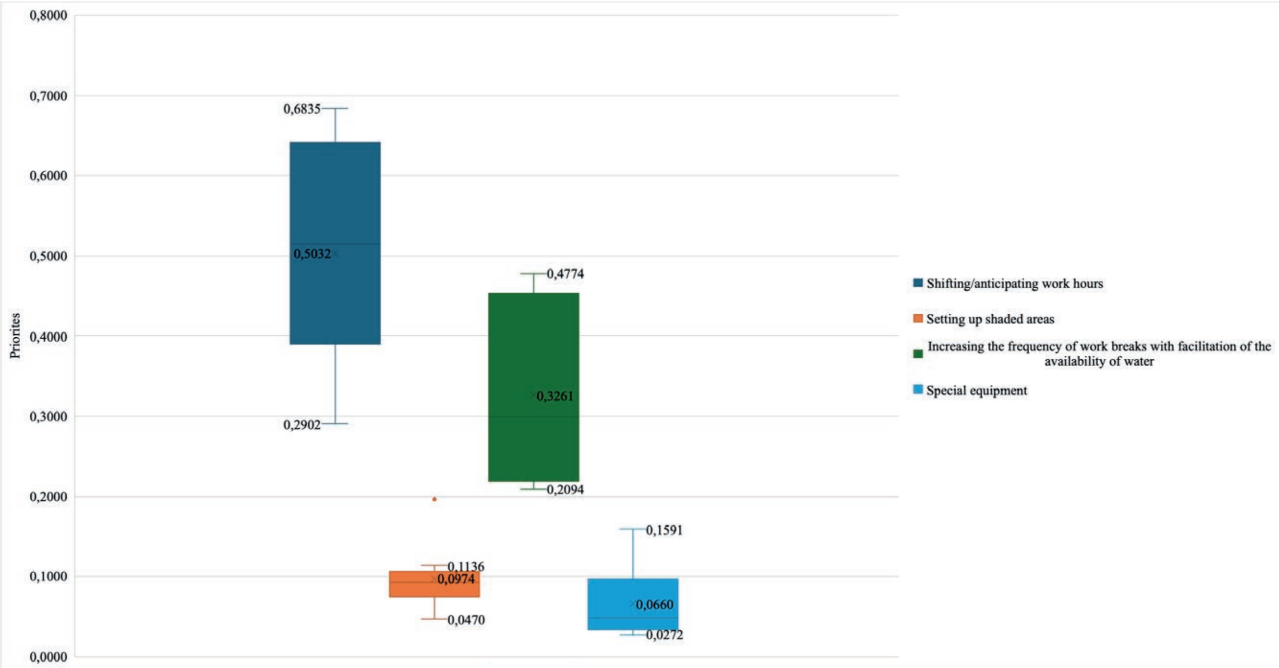

Figure 3. Priorities of adaptation measures as resulted in the AHP analysis.

tation measures based on the selected criteria: worker acceptability, timeliness of implementation, and flexibility of application. As shown in Fig. 3, the adaptation measure with the highest ranking is the shifting or anticipation of working hours, with an average priority value of 0.5032. The second-highest ranked measure is increasing the frequency of work breaks and ensuring access to potable water, with a value of 0.3261. Considerably lower priority values were assigned to the creation of shaded areas (0.0974) and the use of special equipment (0.0660). The consistency ratio for the group of respondents was 0.20. This value is above the commonly accepted threshold (0.1), and indicates that the evaluation process posed a considerable cognitive challenge for respondents, likely due to the complexity of comparing multiple criteria and adaptation options.

The third part of the survey asked participants to provide an estimation of the average percentage of daily productivity loss observed among both common and specialized workers in case of heat waves. The results showed that the most relevant productivity losses occurred among common workers, with reduction rates ranging from 20% to 30% or more (44 % of respondents). As for specialized workers, such as tractor drivers, most respondents (44%) reported productivity losses between 0% and 10%.

4. DISCUSSION

The study, for the first time, explores the perception of land managers regarding heat wave adaptation measures that farms could easily implement to reduce the impact on productivity losses.

Overall, we found that common workers, especially those involved in fruit harvesting, can have productivity losses of over 30% in the absence of adaptation measures; this is confirmed by evidence in the literature, where productivity losses of this magnitude are reported (Morabito et al., 2021). Beside this and according to the perception of land managers, the most effective adaptation measure to reduce productivity losses is shifting/anticipating working hours. This evidence is based on the criteria of worker acceptability, timeliness of implementation, and flexibility, and it is also reported in some of the regulations focusing the reduction of heat wave impacts on workers (Emilia-Romagna region).

Common workers is the category that is most at risk during heat waves because of their exposure to outdoor activities performed in periods that can be affected by heat waves such as fruit picking. Thus, this worker category is exposed to heat and a higher risk of physical stress and reduced productivity. Specialised workers, such as tractor drivers, work in more favourable conditions (e.g. air-conditioned cabins) that mitigate the negative effects of high temperatures and preserve work capacity.

In this context, a more specific focus on the potential heat-related threats that can affect tractor drivers is necessary as the frequency of getting-on and -off tractors to e.g. operate changes/adjustments on equipment could generate abrupt changes of temperature and impact the workers' health.

We also found that the interviewed land managers believe that the shifting/anticipating of the working hours is the most effective measure to reduce productivity losses, probably because it is easy to use low cost and immediately implementable. The effectiveness of this measure is also supported by Morabito et al., (2021), that showed how the adoption of such a measure reduces workers' productivity losses by up to 33% and lowers the economic costs associated with such losses. Moreover, earlier working hours would have positive effects on the quality of the harvest, as it would not be exposed to the heat and delivered earlier to the harvest centres

Nonetheless, as also highlighted by Day et al. (2019), changing working hours could impact total working hours, associated income and economic and social costs that should not be underestimated. Indeed, anticipating the working schedule involves a range of benefits, but it is important to consider that this change could cause disadvantages and reorganization of workers' routines, especially for those who have long commutations to reach the working place. In addition, the measure would have a significant impact on the various costs that the farm has to bear, including organisational, operational and logistic costs. In fact, 25% of the respondents reported the need to add about one extra working day per week, to compensate for the reduction in working hours. This also involves the need of additional workers or of additional trips to storage points during the week. Another challenge for the adoption of this measure is the limited availability of light in the early morning hours, which is essential for fruit picking.

It is therefore essential to make workers aware of the importance of this measure and to ensure the smooth running of activities. This is possible thanks to the presence of adequate infrastructure, implemented by companies to enable optimal harvesting even in low light conditions. For example, the installation of appropriate lighting systems can support early operations at dawn, ensuring effective implementation of activities.

Our results show that other simple adaptation measures such as increasing the frequency of breaks and providing shaded areas are also effective in protecting workers from heat and reducing production losses according to the land managers. Shade areas are understood to be groves and hedges or mobile shade structures such as canopy shelters. Despite the benefits of these measures, they represent an economic cost that could be significantly higher than the anticipation of the working time because workers are paid even during breaks and because setting up shade zones requires some investments for farms.

Lastly, the least effective measure for managers is special equipment (ventilated jackets and clothing in technical, breathable fabric) because, beside its cost, it is expected to be hardly acceptable by workers. Measures such as the use of special equipment may be rejected if they are considered inconvenient or unnecessarily complex. For this reason, whatever the measure, it is essential to involve workers in the decision-making process and to gather their feedback in order to identify the most practical and valued solutions.

The limitations of this study lie in its focus on data from a limited geographic area within Italy. However, the selection of large farm cooperatives with strong attention towards working conditions and safety allowed to collect the perception of adaptation measures and their effectiveness in farms with relevant awareness of the problem. This sampling approach may have introduced a bias linked to the farms' greater capacity to implement adaptation strategies. Consequently, the findings reflect a localized perspective that may not be representative of the views of entrepreneurs at the national level or in other parts of the world. Significant differences could emerge if the research were conducted nationwide or expanded to include a broader range of Italian regions and farm types. Additionally, the CR of 0.2 points to some cognitive stress. This could be due to the small sample size or respondents' lack of experience with such specific questions on heat waves and adaptation measures. This might have caused difficulties in fully understanding and evaluating the question, affecting the consistency of their responses.

5. CONCLUSIONS

This study presents an overview of how land managers perceive the impacts of heat waves on agricultural workers and assesses the perceived effectiveness of various adaptation measures. The research is based on empirical data collected from nine farms in Emilia-Romagna, each demonstrating a long-standing commitment to improving working conditions and mitigating heat-related risks in agricultural operations.

Although the sample size limits the statistical generalizability, our results offer valuable insights to inform future policy interventions. One key recommendation emerging from the study is the potential introduction of targeted incentives to support the adoption of adaptation practices that entail additional costs for farms. Such incentives could be designed to provide economic support for more resource-intensive but highly effective measures, such as installing shading infrastructure or rescheduling work to nocturnal hours.

Another crucial aspect relates to institutional collaboration in developing early warning systems and heat alert tools. These tools could serve both farms and regulatory bodies as a reliable reference for determining the timing and geographic location for the applicability of mandatory or recommended heat adaptation actions.

The findings confirm that heat waves have a significant impact on business operations and reduce labor productivity, particularly in open-field tasks such as fruit harvesting. The selected adaptation strategies, many of which are low-cost and easy to implement, provide effective ways to reduce productivity losses and enhance worker protection. Among the most effective measures identified are adjusting work schedules to earlier hours and increasing the frequency of breaks with access to potable water. These actions were recognized as widely applicable, simple to implement, and well-accepted by both managers and workers.

Beyond improving worker safety and reducing the risk of heat-related accidents, certain adaptation measures can generate operational benefits. For instance, shifting working hours not only reduces exposure to peak temperatures but may also improve the quality of harvest, particularly in sectors such as fruit cultivation.

A crucial aspect is the ease of implementation and high acceptance of many adaptation strategies. This enhances their feasibility and potential for widespread adoption. Because these measures typically do not require complex organizational changes or significant financial resources, they represent a practical starting point for improving heat adaptation of the agricultural sector.

In conclusion, the study underscores the dual benefits of adaptation strategies: they contribute both to worker well-being and to the operational efficiency of farms. By reducing the incidence of heat-related accidents and minimizing inefficiencies due to loss of labour productivity, targeted adaptation measures can serve as a foundation for sustainable and inclusive agricultural policy under conditions of increasing climate stress.

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Factors influencing land rental market participation: A case study in Northern Ireland

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Abstract. Agricultural land mobility through an efficient land rental market has been shown to contribute to the productive and sustainable utilisation of land, by facilitating the transfer of land from less productive farmers to more productive farmers. However, this is not the case in Northern Ireland where the sale of agricultural land is limited with a constrained tenanted sector. The objective of this study is to analyse the factors influencing participation in the land rental market in Northern Ireland. To achieve our objective, data from 1466 farmland owners was analysed using principal component analysis (PCA) and multinomial logistic regression model. The results show that land rental market participation is impacted by motivational and socioeconomic factors. The study recommends the development of schemes that support the early and comfortable retirement of older farmers to increase the access of young farmers to land and improve the land rental market.

Keywords: land, rental market, sustainability, conacre, multinomial logit model.

1. INTRODUCTION

Agricultural land mobility has been shown to contribute to the productive and effective utilisation of land as a resource by facilitating the transfer of land from less productive farmers to more productive farmers (Bradfield et al., 2020; Deininger & Jin, 2008; Li et al., 2020; Tesfay, 2023). This can be achieved through an efficient land rental market, playing an important role in shaping farmers' land-use decisions and supporting sustainable agricultural production (Min et al., 2017; Udimal, Peng, & Guillaume, 2021). A previous study in Poland by Marks-Bielska (2021) has shown that with stable long-term agreements, farming on leased land is comparable to farming on owned land as long as the rights of the lessor and a lessee are protected.

Land mobility is a significant issue in Northern Ireland (NI) as historically there have always been strong sentimental and cultural ties to land (Adenuga et al., 2023; Bradfield et al., 2023a). The majority of farming in the region is undertaken on owned land and the transfer of land through sale is limited due to high land sales prices. For example, the price of agricultural land in NI

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ranges between £11,500 and £20,000 per acre and less than one percent of the total agricultural land area is offered for sale each year (Harris, 2022). This is reflected in the high proportion of farming undertaken on owned land compared to what occurs in other countries. Owned land as a percentage of farmed area in NI is 72% which in relative terms is high compared to other countries such as France and Germany where the proportion is 38% and 39% respectively and at the EU level, which is 48% (Adenuga et al., 2021; DAERA, 2023a; Eurostat, 2022). This makes the purchase of land for agricultural production in NI less optimal (Adenuga et al. 2021). This is because land ownership requires significant capital investment, and further purchases may not be financially optimal when alternative arrangements, such as renting, provide operational flexibility without the long-term financial burden of land acquisition. Additionally, owning a large proportion of land may indicate that a farmer's operational needs are already met, reducing the necessity for further expansion through purchase. In addition, the average agricultural land area in the region can be regarded as small relative to the other regions of the UK and has become highly fragmented with increased concentration and competition for use among active and intending farmers (Adenuga et al., 2023; Milne et al., 2022). The low level of land mobility, and high fragmentation have a consequential effect on the overall competitiveness and productivity of the NI agri-food sector. This potentially constrains opportunities for new entrant farmers to access land (Milne et al., 2022).

Access to land through the rental market provides an avenue for farmers and aspiring farmers to access land and increase their competitiveness since it requires less capital outlay (Adenuga et al., 2021; Bradfield et al., 2020; Jin & Deininger, 2009). With solid legal regulation, the land rental market can be regarded as a rational land management strategy (Marks-Bielska, 2013). Compared to the sale of land, it offers greater flexibility, with an opportunity to design contractual terms to suit both the lessor and the lessee (Zhang et al., 2018) It allows farmers to alter farm size, exploit economies of scale, increase operation as well as technical efficiency, and capture technological advances to achieve an optimal level of production (Bradfield et al., 2021; Bradfield et al., 2020; Geoghegan et al., 2021; Li et al., 2020; Zou & Luo, 2018). In addition, the land rental market makes it possible for rural households to generate additional income from their land (Lan Zhang et al., 2018; Zou et al., 2020). An efficient and fully functional land rental market that supports optimal allocation and transfer of land is therefore necessary to bring land to its most productive use and provide opportunities to transform the rural economies and improve the welfare of rural households (Bradfield et al., 2020; De Janvry et al., 2001; Huy, Lyne, Ratna, & Nuthall, 2016; Jin & Deininger, 2009). For example, a study by Bradfield et al. (2020) for dairy farmers in Ireland, showed that farms that rent land generated a higher net margin than farms with no rented land. The study also showed that increased access to land through the land rental market enhanced farming households' succession plans.

Given the high cost and limited access to the sale of land in NI, an efficient land rental market provides an avenue for farmers in the region to increase their farmland area. This is particularly important given the shift towards sustainable farming with agricultural support policies now targeted at environment-based payments (Adenuga et al., 2023; Little et al., 2023). In addition, it can also provide pathways for accessing agricultural land for those who may otherwise have very limited access, for example, young or new-entrant farmers (Abay et al., 2021). This will be vital for farmers to meet their environmental commitments. This paper sought to examine the determinants of participation in land rental markets in NI as a mechanism to improve access to land. To achieve our objective, we empirically analysed the motivational and socioeconomic factors influencing land rental market participation in NI. To the best of our knowledge, this study provides the first insights into the complex motivations and behavioural factors underlying farmers' decisions to participate in the land rental market. While these motivations may also apply to farming in general, understanding, how they influence farmers' land rental decisions is essential to improving the land market. A previous study in Ireland by Geoghegan et al. (2021) show that attitudinal factors are a significant predictor of openness to land mobility, both on the supply and demand side of the market This study employs the multinomial logistic regression model which allows us to consider not just farmers who rent-in and rent-out land but also those who neither rent-out nor rent-in land. A previous study by Udimal et al. (2021) also employed a similar approach. However, they did not consider motivational factors that could influence participation in the land rental market. It remains unclear how the different farmers' motivations and behavioural factors influence their decision to participate in the land rental market. Results from this study will be useful in providing the requisite evidence base to inform the formulation of policies aimed at encouraging farmers and landowners to engage in the land rental market.

2. RESEARCH METHODOLOGY

In this study, we employed the multinomial logit (MNL) model to analyse the motivational and socioeconomic factors influencing land rental market participation in NI. Farms in NI are typically family-owned with a small, tenanted sector compared to other regions of the United Kingdom. By making use of a couple of attitudinal statements, we derived different farming motivations of farmers using principal component analysis (PCA).

2.1. Data collection

The dataset used in this study was obtained from a cross-sectional survey of farmers in NI. The sampling frame was the farm census data for NI which consisted of 12 747 farmers for the year 2020 from which we selected 4029 farmers using a stratified random sampling technique. The farmers were classified into six strata based on farmland ownership and rental status: those farming solely on owned land, those farming both on owned and rented land, those farming on owned and rented land while also leasing out land, those farming only on owned but also leasing out land, those farming exclusively on rented land and landowners who lease out all their land. Due to the large number of farmers in the "owned land only" and "owned and rented land" groups, we randomly selected 20% of farmers from these two groups. A well-structured questionnaire was developed after a comprehensive literature review and key informant interviews (Adenuga et al., 2021). The questionnaire was organised around some themes. This includes land ownership and rental status and duration, socioeconomic as well as farmers' attitudinal characteristics. The questionnaire was developed in a hybrid format, making it possible to be completed online and on paper. The Snap survey software was used to design the online version of the questionnaire with a QR code that was generated and placed on the front page of the paper version of the questionnaire. Respondents either completed the paper questionnaire directly or scanned the QR code with their phone to complete it online. The survey took place between December 2021 and February 2022. We sent two reminders over this period with the QR code included in the letters and the respondents could request a paper copy of the questionnaire if they require a new one. No personally identifiable information was collected, and farmers were assured of their anonymity in reports or publications resulting from the project. To encourage the farmers to complete the questionnaire, each completed and returned questionnaire was entered into a prize draw for 1 of 10 £100 e-vouchers. This was for farmers who had indicated their intention to participate in the draw. Out of the 4029 questionnaires administered, 1228 paper questionnaires were returned in the pre-paid envelopes sent alongside the questionnaire while 499 questionnaires were completed online. In total, we received 1727 responses. This number was reduced to 1466 following the dropping of 91 farmers who both rented out and rented in land, and farmers with no information relating on land ownership or rentals. Table 1 gives a summary of the socioeconomic characteristics of the farmers. Some of the variables do not add up to 1,466 because some of the farmers did not fully complete the questionnaire, omitting some questions.

2.2. Empirical model

The land rental market participation is modeled based on the random utility theory (Udimal et al., 2021). The theory assumes that each farmer i has different options ($k = 1,2,3 \ldots K$) available to them and they chose a particular option (y) that offers the maximum utility by considering the economic and environmental risk associated with the various options (Diriye et al., 2022; Grant et al., 2019; McFadden, 1972). To analyse the factors influencing land rental market participation in this study, we employed the multinomial logit model (MNL)(Daly, 1987; Gensch & Recker, 1979). The MNL model has been used extensively in the literature to analyse farmers' behaviour and choices in decision-making (Diriye et al., 2022; Duressa, 2021; Otieno, 2022; Ouattara et al., 2022). The model, unlike the bivariate Tobit model employed in previous studies, for example, the study by Rahman (2010), can accommodate the non-binary, multivariate nature of the dependent variable (Dang & Pham, 2022; Osanya et al., 2020; Yasmin et al., 2022). Previous studies have also shown that the MNL model performs better than the multinomial probit model (MNP) (Dow & Endersby, 2004). Besides, the MNL model possesses fewer computational problems compared to MNP because the probit likelihood function is often flat near its optimum and it generally requires numerical approximation for the multivariate integrals(Dow & Endersby, 2004). It is also not prone to optimization errors. Although it should be acknowledged that MNL model relies on the Independence of Irrelevant Alternatives (IIA) assumption, which requires that the relative probabilities of choosing between any two alternatives remain unchanged when other alternatives are introduced or removed. In this study, certain alternatives, such as the sale and purchase of agricultural land, were excluded due to the thin market for land transactions, as discussed in the introduction. While these alternatives may theoretically exist, their practical relevance is limited in this context. Nevertheless, we assess the validity of the IIA assumption and the results indicate that the exclusion of these alternatives does not significantly influence our findings.

Generally, our choice of a multivariate dependent variable is based on the need to capture the multiple dimensions of farmers' land rental behaviour within a single model framework which allows us to identify distinct factors influencing each dimension simultaneously. It should also be acknowledged however that our use of the MNL model means we are not modelling the actual amount of land rented-in or rented-out which could provide additional insight. The choice of our model is in line with the objective of this paper which was mainly to identify factors influencing farmers' land rental behaviour. In this study, it is assumed that a farmer can choose from any of three alternatives. That is rent-out land; rent-in land and neither rent-in nor rent-out land. The observed outcome, Y_{ik}as a function of the variables X_{ik} is presented in equation (1).

$$Y_{ik} = X_{ik}\beta_k + \varepsilon_{ik} \tag{1}$$

Where X is a vector of explanatory variables which include motivational and farmer-specific socioeconomic characteristics that are hypothesised to influence land rental market participation, β represents the parameters to be estimated and ε is the error term or random component of the model and it is assumed to be independently and identically distributed (Diriye et al., 2022). The choice probability of the i_{th} farmer in choosing option k from the list of K options following Mellon-Bedi et al. (2020) is presented in equation 2.

$$(Y_i = k|X) = \frac{exp(\beta_k X_i)}{1+\sum_{j=2}^{K} exp(\beta_j X_i)},\ for\ k > 1 \tag{2}$$

In estimating the model, one of the categories was normalised by equating it to one (equation 3). In our analysis, we used neither renting-out nor renting-in land category as the baseline such that only two equations are estimated. The probability of renting out and renting in land is compared to the probability of neither renting in nor renting out land.

$$P(Y_i = 1) = \frac{1}{1+\sum_{j=2}^{K} exp(\beta_j X_i)},\ for\ k = 1 \tag{3}$$

Based on this parameterisation, the *j*th element of the vector β_k is interpreted as the increase in the log-odds ratio of the *k*th category relative to the reference category holding the other explanatory variables constant to their mean values (Carpita et al., 2014). $Y_i$is the dependent variable representing farmers that rent out and rent in land in the two models respectively. The variables hypothesised to influence participation in the land rental market include the age of the farmer measured in years, membership of a business development group (BDG) measured as a dummy variable, having a diversification enterprise (this refers to owning a diversification enterprise on the farm) measured as a dummy variable, off-farm employment (defined as income earned outside of the farm by the primary decision-maker and may include spousal income, which could influence household labour availability and financial stability) measured as a dummy variable, identification of a successor measured as a dummy variable, the enterprise type of the farmer (dairy, beef sheep and others which include arable and horticulture enterprises), area of farmland owned measured in hectares, level of agricultural qualification measured as a dummy variable, level of formal education, time commitment to farming (full-time or part-time) and land type (land classification based on their agricultural conditions as lowland, disadvantage or severely disadvantaged). These variables were obtained from the literature and are considered important factors likely to influence land market participation (Adenuga et al., 2021, 2023; Bradfield et al., 2020; Che, 2016; Zou et al., 2020). The descriptive statistics of the variables are presented in Table 1.

To incorporate the motivational factors into our analysis, principal component analysis (PCA) was employed. The PCA is a statistical technique that examines the pattern of correlations amongst the explanatory variables and creates a smaller set of uncorrelated linear combinations of the original variables (Lapple & Kelley, 2010; O'Kane et al., 2017). The higher a respondent's score on each of the factor variables, the higher their associated level of agreement with the specific attitudinal component (Howley, 2015; O'Kane et al., 2017). The analytical technique was used to reduce sixteen attitudinal statements which represent varying motivations of farmers into four components. The statements included in our principal component analysis were obtained from a comprehensive review of related literature on farmers' behaviour (Adenuga et al., 2023; Howley, 2015; Howley et al., 2015). We used the promax rotation to facilitate the interpretation of the components. As is the usual practice, components with an Eigenvalue of at least one were retained (O'Kane et al., 2017). We retained statements with loadings greater or equal to 0.3 on their target factor. Statements that did not load greater or equal to 0.3 on any component were dropped. The four motivational components obtained from the PCA include Principal Components (PC) 1 which shows high loadings for items relating to efficient farm management and technology adoption and was termed "progressive construct", PC2 loads highly on statements that do not support pro-environmental behaviour such as "I am not that concerned about environmental issues" and was termed "environmental apathy" construct, PC3 which loads on the statements that prioritise the protection of the environment was termed "pro-environmental construct" and PC4 which loads highly on statements that relate to being risk averse and was termed "risk averse" construct. Two statements that did not align with any of the four components were dropped. The internal consistency of each component was assessed using Cronbach's alpha coefficient which ranged between 0.60 and 0.68, showing good reliability. With a Kaiser–Meyer–Olkin measure of sampling adequacy of 0.75, the components represent a significant proportion of the variance in the data (Läpple & Kelley, 2013). The results of the PCA analysis are presented in Table A1 in the appendix. The STATA spost13 post-estimation command was employed to allow the coefficients of the MNL model to be interpreted in terms of the percentage change in odds for a unit change in the explanatory variable (Long & Freese, 2005).

3. RESULTS AND DISCUSSION

3.1. Descriptive and socioeconomic characteristics

Table 1 gives an overview of the socioeconomic and farm characteristics of the respondents. Similar to the general farming population in Northern Ireland, about 90% of the farmers in our sample are livestock farmers (DAERA, 2023b). Our analysis showed that more than half (55%) of the farmers undertake their farming activities in land categorised as either disadvantaged (DA) or severely disadvantaged areas (SDA). The SDA or DA (less favoured areas (LFA)) land types refers to land located in parts of the country which, because of their relatively poor agricultural conditions, have been so designated under EU legislation(Caskie et al., 2001; DAERA, 2023b). The majority of respondents are male (91.5%) and 75% of respondents are married. Thirty-two percent of the farmers stated that they had no general education qualifications. Based on land rental participation status, about 45% of those who rent out land have a diploma or degree level education while it is 35%, of those who rent in land. In terms of agricultural qualification, 33% of the farmers stated that they have formal agricultural qualifications. The value is higher for those that rent in land with 40% of them stating that they have a formal agricultural qualification. Only 30% of those who rent out land stated that they have formal agricultural qualifications, and it is 33% for those who neither rent in nor rent out land. For 37.9% of respondents, farming was on a full-time basis (these are farmers who work, at least on average, 38.0 hours per week on the farm). Twenty-six percent of sheep farmers surveyed reported that they were farming full-time. Ninety-eight percent of the farms are family farms held either as sole ownership or partnership. The average years of farming experience is 35 years and 55% of the farmers stated that they have off-farm employment. The proportion of farmers with off-farm employment that rent in land was 61% while it was 47% for those that rent out land and 55% for those that neither rent in nor rent out land. Only 13% of the farmers are members of the Business Development Groups (BDGs). Nineteen percent of those who rent in land were in the BDG group compared to just 9% for those who rent out land and those who neither rent in nor rent out land. The BDGs is a knowledge transfer scheme developed by the Northern Ireland College of Agriculture, Food and Rural Enterprise (CAFRE) in March 2016. The scheme employs a group approach aimed at improving the performance of farm businesses through facilitated 'peer-to-peer' learning to encourage the fostering of knowledge capital and knowledge exchange between actors (Jack et al., 2020). Forty percent of the farmers stated that a successor to the farm has been identified. This was 34% among those who rent out land, 41% among those who rent in land, and 42% among those who neither rent out nor rent in land. The modal age group was 55 to 64 years and 68% of the farmers are aged over 55 years. Based on land rental market participation, as much as 83% of those who rent out land are older than 55 years, while it is 44% of those who rent in land and 66% of those who neither rent in nor rent out land. This is an indication that those who rent out land are older and more likely to include retired farmers. The average amount of cultivated land owned is 36 hectares. The value is 43 hectares for those that rent in land, 37 hectares for those that rent out land, and 28 hectares for those that neither rent in nor rent out land.

3.2. Land market participation

The results of our analysis in terms of land rental characteristics showed a relatively even distribution among the three categories of farmers. We found that 31% of the farmers farmed on owned land only (i.e., neither rent in nor rent out land) while 37% and 31% of the farmers rented in and rented out land respectively. Table 2 provides an overview of how land is rented in and rented out in conacre and on long-term lease. The conacre is the predominant form of land rental system in the region. It is a traditional short-term land rental system unique to the island of Ireland in which land is let to a

Table 1. Socioeconomic characteristics of respondents.

Variables	Frequency	Percentage (%)
Time commitment (n= 1354)		
Full-time	513	37.9
Part-time	841	62.1
Land types (n = 1351)		
Lowland	608	45.0
Disadvantaged	428	31.7
Severely Disadvantaged	315	23.3
Diversification activities (n=1466)		
Yes	258	17.6
No	1,208	82.4
Identification of successor (n=1347)		
A successor has been identified	536	39.8
Successor not yet identified	811	60.2
BDG membership (n = 1466)		
Yes	192	13.1
No	1,274	86.9
Age of the farmer (n = 1466)		
Less than 30	49	3.3
30-40	118	8.05
41-54	303	20.7
55-64	400	27.3
65-74	358	24.4
75 or older	238	16.2
Education of the farmer (n=1466)		
No formal qualification	471	32.1
Less than 5 GCSEs	136	9.3
5 GCSEs or equivalent	219	14.9
A level or equivalent	97	6.6
Higher education - diploma or equivalent	242	16.5
Degree level or higher	301	20.5
Agricultural qualifications (n=1447)		
No formal agricultural qualification	963	66.6
National Diploma NVQ Level 2 or equivalent	171	11.8
National Diploma NVQ Level 3 or equivalent	101	6.9
HND Level or equivalent (just below degree level)	74	5.1
Degree level or equivalent	68	4.7
Others	70	4.8
Off farm employment (n=1466)		
Yes	808	55.1
No	658	44.8

Source: own elaboration.

farmer nominally for 11 months or 364 days without the need for either party to enter a long-term commitment. Specifically, 91% and 78% of the land that is rented out and rented in respectively are in conacre (Adenuga, Jack, & McCarry, 2023). While the duration for renting land in conacre is 11 months or 364 days, the arrangement between the landlord and the tenant is such that it can be rolled over for several years with no formal contract signed. For example, as shown in Table 2, among landlords renting out and farmers renting in land, it can be observed that 48% and 67% have been rented out and rented in respectively for more than 10 years. The long-term lease refers to a land rental arrangement in which a formal contract has been signed between the landlord and the tenant. This proportion of long-term leases among landowners and farmers in NI is still relatively small with a higher proportion on 5-year leases as shown in Table 2.

As presented in Table 3, we also analysed the land market participation characteristics of the respondents based on enterprise types. The results show that renting in land was more common among dairy farmers compared to other enterprise types with 79% of the dairy farmers renting in land, in addition to farming on owned land. Only 5.5% rented out land. This may reflect the intensive nature of dairy farming in Northern Ireland (Adenuga et al., 2020). It also may have been driven by the relatively higher incomes of dairy farms and their ability to pay higher rents. This is evidenced by the high percentage (84%) of dairy farmers who undertake farming on a full-time basis. Although the majority (84%) of the land rented in was in conacre rather than long-term leases.

3.3. Results of econometric analysis

The results of the parameter estimates resulting from the MNL model are presented in Table 3. The likelihood ratio chi-square of 366.61 with a p-value < 0.0001 indicates that the model fits well. A test for The Independence of Irrelevant Alternatives (IIA)showed that it was not violated. Like other categorical response models, the interpretation of the MNL model is complex because of its nonlinearity. To interpret our MNL model, we have employed the Long and Freese (2006) SPost13 command, listcoef which can provide a single table of the estimates for all the comparisons of outcome categories for each variable included in the model. The coefficients are interpreted in terms of the standardized or percentage change in odds for a unit change in the explanatory variable holding all other variables constant (Howley et al., 2015; Long & Freese, 2006).

The results show that motivational and socioeconomic factors influence the likelihood of land rental market participation. In total, fourteen explanatory variables were statistically significant for factors influencing the decision

Table 2. Land rental system and duration of rental.

Land Rental Characteristics	Renting out land		Renting in land	
	Frequency	Percentage (%)	Frequency	Percentage (%)
Ways by which land is rented				
Conacre	422	91.1	426	78.0
A long-term lease	22	4.8	66	12.1
A combination of conacre and long-term lease	19	4.1	54	9.9
Duration of Conacre (years)				
Less than 3	40	9.1	34	7.1
3	413	9.3	17	3.5
4	25	5.7	11	2.3
5	34	7.7	28	5.8
More than 5 but less than 10	88	20.0	68	14.2
10 or more years	212	48.2	322	67.1
Duration of long-term lease				
Less than 3	2	4.9	9	7.5
3	2	4.9	8	6.7
4	1	2.4	0	0
5	20	48.8	42	35.0
More than 5 but less than 10	5	12.2	15	12.5
10 or more years	11	26.8	46	38.3

Table 3. Land rental characteristics by enterprise type.

Enterprises	Frequency	Percentage	Rent out land (%)	Rent in land (%)	Neither rent out nor rent in land (%)	Proportion that are full-time farmers (%)
Beef suckler	409	32.2	18.3	43.3	38.4	36.3
Beef finishing	316	24.9	25.0	39.9	35.1	35.4
Sheep	306	24.1	29.1	35.3	35.6	25.8
Dairy	110	8.7	5.5	79.1	15.5	83.6
Arable	81	6.4	49.4	27.2	23.5	43.2
Poultry	30	2.4	33.3	23.3	43.3	66.7
Horticulture	13	1.0	61.5	23.1	15.4	38.5
Pig	5	0.3	20.0	60.0	20.0	80.0

Source: own elaboration.

to rent out, land. For the factors influencing the decision to rent in, land, we found seven explanatory variables to be statistically significant compared to the baseline (the decision to neither rent in nor rent out land). We found the progressive construct variable to be a statistically significant factor ($p < 0.05$) for the decision to rent out and rent in land. In specific terms, one standard deviation increase in the progressive orientation factor decreases the odds of renting out, land for the average farmer by 15.9%. On the other hand, a standard deviation increase in the progressive orientation factor increases the odds of renting in, land by 18.6%. This implies that farmers, with a progressive and positive mindset and the motivation to maximise profit, have a lesser tendency to rent out land compared to the baseline and are more likely to rent in land. This is understandable as more land is often required to take advantage of economies of scale, adopt new technology, and increase farm incomes (Huy et al., 2016; Geoghegan et al., 2021). The pro-environment factor was found to have a positive relationship with renting out land, but it was not statistically significant. It was however statistically significant and negatively related to renting-in land. A standard deviation increase in the pro-environment factor reduces the odds of renting in, land by 13.5%. The negative relationship between pro-environmental behaviour and renting in, land may be linked to the predominantly short-term conacre land rental system predominant in NI. This is because environmentally friendly agricultural practices often require long-term investments in soil health and this is difficult to achieve on short-term land rentals without adequate tenure security. Besides, farmers with pro-environmental behaviour may avoid renting additional land to retain effective control of their land in line with their values of ensuring proper stewardship of the land.

In terms of the socioeconomic characteristics, we found the enterprise type and the time commitment to farming to be statistically significant factors in both the decision to rent out and rent in land but with opposite signs. Specifically, farms that are classified as dairy, beef or sheep enterprises are less likely to rent out land and more likely to rent in relative to the baseline enterprises of arable, horticulture, poultry, and pig farms which were categorised as “others”. Having a dairy, beef or sheep enterprise reduces the odds of renting out land by 75%, 63% and 46% respectively and increases the odds of renting in land by 378%, 68% and 28% respectively. This reflects the intensive nature of land usage in livestock production in NI relative to other enterprises with about 79% of the total farmed area used for livestock production (DAERA, 2023a).On the other hand, the age of the farmer, land type, identification of a successor, the education of the farmer, the area of land owned, and land type were found to be a statistically significant factors influencing the decision to rent out land. Membership of the BDG and access to off-farm income were found to be statistically significant factor influencing the decision to rent in land.

The identification of a successor reduces the odds of renting out land by 37% relative to the baseline. With a successor already identified, farmers would rather keep their land to themselves to keep the successor on the farm rather than renting out land. A previous study by Bradfield et al. (2020) has also shown that with a successor identified, farmers are more likely to keep their land and instead rent in land to provide the successor with immediate employment and skill development. Similarly, study by Daniele (2024) has shown that the identification of a successor in a farming household significantly influences farmers’ strategic choices. Farmers with higher education are more likely to rent out land. A standard deviation increase in degree level or higher education increases the odds of renting out land relative to the baseline by 34%. This may imply that farmers who are highly educated may be spending less time in direct farming activities. This is because higher education tends to increase the opportunity cost of farming due to the increased potential of securing higher-paying jobs outside agriculture. Consequently, these farmers may choose to rent out their land instead of farming it themselves. This connection between education and land rental decisions reflects broader economic trends where higher education leads to more diverse career options, thereby influencing land use choices. This result corresponds to that obtained by Rahman (2010), Bizimana (2011), and Zhang et al. (2022) in which they found that farmers with higher levels of education are more likely to rent out land. The result is however in contrast to that obtained by Tesfay (2023) in which they found that the less educated farmers are more likely to rent out their land.

Our result also showed that farmers older than 55 years are more likely to rent out land. These are farmers who may be approaching retirement and probably do not have a successor. Such farmers will be better off renting out part of their land for additional income. This result corresponds to that obtained by Tesfay (2023) and Min et al. (2017) in which they found older farmers to be more likely to rent out land. The result is also in line with that obtained by Mellon-Bedi et al. (2020) in their study of smallholder participation in the land rental market in China in which they found that households with a higher share of older people were more likely to participate in the land rental market, It is however in contrast to that obtained by Zhang et al. (2022) who found that aged farmers participate less in renting out land. Our result also shows that farmers who own larger farm areas are more likely to rent out land. One standard deviation increase in owned land area increases the odds of renting out land by 34% relative to the baseline. A similar result was obtained by Vranken and Swinnen (2006) in which they found farming households who own more land to be more likely to rent out land. Farmers that farm in lands categorised as disadvantaged or severely disadvantaged are less likely to rent out land compared to farming on low land relative to the baseline. This may be because most of the farmers that farm on disadvantaged and severely disadvantaged lands are small beef and sheep farmers who undertake farming usually on a part-time bases. For this group, farming is mostly to keep the family enterprise with a greater attachment to the land. As a result, they are less likely to rent out their land.

The result for the factors influencing the decision to rent in land showed that farmers with off-farm income have a positive and statistically significant ($p < 0.01$) effect on the decision to rent in land. This may imply that the farming households with off-farm income have enough money to invest in and expand their farm-

Table 4. Determinants of land market participation (N= 1,121).

Variables	Rent-out land				Rent-in land			
	Coef.	Std. Err.	%	%StdX	Coef.	Std. Err.	%	%StdX
Environmental- apathy	0.029	0.052	2.9	4.7	-0.035	0.047	-3.5	-5.6
Risk-averse	0.117	0.080	12.4	13.5	0.051	0.068	5.2	5.6
Pro-environment	0.079	0.078	8.2	9.3	-0.128*	0.071	-12.0	-13.5
Progressives	-0.104**	0.052	-9.9	-15.9	0.103**	0.049	10.8	18.6
BDG membership	0.187	0.267	20.5	7.0	0.611***	0.223	84.1	24.6
Off-farm income	-0.149	0.195	-13.8	-7.1	0.484***	0.185	62.3	27.3
Successor	-0.466***	0.175	-37.3	-20.5	-0.095	0.159	-9.1	-4.6
Dairy enterprise	-1.376***	0.534	-74.7	-32.9	1.566***	0.375	378.8	57.5
Beef enterprise	-0.989***	0.231	-62.8	-38.9	0.520**	0.264	68.2	29.6
Sheep enterprise	-0.609**	0.259	-45.6	-22.1	0.250	0.296	28.4	10.8
Owned land area (ha)	0.006***	0.002	0.6	33.5	0.003	0.002	0.3	17.7
Agricultural qualification	0.251	0.210	28.5	12.7	0.021	0.195	2.2	1.0
Lower than 5 GCSEs	-0.590*	0.348	-44.6	-15.5	-0.266	0.276	-23.3	-7.3
5 GCSEs or equivalent	0.070	0.273	7.3	2.6	-0.206	0.238	-18.7	-7.2
A level or equivalent	0.758**	0.352	113.5	21.0	0.251	0.345	28.5	6.5
Higher education—diploma or equivalent	0.540*	0.283	71.6	22.7	0.126	0.263	13.4	4.9
Degree level or higher	0.724***	0.253	106.3	33.6	-0.260	0.258	-22.9	-9.9
Full-time	-0.402*	0.206	-33.1	-17.9	0.804***	0.184	123.4	48.4
Age (greater than 55)	1.142***	0.225	213.2	70.6	0.003	0.191	0.3	0.1
Disadvantaged	-0.656***	0.189	-48.1	-26.4	-0.191	0.180	-17.4	-8.5
Severely Disadvantaged	-0.984***	0.231	-62.6	-33.8	-0.159	0.194	-14.7	-6.5

Source: own elaboration.
Note: % is the percent change in odds for unit increase in our explanatory variable; %StdX is the percent change in odds for a standard deviation change in our explanatory variable; single, double, and triple asterisks (*, **, ***) indicate significance at the 10%, 5%, and 1% level, respectively.

ing activities compared to households with no off-farm income. A previous study by Zou et al. (2020) has also found that farmers with part-time, off-farm employment have a greater likelihood of renting in, land. Similar result was obtained by Geoghegan et al. (2021). However, the studies by Vranken and Swinnen (2006) and Kung (2002) found a contrasting result as they showed that greater availability of off-farm income reduces the probability of renting in land. One possible explanation for the contrasting result is that off-farm income, as defined in this study, may include spousal income. If this is the case, the variable may also serve as a proxy for household labour availability, as married farmers may have additional family members contributing to farm work. This increased labour capacity could, in turn, make land expansion through rental agreements more viable. Farmers who are members of the BDGs are also more likely to rent in, land. A previous study by Adenuga, Jack, Ashfield, et al. (2021) has shown that farmers who are members of the BDG operate a more profitable enterprise. Their higher profitability and access to information through membership of the BDG may contribute to the decision to rent in, more land and earn more income from farming. Similarly, farmers who undertake farming on a full-time basis are more likely to rent in, land compared to the baseline. This may be linked to the assumption that farmers who undertake farming on a full-time basis are more likely to increase their farm size by renting more land.

4. CONCLUSIONS

In this paper, the effect of motivational and socio-economic factors on farmers' participation in the land rental market has been analysed using a multinomial MNL model. The use of the MNL model allows for greater flexibility as it is able to incorporate not just the demand side but also the supply side of participation and non-participation in the land rental market simultaneously. An efficient land rental market is essential to increase the efficiency and sustainability of agricultural production through greater access of young and productive farmers to land. Our results showed that participation in the land rental market is not only influenced by socioeconomic factors but also motivational factors. Most land rentals in NI are still on short-term leases called conacre with a majority of the farmers undertaking farming on owned land. From a policy perspective, it implies that the development of appropriate strategies to encourage land market participation can contribute to the transformation of the rural economy through efficient land use. The enterprise type of the farmer, the identification of a successor and the amount of time devoted to farming are particularly significant factors in the decision to participate in the land rental market. While the result shows that farmers with successors are less likely to rent out land, only 40% of the farmers in our sample already have a successor identified. Policies that support succession planning and the transfer of sustainable practices could help maintain the viability of farms in disadvantage areas while programmes that facilitate the transfer of land from farmers without successors to younger and more productive farmers will strengthen the rental market. Our results showed that older farmers are also more likely to rent out their land compared to younger farmers.. The study recommends the development of policies that encourage the younger generation to engage in farming on a full-time basis through schemes that allow for early and comfortable retirement of the older farmers who are happy to make their land available for rent. An example is the NI land mobility scheme which although has now been replaced with a new scheme (farming for future generations) gave young farmers the opportunity to partner with retiree farmers. This allowed young farmers to learn their trade from those hoping to retire and prove themselves with the eventual aim that they will be able to take over and lease the land in a few years. This is essential to promote generational renewal and the modernisation of agriculture for environmental improvements.

Another important result of this study is the negative relationship between pro-environmental behaviour and renting in, land. While this may be linked to the fact that sustainable agricultural practices often require long-term investment in land, an alternative explanation is that more intensive farming systems, which tend to generate higher profits, create a greater demand for rented land. This is supported by our data in Table 3, which shows that dairy farmers, who typically engage in more intensive production, rent the most land. These factors highlight the complex relationship between environmental practices and land rental decisions. This supports the need for policymakers to develop measures aimed at encouraging the adoption of long-term land leasing which provides the tenure security needed to invest in sustainable practices. This could incentivise farmers with pro-environmental behaviour to rent in, land, improving land quality and protecting the environment. Financial incentives could also be provided to landowners to rent to less intensive tenants. A previous study by Adenuga et al. (2023) has shown that incentives such as income tax incentives to landlords and tenants for sustainable management of agricultural land could encourage long-term land leasing and increase the likelihood of farmers with pro-environmental behaviour renting in more land. This will enhance long-term productivity and improve the efficiency of land use by allowing more diverse and sustainable practices.

Our finding that progressive farmers are less likely to rent out land and more likely to rent in land also has important policy implications. By developing a policy framework that encourages the renting of more land by progressive farmers, land will be put to more effective and productive use, leading to a more functional land market. This can be achieved if the government enacts policies that promote long-term flexible arrangements and encourage landowners to lease out their land to more productive farmers if they are not being used efficiently. The creation of an enabling environment that allows progressive farmers to rent in more land will contribute to a more dynamic and competitive land market

The fact the majority of the land in the region is located in disadvantaged areas has implications for the rental market with most farmland being fragmented. This supports the need to encourage pro-environmental practices that ensure long-term stewardship of the land. There is also the need to provide targeted financial incentives and infrastructure to make the renting of the land more attractive. A previous study by Onofri et al. (2023) also supports the need to provide incentives (tax incentives and subsidies), to drive decision-making of both tenants and landowners. Income tax relief provided for renting out land on long-term lease in the Republic of Ireland has resulted in increased land rental (Bradfield et al., 2023b). Recently, the NI government has embarked on a soil health nutrient scheme (SHNS) aimed at testing all soils in NI between 2022 and 2026 to improve sustainability and efficiency in the farming sector. This is a good starting point as it provides up-to-date data on the conditions of the land and how it can be improved. This may encourage a more balanced land rental market in which disadvantage areas are not left behind in terms of productivity gains and land market participation. A limitation of our study is that our methodology does not consider the area of land (as a proportion of total land area) rented in or rented out. This should be considered in future research as it has the potential to influence landowners and farmers' motivations to rent out or rent in land. Future research should also consider possible interaction between the explanatory variables as this could have an effect on the results.

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APPENDIX

A. Principal component analysis

This study employed the principal component analysis (PCA) to reduce 14 attitudinal statements to four main motivational constructs which were hypothesized to influence farmers' participation in the land rental market. The statements and the constructs are included in Table A1.

Table A1. Principal components (component loadings) for farming motivations (values > .3 are highlighted in bold) (N= 1,121).

Variables	PC1	PC2	PC3	PC4
	Progressive (α = 0.68)	Environmental apathy (α = 0.60)	Pro-environment (α = 0.63)	Risk Averse (α = 0.66)
I am generally keen to adopt new technologies	0.5360	-0.0368	0.0201	-0.2164
I try to find new ways of increasing profit on the farm	0.4888	-0.0139	-0.0174	-0.0547
I find farming rewarding from a quality-of-life perspective	0.3374	-0.1124	-0.0162	0.1251
I think good record keeping is very important in managing a farm business	0.4264	-0.1116	0.0329	0.0461
It is more important to maximize profits than protect the environment	-0.0833	0.4775	0.0411	-0.0721
I believe society places too much emphasis on environmental issues	-0.0387	0.5274	0.0356	0.0335
I am not that concerned about environmental issues	-0.1169	0.4402	-0.0541	-0.0787
I think the media exaggerate the negative impact of agricultural activities on the environment	0.1206	0.3663	0.0557	0.0120
I take some actions to protect the environment when managing my farm because I feel it is the right thing to do	0.0919	0.0829	0.4373	0.0621
Farmers should receive subsidies for protecting the environment and not for the total amount of land farmed	-0.0818	0.0928	0.5357	0.0333
In terms of what I produce on my farm, I think it is important to take the environment into consideration, even if it lowers profit	0.0119	-0.0593	0.4794	-0.0226
I am concerned about the loss of biodiversity in our farmed environment	0.0293	-0.0479	0.5210	-0.0420
I try to avoid taking risky farm business decisions	-0.1034	-0.0046	-0.0144	0.6889
I try to keep debt levels as low as possible	-0.0568	-0.0381	0.0267	0.6628
Initial eigenvalues	2.92	2.70	1.38	1.17

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Agriculture and Environment: The inclusion of Italy in the SIMPLE and SIMPLE-G models

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Abstract. The paper presents a methodological contribution to analysing the interactions between economic and environmental factors by using the Simplified International Model of Agricultural Prices, Land Use and Environment (SIMPLE) model and its gridded version (SIMPLE-G). While SIMPLE addresses national agricultural trends, SIMPLE-G offers a detailed, spatially disaggregated analysis essential for assessing local impacts. We improve these models by building a comprehensive database, capturing aggregate and georeferenced data regarding Italy. The use of the models with the extended dataset may support the implementation of adaptation strategies offering boundary conditions for local decision-makers while reflecting the impact of policies on national and global variables. The article outlines the models' structure, data sources, and calibration process, providing a preliminary application of SIMPLE for updating the baseline.

Keywords: Agriculture Sustainability, Climate Change, Simulation Models, SIMPLE, SIMPLE-G.

1. INTRODUCTION

Agricultural sustainability and food security face threats from unpredictable climate variations, especially in temperature and precipitation (World Bank, 2022). Like many other regions, Italy has witnessed a discernible rise in severe drought events over the last two decades, profoundly affecting crop yields in some of the most agriculturally crucial areas of the country (Spano et al., 2020). These changing and heterogeneous climatic events have distinct impacts on regional water availability, posing location-specific challenges for agricultural production and affecting prices and output both at a national and local level. In this context, tools are crucial to assess the local and global socio-economic consequences of extreme weather events and shed light on effective adaptation strategies (Dorfman et al., 2024).

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The paper presents a methodological contribution to analysing the interactions between economic and environmental factors by extending the Simplified International Model of Agricultural Prices, Land Use and Environment (SIMPLE), and its georeferenced gridded version SIMPLE-G, to Italy. [1] Initially developed by Baldos & Hertel (2013) and later expanded by Liu et al. (2017) and Baldos et al. (2020b), both SIMPLE and SIMPLE-G are partial equilibrium models designed to analyse the dynamic interactions between economic and environmental systems. So far, the models are based on 17 regions, and the EU, including all of the Member States, is one of them. Our main contribution is to extend the resolution of the models and create a database where Italy is singled out from the rest of the European Union (EU).[2]

Italy is an ideal setting to test the model's validity for an EU country. First, several extreme climatic events have occurred in Italy over the last few years, and they most affected agriculture. The number of severe floods, river overflows, record heatwaves in urban and rural areas, landslides, and glaciers retreated is constantly increasing, exacerbating climate stressor effects on agricultural production.[3]

Second, the agrifood sector in Italy still accounts for a significant part of the national GDP, much more than in a number of other EU countries. The Italian agrifood sector plays a key role in the national economy, mainly thanks to the added value generated by traditional processed products (e.g., tomato industry, pasta and wine). At the same time, Italy is the EU country that accounts for the highest number of geographical indications (GIs), representing high-quality traditional local production that must be produced in specific areas of the country (Reg. (EU) 2024/1143). The GI scheme aims to preserve local production by officially certifying their linkage with the territories of origin and limiting the production to those areas to avoid fraud competition and *Italian sounding*. The production process must be located within the demarcated area (i.e., list of municipalities) defined by the official Product Specification, and it cannot be delocalised. In this context, evaluating the effects of climatic events at the local level becomes even more relevant to understanding future projections of such productions (Tscholl, 2024). For example, as of today, most of the GI wines cannot be irrigated. However, over the past few years, irrigation needs have arisen to avoid production loss due to increasing temperatures.

The SIMPLE model facilitates the analysis of agricultural production and consumption at an aggregate territorial level (i.e., countries or world regions), offering insights into how crop demand and supply might respond to external factors such as income, population, and technology changes. SIMPLE-G provides, instead, a georeferenced extension that focuses on the effects of policies on agricultural production, land exploitation and water use, all within the broader context of regional and global commodity markets (Haqiqi & Hertel, eds.). In SIMPLE-G, while a specific country is considered at the grid level (i.e. *local* market), the rest of the world is considered at the national or regional world level (i.e., *global* market). This detailed representation allowsto capture the territorial diversity regarding cropland distribution, crop production, nitrogen application, and surface and groundwater irrigation. By integrating economic theories with environmental sciences, these family of models allows for the assessment of biophysical and economic impacts across various geospatial scales. In doing so, they differ from most previous partial economic models by investigating the *global-to-local-to-global* interactions.

The main challenge that researchers must address to run the model is the construction of an *ad-hoc* dataset for the country of interest. While national aggregate data are used to inform the SIMPLE model, georeferenced data sources are therefore needed to create a spatially disaggregated database for SIMPLE-G, with a resolution of 5 arcmin grids (approximately 10 km by 10 km) covering the entire country. From the methodological perspective, therefore, the extension provided in this paper contributes to the recent stream of research by creating the SIMPLE and SIMPLE-G datasets for an EU country. In addition, from the policy perspective, this study provides a new toolbox to investigate the effects of policy interventions and external shocks, such as climate change perspectives, at global and local levels. These results can be used to assist policymakers and practitioners in designing mitigation strategies and policy agendas.

The remainder of the paper is organised as follows. Section two provides an overview of the SIMPLE and SIMPLE-G models, focusing on the existing specifications and the models' structure. Section three discusses the details of the Italian database construction and an in-depth explanation of model assumptions and calibration. Section four presents a first application of SIMPLE for Italy and, lastly, the conclusions discuss limitations, next steps and future application.

[1] Grids are spatial units of equal length and width, with the area varying according to the latitude of the grid cell (larger at the equator and smaller moving toward the poles).

[2] The database already includes specific countries, such as the US, China, and Brazil. In all these cases, gridded data was collected by merging data from different data sources and harmonising the dimensions of the grids at a unique scale.

[3] More information available at Climate Change Knowledge Portal, World Bank Group: https://climateknowledgeportal.worldbank.org/country/italy

2. SIMPLE AND SIMPLE-G MODELS FOR AGRICULTURE

2.1. Existing specifications and applications

In recent years, a growing body of literature has aimed at extending equilibrium models to consider the complex interdependencies governing global crop production, land and water use, and food demand. SIMPLE and SIMPLE-G models go in this direction, given their focus on the agriculture sector. In 2013, Baldos & Hertel (2013) introduced the SIMPLE model to comprehensively capture the main relevant socioeconomic factors influencing cropland use in 15 world regions. The initial SIMPLE model was further expanded to integrate additional modules accounting for different issues related to agriculture and agrifood sectors.

First, a module accounting for greenhouse gas emissions (GHG) linked to agricultural activities was introduced by Lobell et al. (2013) and Hertel et al. (2014). Secondly, Baldos & Hertel (2014) extended the SIMPLE model by adding a food security module, which analyzed the global and regional effects of climate change and mitigation policies on caloric intake. They found that the model accurately reflects global data. By using this model, Baldos & Hertel (2015), for example, demonstrated that reducing market barriers could bolster food security worldwide and regionally in the face of climate change challenges to agriculture. More recently, Kabir et al. (2023) evaluated the effects of different policy scenarios on food security outcomes in rural and urban Niger into 2050.

Third, this framework has also been extended to Research & Development (R&D) activities, linking them with Total Factor Productivity (TFP) growth (Baldos et al., 2020a), food prices, land use and GHG emissions (Hertel et al., 2020; Fugile et al., 2022; Baldos, 2023a).

Despite its computational capacity and projection performance, the SIMPLE model lacks a detailed spatial resolution, limiting the analysis at the regional, or at maximum, national level (Hertel, 2018). To evaluate sub-national effects, in fact, the model should be based on a more disaggregated territorial level of analysis and include spatial data. The construction of the model requires, in fact, to build a database collecting a huge amount of different data (see the next section for more details), which are not always available and easily to access at the local level. Even when available, data comes from different sources, meaning a significant challenge in data collection and harmonisation. In 2017, Liu et al. (2017) published a gridded version of the SIMPLE model, called SIMPLE-G, that divided the world into over 39 thousand grids (30 arc-min,) to capture local patterns in crop supply and demand. As in the case of SIMPLE, also in SIMPLE-G specific countries can be isolated from the global context and considering for specific local analysis. To do that, a gridded database for the country must be created including all the data needed to run the model. Following this idea, Baldos et al. (2020b) developed the SIMPLE-G model for the USA, while Wang et al. (2020) and Liu & Wang (2021a) for China, and Wang et al. (2022a) for Brazil.[4] Additionally, Haqiqi et al. (2023a) have employed a worldwide model to evaluate the implications pandemic-weather stress events.

Several are the modules that theoretically can be added at SIMPLE and SIMPLE-G databases to capture the intricates *global-local-global* interactions within economic and environmental systems. However, all the modules are conditioned at data availability, which become even more severe when we look at specific issues. For example, in the case of the US, Baldos et al. (2020b) could distinguish at the grid level between rainfed and irrigated water, as well as between ground and surface water, while Liu et al. (2022) focus their analysis solely on some specific crops such as corn and soybean. The availability of these data for the US allows, for example, Baldos et al. (2020b) and Haqaqi et al. (2023b) to study the implications of future population growth trends and groundwater management policies on local crop production and demand. Data on water were also available for China, enabling Wang & Liu (2021b) to analyse the impact of a new water policy, specifically the South-North Water Transfer Project.

More recently, Wang et al. (2022b) integrated a transportation module to explore the local responses to macro-level policies with a focus on the relationship between transportation costs, agricultural production and grid-level cropland expansion.

Lastly, Ray et al. (2023) incorporated data at the gridded level on agricultural labour market and mobility to simulate the impacts of agricultural policies not only on production, but also on wages and employment rate at both local and global levels.

The construction of the database to extend the model at a new country is, therefore, a fulcrum of this research field. The next section presents the general structure of the model, which clarify even more the amount of data required.

[4] The USA was divided into over 75 thousand grids, China in 41 thousand grids by Wang et al. (2020) and 88 thousand grids by Liu & Wang(2021a) and Brazil in 50 thousand grids by Wang et al (2022a). The rest of the world was aggregated into world regions.

2.2. The general structure of the models

Starting from the SIMPLE, the model operates on the assumption of a single aggregate crop produced and consumed across 17 distinct regions (see Table A1 in the Appendix for the list, Baldos et al., 2020b; Baldos 2023b). The crop sector encompasses various uses, including consumption as food, feedstock for biofuels, and inputs for livestock and the processed food industry. On the supply side, the model operates under the assumption of a single agricultural sector at a regional level that uses land and non-land inputs (such as labour, capital and purchased materials) to produce homogeneous crops, aiming to minimize costs with a constant return-to-scale technology. The availability of cropland varies region by region and is influenced by the returns on cropland in each area, while non-land inputs also depend on the regional prices given. On the demand side, demand for agricultural products is based on the intuition that exogenous factors - such as population growth, income per capita, and biofuel demand -positively influence the quantity of agricultural products demanded. Conversely, endogenous changes in agricultural prices negatively impact demand. Regarding prices, agricultural prices are defined taking into consideration both potential drivers of food prices and economic responses. Demand and supply for crops clear in local and global markets, meaning that consumers and producers face two distinct crop prices, one in the local market and one in the global one. For other commodities, market equilibrium is achieved at the regional level. As a result, processed food, livestock, and non-food products each have unique regional prices. As far as endogenous and exogenous variables are concerned, the model endogenously determines agricultural crop production and prices. When it comes to inputs of production, these are partly influenced by exogenous variables such as land variations due to environmental or urban reasons as well as slack variables. These assumptions go in line with the first version of the model presented by Baldos & Hertel (2013).

The overall structure of SIMPLE is described by Figure 1 (panel a), while technical details are provided in Annex I.

SIMPLE-G structure is built on SIMPLE but enabling crop production to be analysed at the grid level (Figure 1, panel b). Crop production in SIMPLE-G is no longer modelled at a world regional scale, but at a finer grid level.[5] Since this model is georeferenced, it enables a more detailed representation of the various inputs used in crop production, such as land type, water use, and fertilizer application rates. Although this added complexity makes SIMPLE-G a more intricate variant of SIMPLE, both in modelling and scale, it also makes it a significantly more powerful analytical tool. First, it accounts for human systems' responses to environmental changes, including adjustments in food consumption, agricultural production, land use, and water withdrawals, all influenced by shifts in market prices. Second, it offers a framework for measuring spillover effects transmitted between locations through market interactions. The ability to incorporate market-mediated effects and feedback loops between human and natural systems is, in fact, one of the advantages of SIMPLE-G over other traditional biophysical models (Hertel & Haqiqi, eds.). Another strength is the multi-scale approach used in SIMPLE-G that facilitates the connection between local-to-global changes, as presented in Figure 2. At the grid level, there could be a different composition of crop production, driven by differentiated contextual conditions (e.g., agroclimatic conditions). At the national, the overall quantity can be obtained by aggregating the grids' amount based on assumptions about product differentiation. The procedure is the same to obtain world regional values, starting from aggregating national values. The greater the diversity of crops grown within a region, the lower the elasticity of substitution between these grid-based crop outputs.

In this scenario, crop production can be supplied domestically (i.e., consumed within the country of origin) or exported. The decision to export or supply domestically depends on several factors, including the relative price of crops, which is influenced by production costs.

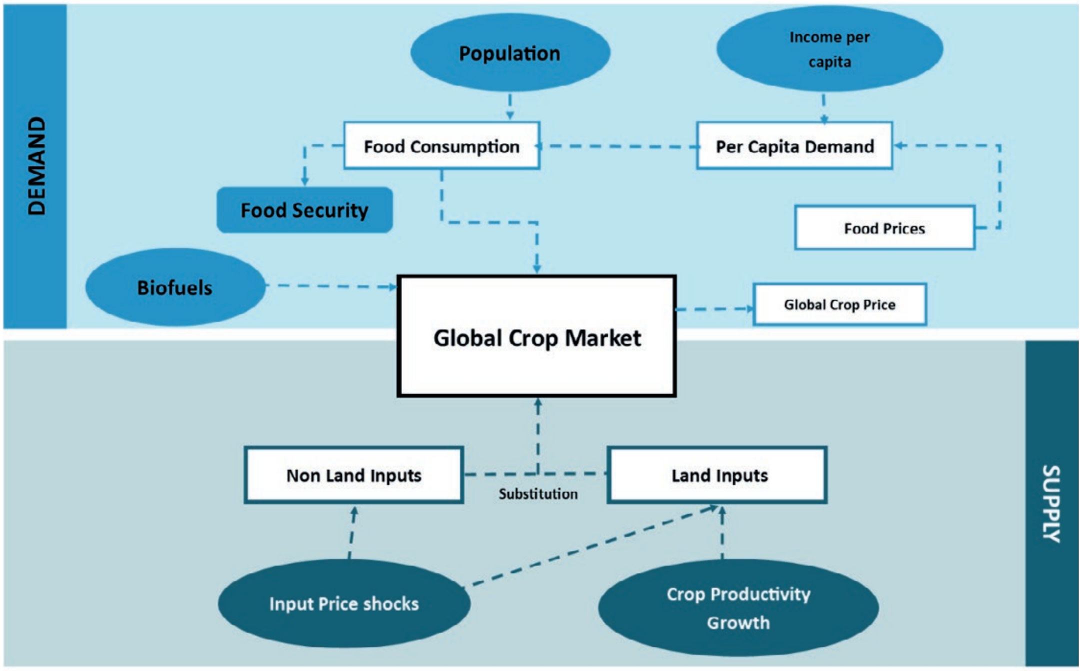
3. THE ITALIAN DATABASE

In this section, we describe the process followed to single out Italy from the macro-regional EU dataset, dividing the SIMPLE and SIMPLE-G world into 18 regions rather than 17 as in Baldos (2023b). The SIMPLE-G database follows, in fact, the structure and data of the SIMPLE model, but with Italy no more aggregated at the national level but rather subdivided into 5-arc-minute grids (the remaining 17 regions are aggregated) (Baldos et al., 2020b; Haqiqi et al., 2023b). The two databases were constructed separately but in tandem. To collect data, and in alignment with the Baldos (2023b) database, we referred, reviewed and processed various economic and biophysical information (Table 1).[6] The benchmark

[5] Grid cells need to be small enough to allow both the incorporation of available heterogeneity in data and parameters as well as not to influence commodity prices, so they can be treated exogenously.

[6] Due to heterogeneity in terms of years and geographical coverage, certain assumptions have been done to ensure consistency. Due to

(a) SIMPLE



(b) SIMPLE-G

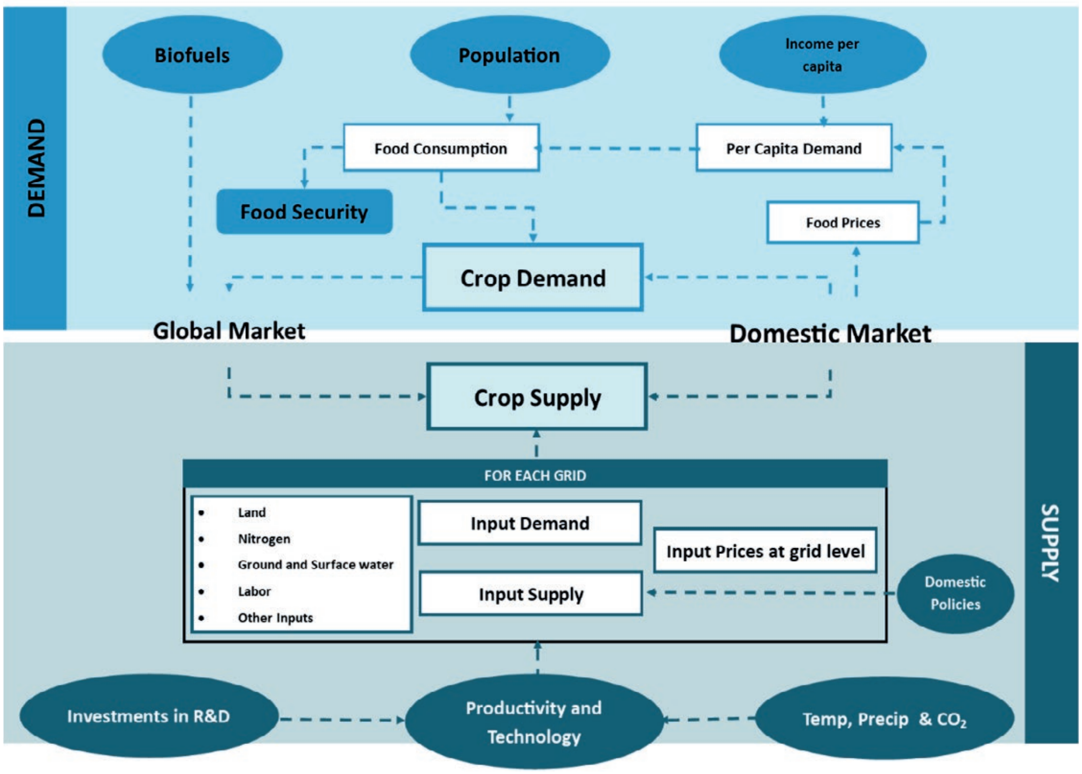


Figure 1. Basic structure of the models. Source: Own elaboration based on Baldos & Hertel (2013) and Baldos et al. (2020b).

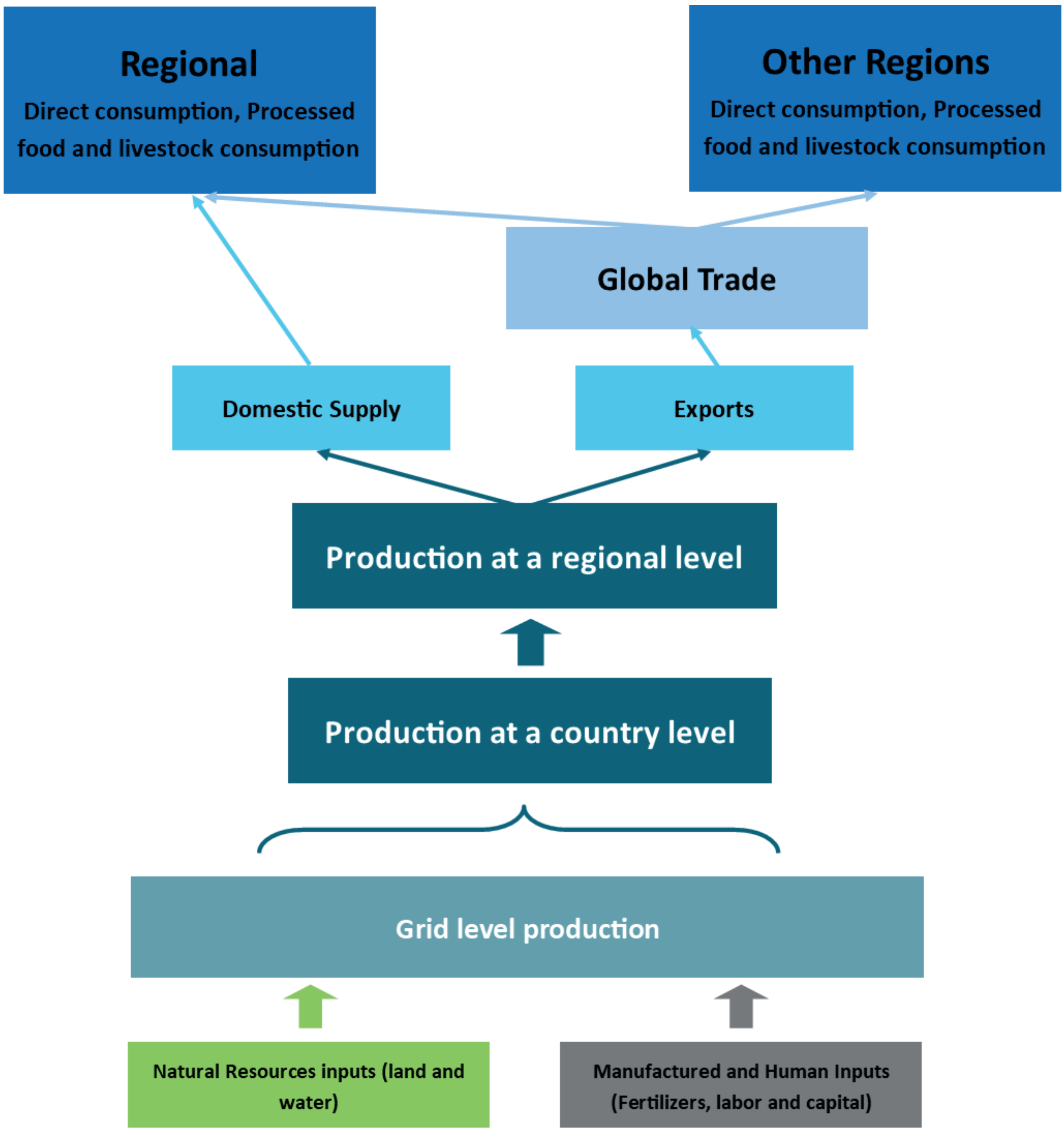


Figure 2. Representation of the local-to-global supply linkages in SIMPLE-G. Source: Own elaboration based on Haqiqi & Hertel (eds.).

primary data source was FAOSTAT, which provides different datasets at the national level (Table 2). However, FAOSTAT does not provide georeferenced data, so to create the SIMPLE-G model, we needed to consult the Earthstat database (Ramankutty et al., 2008). This database provides information on cropland, crop production, and fertilizer use by combining agricultural inventory data with satellite-derived land cover data, offering, thereby, information at a 5-minute (~10 km) spatial resolution.

SIMPLE-G's grid-based structure, datasets, typically presented in raster format, have been reviewed and processed using QGIS as a geoprocessing tool.

Table 1. Datasets reviewed, base year and geographical dimension.

Dataset	Time span	Geographical Dimension	Links
FAOSTAT	From 1961 to 2023	Country level	https://www.fao.org/faostat/es/#data
Earthstat	2000	10km x10 km	http://www.earthstat.org/
ISIMIP	From 1861 to 2017	50 km x 50 km	https://www.isimip.org/
Agri4Cast	1980-2022 / 2010	25 km x 25 km / 10 km x 10 km	https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx
AQUASTAT	2005	10 km x 10 km	https://www.fao.org/aquastat/en/
GCWM	1998-2002	10 km x 10 km	https://www.uni-frankfurt.de/45217988/Global_Crop_Water_Model__GCWM
ISMEA Mercati	Up to 2024	Italian regional level	https://www.ismea.it/mercati
Italian Farm Accountancy Data Network (FADN) Rete di Informazione Contabile Agricola (RICA)	2017	Italian provincial level	https://rica.crea.gov.it/
Indagine Mercato Fondiario - CREA	Up to 2022	Italian regional level	https://www.crea.gov.it/web/politiche-e-bioeconomia/-/indagine-mercato-fondiario

Source: Own elaboration.

Table 2. FAOSTAT data sets used to calibrate the SIMPLE model.

Dataset	Description
Production	Provides country-level data on crop and livestock production, including variables such as harvested area, production, yields, and animal stocks.
Population	Contains data on each country's total population, disaggregated by gender and by rural and urban areas.
Macroeconomic Statistics	Offers country-level data on GDP, gross output, value added, and gross capital formation for land-intensive sectors and the food processing industry.
Land Use	Contains country data for crop area and value of agricultural production.
Prices	Presents prices for all crops and livestock at a country level.

Source: Own elaboration.

The Earthstat database was used to determine the structural base of the SIMPLE-G model, meaning the number of grids of the model. In doing so, we followed the construction of SIMPLE-G Brazil (Wang et al., 2022a), wherein crop production estimates are formulated by considering only the top 80% of the most significant crops in the country. This approach helps eliminate potential statistical errors associated with minor crop estimates from Earthstat (Ramankutty et al., 2008).[7]

The final database is composed of 3,745 grids, which exhibited both cropland and agricultural output (Table 3).

[7] Earthstat provides, in fact, reliable estimates only for major crops, leaving minor crops with some biases in the estimations. Considering all the crops in the sample would, therefore, imply severe limitations for the application of the model and huge discrepancies with the benchmark aggregate production values reported by FAOSTAT. According to FAOSTAT, these are: Sugarbeet, Maize, Grapes, Tomatoes, Wheat, Olives, Apples, Potatoes, Oranges, Barley and Peaches.

However, information coming from Earthstat needs to be historically validated. To do that, we used data provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which consists of a time-varying historical land-use (LU) dataset including various land-use categories such as pastures, rangeland, and five distinct crop types.[8]

The ISIMIP's geographical coverage is lower than Earthstat's, and the geographical disaggregation is less fine (50 km by 50 km grid dimension), which is why we decided to consider Earthstat's data in the model. The same applies to crop data from the Agri4Cast toolbox (25 km by 25 km grid dimension). Although the irrigation data available in the toolbox has a grid dimension equal to the one used (10 km by 10 km), it is outdated, corre-

[8] This time series spans from 1861 to 2018 and primarily relies on the HYDE 3.2 dataset by Klein Goldewijk et al. (2017).

Table 3. Grid definition based on Earthstat datasets.

Number of grids		Output	
		0	>0
Cropland	0	346	328
	>0	396	3745

Source: Own elaboration.

sponding to 2010, and lacks information on rainfed land.

Given the current extreme relevance of water issues in the SIMPLE-G database for Italy, we decided to include the water model, following Haqiqi et al. (2023b). This extension allows for the estimation of local demand for agricultural water for irrigation water, which is crucial to modelling the impacts of sustainability policies and climate change shocks. These external events can have, in fact, different effects on irrigated versus non-irrigated (i.e., rainfed) crops due to their varying responses to heat and water stress.

This approach means that within each grid cell, two distinct production functions, rainfed and irrigated crops, compete for irrigable land.

Regarding data on water, we started collecting information from AQUASTAT (source: FAO), a global information system focused on hydric resources and agricultural water management. AQUASTAT provides georeferenced information at a 5-minute (~10 km) spatial resolution. Information on irrigated and rainfed hectares came from the Global Crop Water Model (GCWM) database, developed by Siebert & Döll (2008) within a 5-minute (~10 km) grid dimension. In addition, to obtain information on prices and values of irrigated vs non-irrigated land and crops, we consulted the Italian Farm Accountancy Data Network[9] (FADN).[10]

Another option for estimating crop prices in Italy is using data provided by ISMEA (*Instituto di Servizi per il mercato agricolo alimentare*), which represent market prices from the most representative local markets specific to product varieties and sales conditions.[11]

However, reliance on this dataset could lead to misleading estimates, given that the dataset provides prices differentiated for crops and regions rather than an aggregated crop price, as needed for the models. SIMPLE and SIMPLE-G models lack, in fact, differentiation among various crops. In addition, prices are provided only for specific groups of crops, differentiated by regions, which are those crops considered the most relevant for the regional agricultural economic output. This dataset is not, therefore, suitable to generate a representative and comparable regional aggregate crop price, as requested by the model, generating potential estimation biases.

Finally, we need data on the land market, collected from the dataset provided by the Council for Agricultural Research and Economics (CREA), to define the average farmland values at regional and national levels.

To sum up, by utilizing the dataset mentioned above and applying the parameters provided by Baldos (2023b) regarding country-specific production shares in global and local markets, as well as income and price elasticities, we were able to build a new database for SIMPLE with 18 regions, specifically distinguishing Italy. For both SIMPLE and SIMPLE-G models, the base year is 2017. The choice of the base year is mainly due to the availability of data that would enable the construction of a coherent dataset for both SIMPLE and SIMPLE-G.

Table 4 presents the estimated values for Italy in 2017 alongside the aggregate values for the remaining 17 regions, covering the key variables required for the model.

3.1. Database illustration and calibration

Figure 3 illustrates the 3,745 grids with cropland and crop production in Italy obtained from Earthstat database.

The data populating the Italian dataset come from the data sources described in the previous section, and they are better discussed and visualised here.

A first group of variables refers to environmental issues: nitrogen and water use.

The SIMPLE-G model considers nitrogen fertilizers as one of the key inputs of production function, and, therefore, the amount of nitrogen applications in each grid is needed to calibrate the base year. To achieve this, we used the Earthstat database, which collects national

[9] Established by the European Economic Commission in 1965 and conducted in Italy since 1968, FADN survey targets professional, market-oriented agricultural companies. It provides representative data across three dimensions: region, economic size, and technical-economic order. The current sample includes approximately 11,000 farms, covering around 95% of the agricultural area, 97% of standard production value, 92% of work units, and 91% of livestock units in Italy. The database, organized by thematic area, includes detailed farm-level information on production, input use, costs, and crop types, with identifiers for province and region.

[10] It should be noted that the information on prices from FADN has some limitations, as the water cost reported by the survey is defined as the total cost of water without clarifying the potential exclusion of certain types of water. Conversely, in the case of water consumption, the metadata file only mentions "water distributed," suggesting that water from private sources may not be included. We are not aware of any databases providing information on private withdrawals.

[11] It is a weekly survey encompassing minimum, maximum, and current price values.

Table 4. Key Variables Estimated for the SIMPLE Model Including Italy 2017.

Variable	Italy	Other Regions
Income per capita (in USD)	31,509	278,783
Population (in 1000 person)	60,004	7,524,960
Crop Use: Regional Biofuels (in 1000 Mt: Corn Eq)	3,013	447,499
Crop Output (in 1000 MT: corn-eq)	132,549	12,789,222
Value of Crop Output (in 1000 usd)	29,028,232	2,800,839,581
Cropland cover (in 1000 ha)	9,218	1,557,064
Value of Cropland (in 1000 usd)	4,830,646	540,050,675
Value of Non-Land Inputs (in 1000 usd)	24,197,586	2,260,788,898
Crop Use: Livestock sector (in 1000 Mt: Corn Eq.)	32,450	2,538,728
Crop Use: Food processing sector (in 1000 Mt: Corn Eq.)	37,698	3,100,306

Source: Own elaboration based on FAOSTAT and Baldos (2023b).

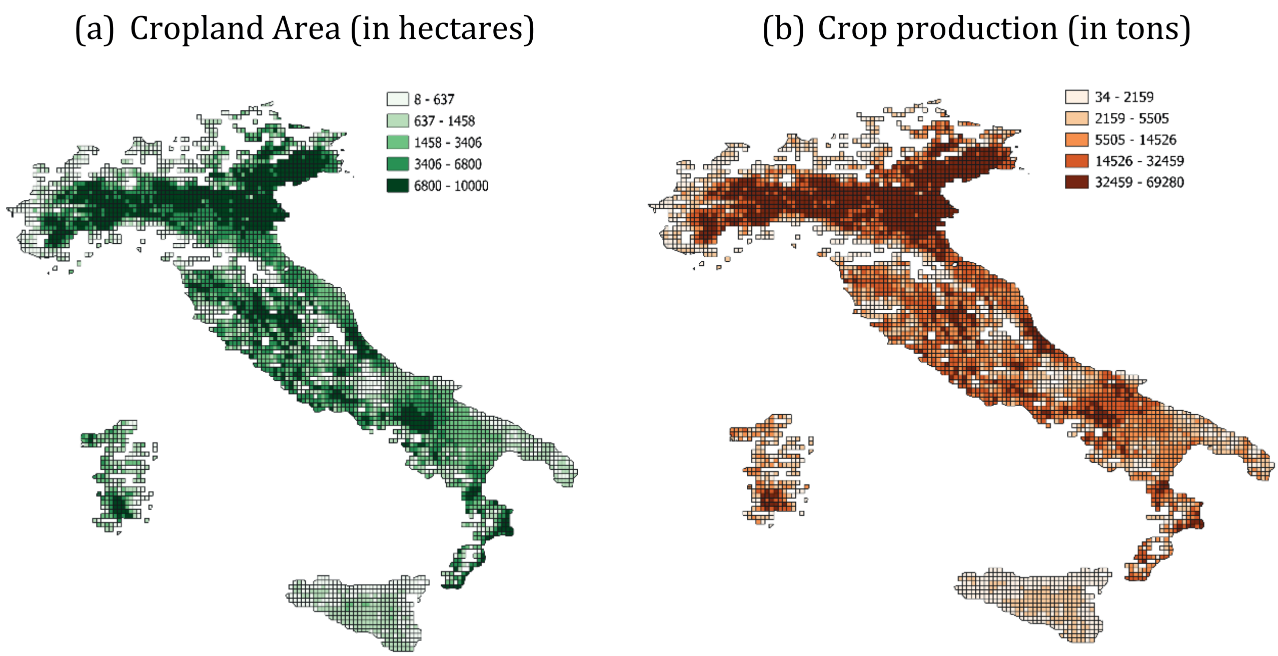


Figure 3. Distribution of cropland area and crop production for Italy. Source: Own elaboration based on Earthstat database from Ramankutty et al. (2008).

and sub-national data on fertilizer application rates for crops and crop groupings from the National Institute of Statistics (ISTAT). Figure 4 depicts the distribution across Italy depicting a more intensive use in the northern part of the country, which aligns with results obtained for cropland area and production.

In the case of water use, SIMPLE-G model incorporates rainfed and irrigated water use as critical inputs for crop production, differentiating between irrigated and rainfed crop supply. In addition, in the irrigated crop production function, the demand for water is subdivided into groundwater and surface water. Figure 5 shows the distribution of irrigated (panel a) and rainfed (panel b) cropland hectares in each grid (source: GCWM), while Figure 6 depicts the gridded distribution of irrigated land through groundwater (panel a) and surface water (panel b) (source: AQUASTAT).[12]

Regarding economic variables, the model needs price information, specifically on land, crop, fertilizers and water prices. To estimate the prices of crops

[12] AQUASTAT provides data on the percentage of land equipped for irrigation using groundwater and surface water.

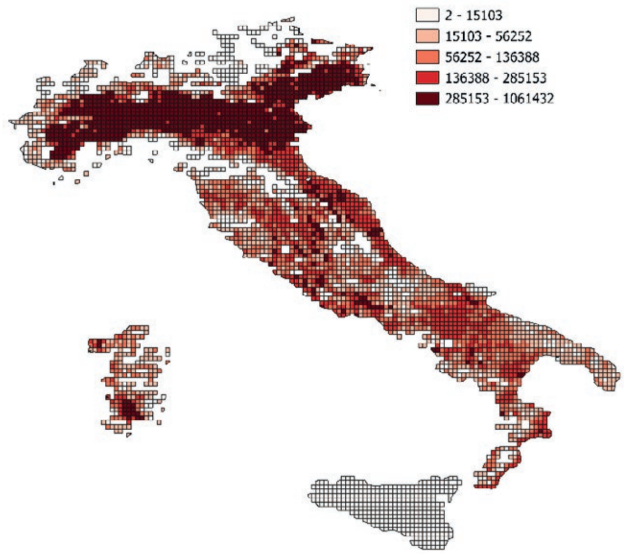


Figure 4. Total nitrogen application distribution for the year 2000- In kilograms. Source: Own elaboration based on Earthstat database from Ramankutty et al. (2008).

and fertilizers, we used the Italian FADN database at the NUTS3 level and considered the ratio between values and volumes (Figure 7). In estimating crop (panel a) and fertilizer (panel b) prices, to be faithful to Earthstat database, we considered crops included in the 80% of total production. In the case of water (panel c), prices were also calculated starting from the Italian FADN data on total water use in m3.[13]

We also extracted data on farmers' expenses from the Italian FADN database to estimate the prices and values of non-crop inputs for livestock and processed food (Figure 8 and Figure 9).[14] To calculate the total value of non-crop inputs, we considered water, electricity, fuels, veterinary and machinery expenses, commercial and processing expenses, general and land expenses, and salaries. The total values obtained were then divided by their corresponding quantities, distinguishing between the two types of activities to obtain prices.[15]

Finally, calibrating the SIMPLE-G model requires determining the cropland values at a grid level. As anticipated in the previous section, we collected data from the CREA's land market database (*Indagine-mercato-fondiario)* and downscaled them at the grid level (Figure 10). To do so, we have assumed that all cropland has a uniform value (expressed in euros per hectare) within a NUTS2 (Italian region) area.[16]

To ensure time consistency, a final note should be made regarding treating the datasets above. In addition, since most georeferenced datasets are based between 2000 and 2005, it was necessary to update them to 2017 by rescaling the geospecial structures to the values provided by FAOSTAT.

3.2. Estimation of the drivers of the model

The last step was to estimate the main driver variables needed to simulate a baseline scenario to 2030 for both the SIMPLE and SIMPLE-G models, with Italy as a single country. This scenario will serve as the basis for additional simulations.

Population growth rates were derived using the population projections developed by Samir & Lutz (2017), while GDP per capita estimates were based on projections by Crespo Cuaresma (2017). These projections follow the intermediate Shared Socioeconomic Pathway (SSP2) the International Institute for Applied Systems Analysis (IIASA) created. Regarding future biofuel demand, they were constructed using estimates provided by IEA (2024). The adoption of these databases aligns with the methodology proposed by SIMPLE modellers in Baldos et al. (2020b), Haqiqi et al. (2023b), and Baldos (2023b). For the TFP, econometric estimations were performed using a time series model to forecast output and input data for 2030 based on a panel data structure (see Annex I for details).

Table 5 presents the percentage variations of each variable between 2017 and 2030.

[13] For estimating the price of water used by farms, the assumption regarding the crops considered is slightly modified. Specifically, in NUTS3 of Caltanissetta, Monza e della Brianza, Rimini, Siena, and Varese, the restriction of using only the crops considered for production is not applied. While this introduces some inconsistency in the selection of farms in these provinces - since crop production was the original eligibility criterion - maintaining the criterion would have made obtaining water prices in these areas impossible. The surveyed farms in these provinces do not produce the crops selected to obtain crop production at the grid level, so if the eligibility criteria used for crop and fertilizer price estimations were maintained, there would be no price data for water used in the mentioned provinces. Data used are collected in metadata called Uso Acqua and Colture.

[14] It should be noted that these expenses are at the general farm level (see *Bilancio Conto Economico* RICA metadata), so they may include expenses generated by other activities carried out in those farms. The farms to be considered are filtered using tables that identify those producing processed food and raising animals. Only farms that produce processed foods of non-animal origin are included, indeed.

[15] In the case of livestock, quantities correspond to the number of adult animals.

[16] During data processing, outliers were removed, and weights were applied to scale the results to the population level. This process yields variables at the provincial level.

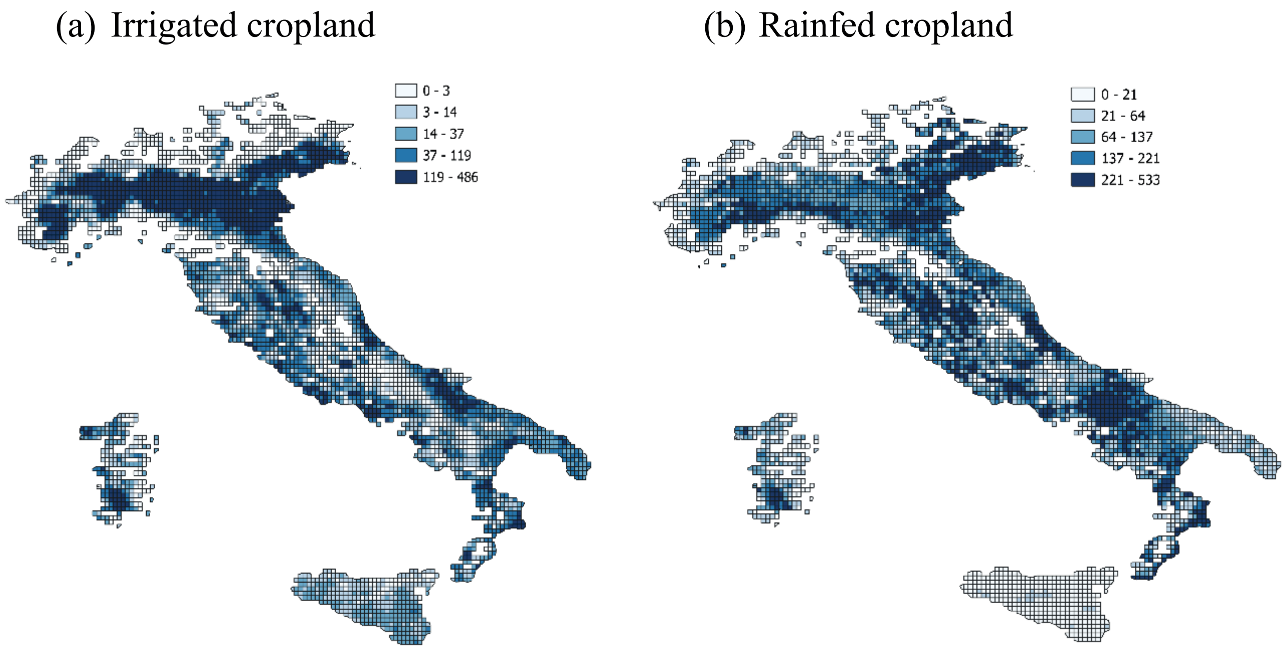


Figure 5. Distribution of Irrigated and Rainfed cropland hectares. Source: Own elaboration based on GCWM data.

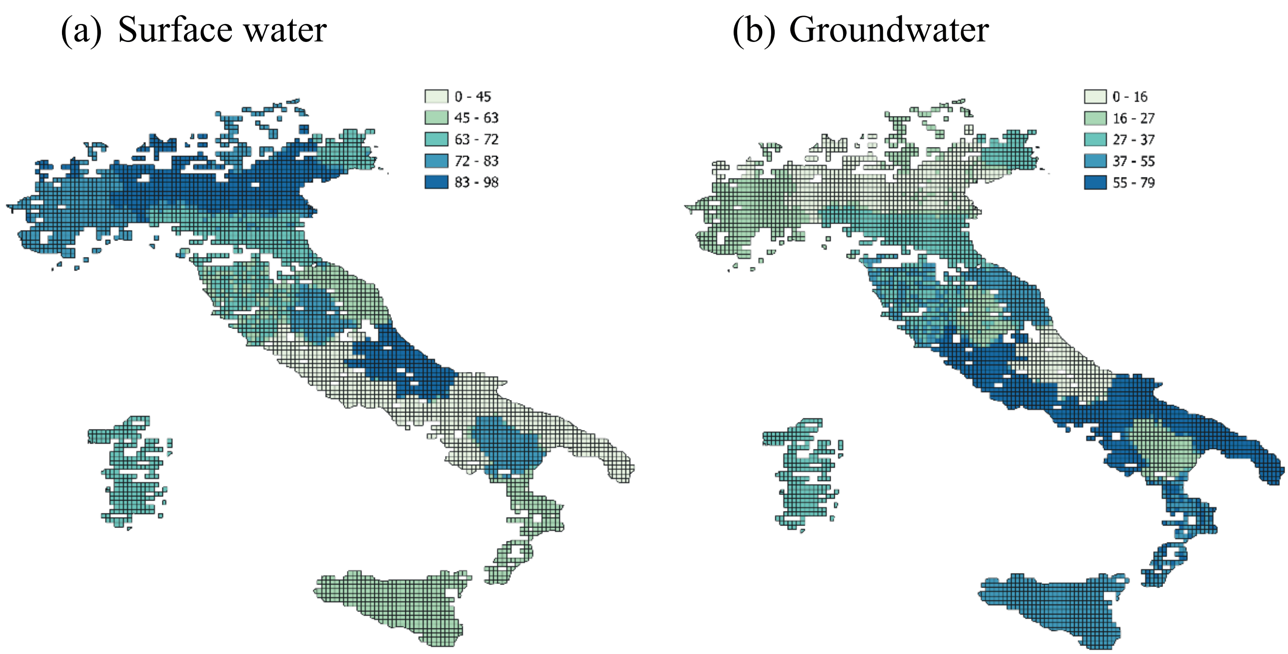


Figure 6. Distribution of surface and groundwater extraction on irrigated hectares. Source: Own elaboration based on AQUASTAT data.

4. A FIRST APPLICATION OF SIMPLE-IT

In the case of SIMPLE, the Italian database has already been properly structured for integration into the GEMPACK software, and the model is ready to be tested. As a first application, we conducted a baseline simulation to evaluate the expected impacts of the evolution of population, GDP per capita, biofuel demand and crop TFP on agricultural production and land use at the national level projected to 2030. Table 6 presents the

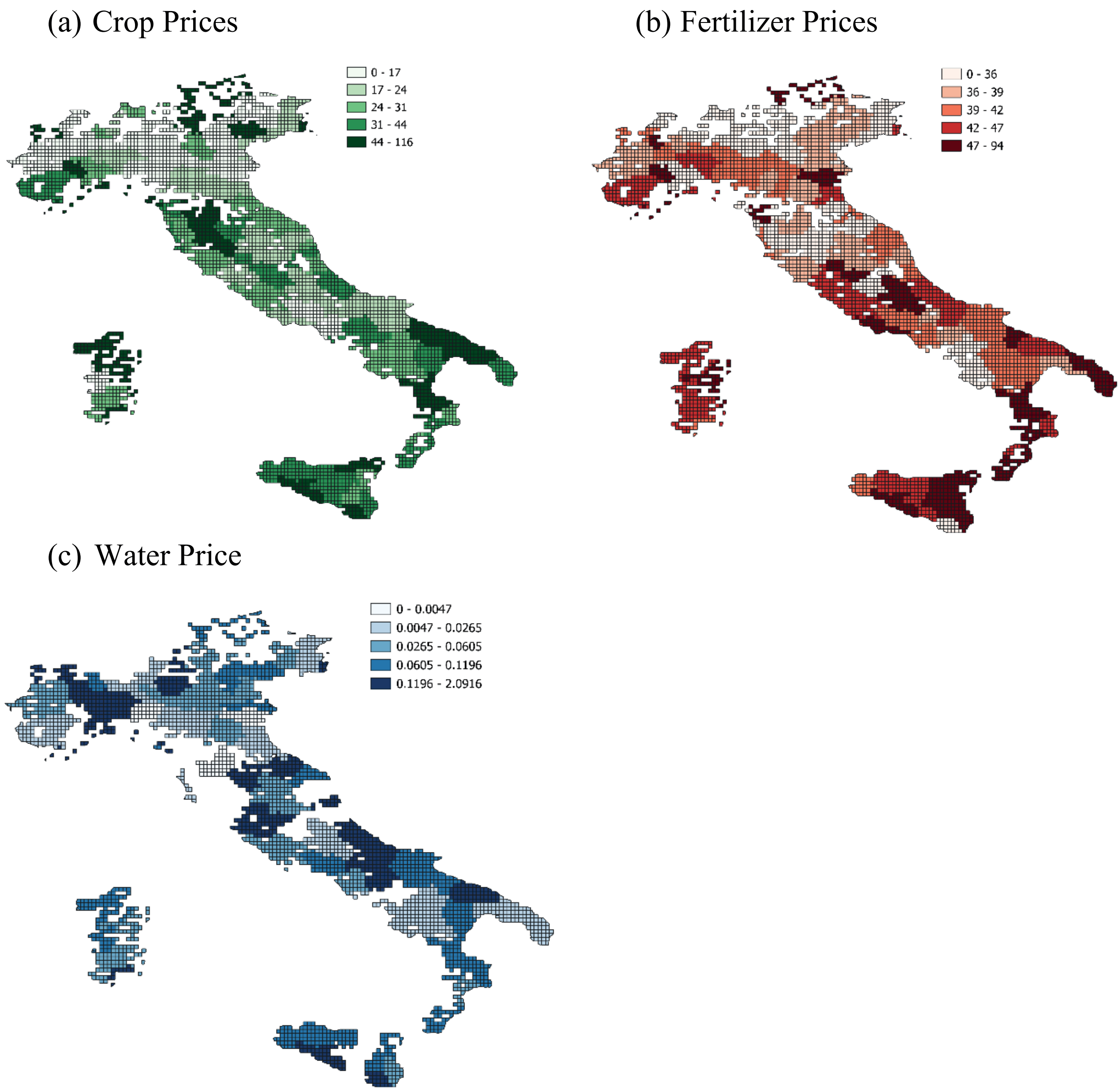


Figure 7. Crop, Fertilizers and Water prices per provinces. Note: Crop and fertilizer prices expressed in current euros; water prices expressed in current euros/m³. Source: Own elaboration based on Italian FADN - RICA.

results showing the percentage impact on crop prices, highlighting the contribution of each driver to the total effect. As shown, the estimated baseline has an overall negative impact on global crop prices (-6.36%) and in most regions, indicating that prices would decrease under the given scenario. This can be explained by the fact that although demand-side drivers (population growth, GDP per capita, and biofuels) exert upward pressure on prices due to increased crop demand (8.85% from population growth, 7.38% from GDP per capita, and 1.32% from biofuels), this effect is more than offset by improvements in sector productivity. Overall, the rise in productivity leads to a global price reduction of 17.21%, increasing production enough to counterbalance the higher demand.

Table 7 illustrates the impact of the simulation on crop production, breaking down the total impact by and the total effect of each driver in the model. Analysing

(a) Non-Crop Input Value for Livestock

(b) Non-Crop Input Value for Processed Food

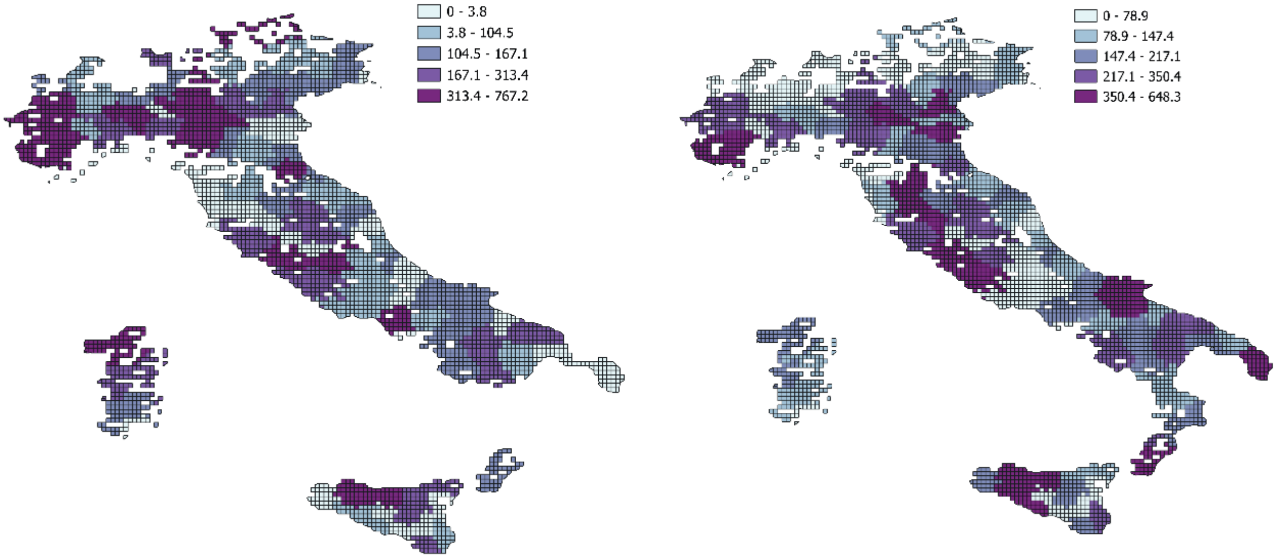


Figure 8. Non-Crop Inputs Values for Livestock and Processed Food per provinces. Note: Expressed in current million euros of 2017. Source: Own elaboration based on Italian FADN - RICA.

(a) Non-Crop Input Price for Livestock

(b) Non-Crop Input Price for Processed Food

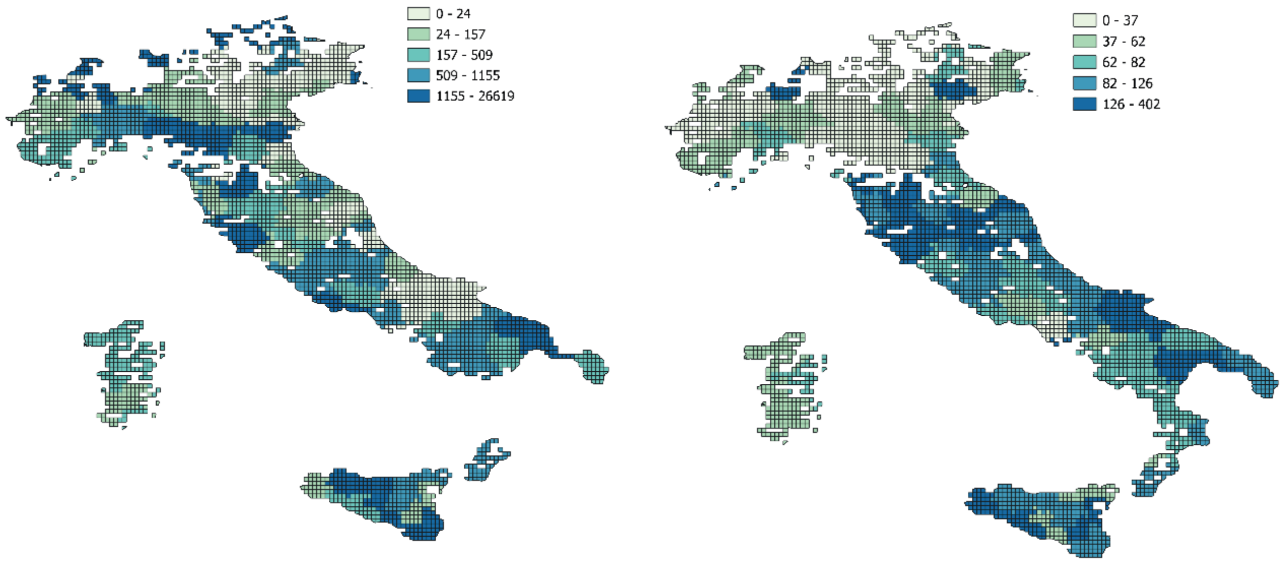


Figure 9. Non-Crop Inputs Prices for Livestock and Processed Food per provinces. Note: Expressed in current euros of 2017. Source: Own elaboration based on Italian FADN - RICA.

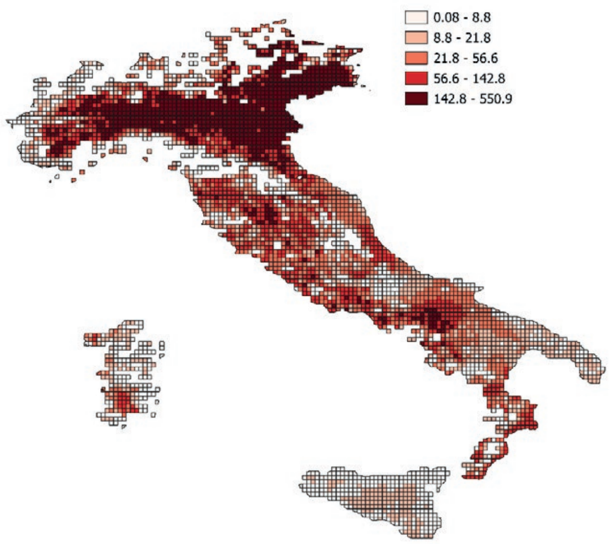


Figure 10. Cropland value. Note: Expressed in current euros of 2017 per hectare. Source: Own elaboration based on the land market database (source: CREA).

Table 5. Estimated percentage variations from 2017 to 2030.

	Population	GDP per capita	Biofuels demand	TFP
AUS_NZ	22.01	40.92	6.67	-0.5
BRA	9.68	38.59	97.74	18.7
CAN	15.41	29.57	64.23	13.3
CC_AMER	13.48	41.23	58.33	0.9
CHINA	1.32	126.32	19.56	10.3
C_ASIA	30.61	334.19	224.75	30.2
EU	4.26	39.46	52.86	7.1
E_EURO	-1.97	59.91	0.00	20.9
ITA	0.77	69.70	103.38	1.7
JPN_KR	-1.92	9.03	224.75	3.9
M_EAST	22.40	30.12	331.03	18.3
N_AFR	17.28	33.27	0.00	48.3
SE_ASIA	12.15	100.20	224.75	4.3
SSA	38.17	67.84	16243.20[1]	15.9
S_AFR	11.90	49.55	0.00	15.2
S_AMER	13.51	46.24	58.33	10.8
S_ASIA	17.80	144.12	0.00	18.2
US	11.83	20.83	24.29	10.1

[1] Note: Estimates for the Sub-Saharan Africa region was unavailable in the IEA (2024) database. Hence, this projection was taken from Baldos (2023b).
Source: Own elaboration.

the contribution of productivity changes to agricultural output, it is evident that productivity growth leads to an overall global production increase (6.54%). However, in some regions, production declines due to lower comparative competitiveness, as seen in Italy, where production decreased by 9.17%. Regarding demand-side drivers, all have a positive impact, as expected, with global effects of 8.73% from population growth, 6.19% from GDP per capita, and 1.82% from biofuels.

Table 6. Crop Prices results as percentage changes.

	Total Effect	Population	GDP per capita	Biofuels Demand	Crop TFP
AUS_NZ	-1.23	8.19	2.11	0.91	-12.43
BRA	-7.64	5.39	3.08	3.62	-19.73
C_Asia	-4.15	14.17	12.94	0.42	-31.68
CAN	-6.26	6.47	2.86	1.62	-17.22
CC_Amer	-1.53	7.05	3.31	0.98	-12.87
CHINA	-7.81	1.83	4.56	0.25	-14.45
E_Euro	-12.57	3.23	3.24	0.65	-19.70
EU	-6.57	5.49	2.30	1.17	-15.53
ITA	-4.62	4.12	1.34	1.56	-11.64
JPN_KR	-6.77	3.05	1.94	0.70	-12.46
M_East	-8.12	9.68	2.06	0.54	-20.39
N_Afr	-20.20	8.53	3.47	0.57	-32.77
S_Afr	-6.96	6.50	3.62	0.75	-17.83
S_Amer	-5.40	6.85	3.24	0.88	-16.38
S_Asia	-1.85	10.74	10.47	0.19	-23.25
SE_Asia	6.91	7.74	8.39	0.50	-9.72
SSA	7.82	18.89	5.41	5.88	-22.36
US	-5.33	5.49	1.91	3.85	-16.59
WORLD	-6.36	6.33	3.40	1.12	-17.21

Source: Own elaboration.

Tables 8 and 9 present the results of cropland use, regarding hectares and land prices. As observed, demand-side drivers increase the need for cropland to meet rising crop demand, leading to a global increase of 7.44% in land use. This, in turn, creates upward pressure on land prices. However, once again, productivity improvements introduce a compensatory effect. As the sector becomes more productive, fewer hectares are required to achieve the same production level, resulting in a global reduction of 2.59% in land use. Although this mitigates the need for additional land, it does not fully offset it, leading to a net global increase of 4.86% in land use. At the regional level, however, some areas fully compensate for demand-side drivers through productivity gains – for example, in Italy, where total land use decreases by 0.44%.

The changes in land use also explain the observed impact on land prices, which increase globally by 10.33%. Since higher land demand drives prices up (with demand-side drivers contributing to a 17.55% global price increase), productivity improvements are

Table 7. Crop Production results as percentage changes.

	Total Effect	Population	GDP per capita	Biofuels Demand	Crop TFP
AUS_NZ	-2.65	10.22	2.63	1.13	-16.63
BRA	33.45	8.30	4.63	5.55	14.97
C_Asia	69.06	22.54	18.90	0.67	26.94
CAN	22.58	9.71	4.19	2.43	6.24
CC_Amer	0.20	7.67	3.59	1.07	-12.14
CHINA	12.26	2.14	5.19	0.29	4.65
E_Euro	29.49	4.91	4.77	0.99	18.82
EU	7.17	6.42	2.66	1.37	-3.27
ITA	-1.56	4.48	1.44	1.69	-9.17
JPN_KR	0.90	2.92	1.85	0.67	-4.55
M_East	30.75	13.91	2.89	0.77	13.19
N_Afr	70.17	10.43	4.08	0.70	54.97
S_Afr	25.32	9.19	5.01	1.06	10.06
S_Amer	16.98	8.80	4.10	1.13	2.95
S_Asia	38.31	13.57	12.80	0.24	11.69
SE_Asia	16.57	8.27	8.89	0.53	-1.12
SSA	48.75	24.93	7.02	7.75	9.06
US	15.56	7.09	2.43	4.98	1.06
WORLD	23.28	8.73	6.19	1.82	6.54

Source: Own elaboration.

Table 8. Cropland results as percentage changes.

	Total Effect	Population	GDP per capita	Biofuels Demand	Crop TFP
AUS_NZ	-1.16	5.48	1.41	0.61	-8.65
BRA	6.38	3.89	2.20	2.61	-2.32
C_Asia	15.68	10.17	9.04	0.30	-3.84
CAN	2.24	2.48	1.09	0.62	-1.96
CC_Amer	-0.22	2.47	1.16	0.34	-4.19
CHINA	0.58	0.66	1.63	0.09	-1.79
E_Euro	3.76	2.35	2.32	0.47	-1.38
EU	0.01	0.82	0.34	0.18	-1.33
ITA	-0.44	0.61	0.19	0.23	-1.47
JPN_KR	-0.44	0.44	0.28	0.10	-1.25
M_East	1.25	1.51	0.32	0.08	-0.66
N_Afr	2.30	1.31	0.52	0.09	0.38
S_Afr	2.53	2.45	1.36	0.28	-1.56
S_Amer	3.12	4.67	2.20	0.60	-4.35
S_Asia	5.28	3.83	3.71	0.07	-2.33
SE_Asia	3.81	2.61	2.83	0.17	-1.80
SSA	15.53	12.64	3.60	3.93	-4.64
US	1.48	2.02	0.70	1.42	-2.65
WORLD	4.86	4.15	2.25	1.04	-2.59

Source: Own elaboration.

Table 9. Cropland Prices results as percentage changes.

	Total Effect	Population	GDP per capita	Biofuels Demand	Crop TFP
AUS_NZ	-2.05	9.76	2.51	1.08	-15.40
BRA	11.68	7.13	4.02	4.78	-4.25
C_Asia	29.70	19.47	17.00	0.58	-7.36
CAN	8.22	9.15	3.99	2.29	-7.21
CC_Amer	-0.80	8.81	4.13	1.23	-14.96
CHINA	2.09	2.39	5.87	0.32	-6.49
E_Euro	6.82	4.26	4.21	0.86	-2.51
EU	0.08	7.48	3.11	1.60	-12.11
ITA	-3.91	5.42	1.75	2.05	-13.13
JPN_KR	-3.93	3.90	2.48	0.90	-11.22
M_East	11.92	14.44	3.03	0.80	-6.35
N_Afr	22.96	13.09	5.21	0.88	3.79
S_Afr	9.32	9.06	4.99	1.05	-5.78
S_Amer	5.64	8.45	3.97	1.09	-7.86
S_Asia	20.17	14.76	14.11	0.27	-8.97
SE_Asia	14.28	9.83	10.60	0.63	-6.78
SSA	29.42	23.98	6.80	7.46	-8.82
US	5.40	7.36	2.54	5.17	-9.67
WORLD	10.33	8.85	7.38	1.32	-7.22

Source: Own elaboration.

unable to fully counteract this effect. While productivity growth reduces land prices by 7.22%, it is not enough to fully offset the upward pressure generated by demand-side factors.

CONCLUSION

External shocks, such as climate change and extreme events, are shaping the sustainability of the agricultural and agrifood sectors worldwide, and this will become even more relevant due to climate scenario projections. Tools for ex-ante analyses are becoming increasingly crucial to understanding how policy design should evolve to address future challenges, such as international competitiveness and food security. In this context, this paper provides, for the first time, the scientific community with the extension of SIMPLE and SIMPLE-G models to a European country, Italy.

The paper not only describes the models, discusses the related literature, and documents the work performed to create the database for a new country but also presents: (i) the estimated values used to calibrate the baseline (in both models for 2017); (ii) the exogenous driver projections extending to 2030; (iii) a fist application of SIMPLE- IT model.

The first application of SIMPLE, integrating for Italy, presented in Section 4, demonstrated that agricultural production is projected to increase due to the included drivers (demand and productivity). The observed reduction in production in certain regions, such as Italy, is primarily explained by the lower productivity gains in comparison to the other regions, leading to a reallocation of production toward these regions. The overall increase in global crop production is associated with a reduction in agricultural prices.

Regarding land use, the results exhibit a similar pattern: an increase in the utilized area, except in regions where production decreased or where the increase was negligible. Higher agricultural productivity reduces the land requirements to achieve equivalent production levels. However, the rise in demand for agricultural products drives additional production, which in turn requires more land. This explains the increase in utilized hectares, although at a lower rate than the growth in production. Moreover, agricultural land prices exhibit an upward trend because of increased demand.

Additional steps are required to validate the SIMPLE-G model presented in this paper before running simulations. Specifically, grid-level elasticities of substitution should be defined in the model, following the methodology employed by Haqiqi et al. (2023b). Once this validation is completed, the model will be ready to conduct location-specific simulations, such as assessing the impacts of local climatic events or policy interventions. Both SIMPLE and SIMPLE-G models can be, in fact, used to simulate policy-oriented shocks, such as changes in agricultural land exploitation, agricultural water use (wastewater), water management strategies (i.e., collective *vs* private) or in farming processing (e.g., organic). The models incorporate, in fact, market-mediated effects and feedback loops between human and natural systems, guiding heterogeneous economic decisions at different spatial levels (national for SIMPLE while gridded for SIMPLE-G). They provide a framework for measuring spillover effects transmitted across locations through markets and accounts for telecoupling distant regions, enabling the analysis of interregional dependencies on a *local-global* scale. The capacity of SIMPLE-G to capture interactions is one of the main strengths of this model, especially for policy design (Baldos et al., 2020b). Overall, the several potential applications of both of these models will provide unique insights for sustainable policy targeting at the local, national and global levels (Hertel & Haqiqi, eds.). Today, the issue is more relevant than ever, given the current vibrant debate on what will come after the 2030 Agenda goals and how to plan sustainable development trajectories in the future within an anticipatory governance framework.

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APPENDIX

Table A1. Original regional disaggregation included in the SIMPLE and SIMPLE-G model.

Name	Region description
E_Euro	Eastern Europe
N_Afr	North Africa
SSA	Sub Saharan Africa
S_Amer	South America
BRA	Brazil
AUS_NZ	Australia & New Zealand
EU	European Union
S_Asia	South Asia
CC_Amer	Central America and the Caribbean
S_Afr	Southern Africa
SE_Asia	Southeast Asia
CAN	Canada
US	United States of America
CHINA	China and Hong Kong
M_East	Middle East
JPN_KR	Japan and Korea
C_Asia	Central Asia

Source: Baldos et al. (2020b) and Baldos (2023b).

Annex I. Technical details of models' structure (Section 2 of the manuscript)

Agricultural prices are defined based on the following equation (1):

$$(1)\quad p_A^* = \frac{\Delta_A^D + \Delta_L^S - \Delta_L^D}{\eta_A^{S,I} + \eta_A^{S,E} + \eta_A^D}$$

The equation indicates that agricultural prices are positively influenced by the increasing global demand in crop demand (Δ_A^D) and a shift of the global supply of agricultural land (Δ_L^S), while negatively affected by variations in the derived global demand for land due to global changes in yields (Δ_L^D) which, in this model, are exogenously determined. The model accounts for the magnitude of these variations on agricultural prices through three economic responses. First, an intensive margin response, represented by the elasticity of substitution between land and non-land inputs ($\eta_A^{S,I}$). Second, an extensive margin response in land use, captured by the land supply elasticity ($\eta_A^{S,E}$). Third, a demand response, reflected in the price elasticity of food demand (η_A^D).

Land use for agricultural production is determined based on equation 2:

$$(2)\ q_L^* = \left[\frac{\Delta_A^D+\Delta_L^S-\Delta_L^D}{1+\frac{\eta_A^{S,I}}{\eta_A^{S,E}}+\frac{\eta_A^D}{\eta_A^{S,E}}}\right] - \Delta_L^S$$

On the one side, quantity of agricultural land positively depends on increasing in global demand (Δ_A^D), potentially motivated by an upward demand of biofuels or food. On the other side, it negatively depends on the related global demand for land (Δ_L^D) that could result from exogenous growth in yields (e.g., due to prior investments in agricultural R&D). Additionally, the quantity of agricultural land negatively depends on the potential shifts of the global supply of agricultural land (Δ_L^S) potentially motivated by different conservation or urbanization policies. Finally, as in the case of agricultural prices, the variation in land quantity is influenced by the relative elasticities incorporated in the model. As shown, a higher land global supply elasticity (i.e., the extensive margin response) leads to greater variations in agricultural land use. Conversely, higher elasticity of substitution between land and non-land inputs (i.e., the intensive margin response) and higher price elasticity of food demand (i.e., the demand response) result in smaller variations in the quantity of land used.

Demand for agricultural products is defined as following:

$$(3)\quad q_A^D = -\eta_A^D p_A + \Delta_A^D$$

Technical details of total factor productivity estimation (Section 3 of the manuscript)

The first step was to estimate the panel data econometric model (Van Beveren, 2007) using a fixed effects estimation and the information in "*International Agricultural Productivity*". We apply a logarithmic transformation to linearize the production function, which depends on capital, labor, materials, and the Hicksian neutral efficiency level[17]. The estimated equation was:

$$(4)\quad \begin{aligned} y_{it} &= \beta_0 + \beta_k Capital_{it} + \beta_l Labor_{it} + \beta_{mfeed} Feed_{it} + \\ &\beta_{mfert} Fertilizer_{it} + \omega_i + \varphi_t + u_{it} \end{aligned}$$

where $Capital_{it}$ includes the value of the agricultural capital stock for region *i* at time *t*, $Labor_{it}$ is the number of economically active people in agriculture, $Feed_{it}$ and $Fertilizer_{it}$ represent the use of materials in agriculture, and u_{it} the error. From this estimation, we obtain the coefficients that can be used to calculate the productivity of the sector, which can be defined as:

$$(5)\quad \begin{aligned} \widehat{\omega_{it}} &= y_{it} - \widehat{\beta_k} Capital_{it} - \widehat{\beta_l} Labor_{it} - \\ &\widehat{\beta_{mfeed}} Feed_{it} - \widehat{\beta_{mfert}} Fertilizer_{it} \end{aligned}$$

With this equation and the available data, productivity (the exponential of ω_{it}) could be estimated for each of the regions between 2017 and 2021. To estimate productivity to 2030, this model has to be complemented with a forecast of the output and inputs, so several time series models were estimated.[18]

[17] While this method can be extended to other production functions if certain additional conditions are met (Ackerberg et al., 2007), it was estimated using a Cobb-Douglas specification for simplicity.

[18] For each of the variables in every region, an ARIMA model was determined for each series4 and with that model each value between 2022 and 2030 was forecasted. Using these forecasts and the parameters estimated in the panel data model, an estimate of productivity in 2030 can be obtained for each of the regions (using equation 5).

Bio-based and Applied Economics Focus and Scope

The journal *Bio-based and Applied Economics* (*BAE*) provides a forum for presentation and discussion of applied research in the field of bio-based sectors and related policies, informing evidence-based decision-making and policy-making. It intends to provide a scholarly source of theoretical and applied studies while remaining widely accessible for non-researchers.

BAE seeks applied contributions on the economics of bio-based industries, such as agriculture, forestry, fishery and food, dealing with any related disciplines, such as resource and environmental economics, consumer studies, regional economics, innovation and development economics. Beside well-established fields of research related to these sectors, *BAE* aims in particular to explore cross-sectoral, recent and emerging themes characterizing the integrated management of biological resources, bio-based industries and sustainable development of rural areas. A special attention is also paid to the linkages between local and international dimensions. *BAE*'s objectives are:

- to stimulate cross-fertilization between the above mentioned research fields;
- to synthesize and integrate lessons learned from current strands of literature in economics;
- to provide a forum for well-established scholars as well as promising young researchers;
- to increase the knowledge about assessment, design and evaluation of public policies;
- to promote the debate on issues relating to the economics profession and its consultancy activities;
- to discuss future research pathways on the above issues.

BAE **publishes high quality research and review papers, after a timely and rigorous double blind peer review process.** ***BAE*** **also publishes book reviews.**

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