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SUSTAINABILITY AND CIRCULARITY OF AGRO-LIVESTOCK FARMING SYSTEMS: DESIGN, MANAGEMENT AND EVALUATION CRITERIA

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GENERAL ABSTRACT

The circular economy (CE) is an approach to sustainable development that is gaining ever more attention among academics, politicians, and people in business. Few authors indicated the CE as a tool to achieve the objective of sustainable development. The need to move from the linear "take-make-waste" to a circular development model, which reduces the pressure on the environment, is increasingly strong. The European Union and other countries have been endowed for some time with policies that favour and encourage this transition, but to date little has been done. This transition must necessarily also involve the primary sector, which is often pointed out as one of the main sources of environmental pollution.

In this Ph.D thesis, we want to analyse how these two concepts, circular economy and sustainability are dealt with in the agricultural sector and, in particular, in the dairy sheep farming sector.

In Chapter I, we focused on the concept of circular economy (CE), estimating the degree of circularity of the economy of the 27 European countries. We found that the level of circularity into the EU economic system is pretty low, equal to 4.1%, with significant differences between the various countries. The primary sector had a predominant role in determining circularity: 80.5% of recycled materials are part of this sector.

Chapter II analyzes a particular aspect of sustainability, represented by the ecosystem and social services deriving from Sardinian dairy sheep farming, focusing on their perception. The results highlight the recognition of the multifunctional role

of sheep farming by part of population even if some services are perceived as more important than others (enhancing cultural identity of Sardinia and safeguard of typical landscape). Furthermore, we found that if a service is attributed as relevant also the other services tend to be important in the population view.

The Chapter III aims to highlight the type of relationship that links economic and environmental sustainability dimensions in dairy sheep farming and if these could be influenced by some farms' structural or socio-demographic variables of farmers. The results arisen from the application of the trade-off analysis showed, firstly, the presence of a slight synergy between the two sustainability dimensions; secondly, highlight that the economic dimensions are positively and significantly influenced by the young age of the farmer and by the application of organic practices.

1. INTRODUCTION

Today, the first thing that comes to mind when talking about Circular Economy (CE) is its contrast with the linear economy, also known as the "take-make-waste" model. In the latter, the product's life is marked by four phases: extraction, production, consumption, and disposal, with reduced possibilities of reusing waste. In the circular model, however, the basis of production is the design phase, during which it is decided a priori how the waste or residues from the production process can be put back into circulation as material for new processes.

This new production model is often combined with the concept of Sustainable Development. However, the relationship between these two concepts, which developed in parallel in the same historical period, is sometimes ambiguous.

The following paragraphs will examine the historical evolution of these two concepts, their current declination, points of contact, and differences. Subsequently, their application in the primary sector will be discussed. Finally, a focus will be made on the Sardinian dairy sheep sector, which will be the subject of particular in-depth analysis in the articles in the following chapters.

1.1 Historical evolution of the Circular Economy concept

Between the 60's and 70's of the last centuries, we began for the first time to talk about topics that today seem obvious. In the early 1970s, the Stockholm conference emphasized environmental issues, while the war between Israel, Syria, and Egypt uncovered the energy supply problem. In this historical and economic context, the origin of the CE concept is unsure, but several studies (Andersen, 2007; Ghisellini et al., 2016; Lieder & Rashid, 2016) attributed it to the work of Boulding (1966), entitled "The Economics of the Spaceship Earth", presented for the first time at the Sixth Forum for the Resources of the Future. According to the economist, the earth is a closed system with limited assimilative capacity. For this reason, economic growth and the environment must coexist in balance.

Later, in 1981, Stahel & Reday-Mulvey published a book that contrasted linear economics with cyclical economics. According to the two scholars, this type of economy presents a production system responsible for what it produces even after selling it. The book concludes that economics should not simply deliver a product but rather a service. In the same year, Giarini, an Italian economist, in his book "Dialogo sulla Ricchezza e il Benessere" analyzed the value of products, no longer as a value in itself but as the value attributed to the service that this product or good performs. In 1982, Orio Giarini and Walter R. Stahel founded the Product-Life Institute in Geneva, where they deepened their studies to give the first definition of the modern circular economy. This theory holds that extending the life cycle of goods can reduce the consumption of raw materials, natural resources, and energy while creating wealth and well-being by establishing jobs, recycling, and reassembly (Stahel, 1982).

To this first line of thinking, another was added, represented by “Industrial Ecology”, proposed by Robert Ayres and based on the laws of thermodynamics (Ayres & Ayres, 1996). According to this theory, the economy and industrial systems are interconnected with the natural ecosystem, and the balance that regulates this connection must be maintained to avoid natural disasters that would restore the starting conditions to the detriment of human survival. The solution of industrial ecology is a closed system in which waste is seen as a new material that is part of the production cycle as soon as it is designed.

New schools of thought on the circular economy flourished between the end of the ’90s and the early 2000s. One of the most important is “Natural Capitalism”, proposed by Paul Hawken, entrepreneur and environmentalist, Amory Lovins, physicist and environmentalist, and L. Hunter Lovins, environmentalist (Hawken et al., 2001). Their theory is mainly based on four pillars:

1) Increase in the productivity of natural resources through the use of new technologies, new production systems, and new product design;
2) Closure of production lines, with reduction or elimination of production waste;
3) Adoption of the “service-and-flow” approach, which consists of greater attention to the quality of products and their utility rather than just extrinsic value;
4) Regeneration of natural capital because if natural resources are limited, investing in their reconstitution and protection is important

After this first current of thought, two other significant theories anticipated the modern concept of CE, the “Cradle-to-cradle” and the “Blue Economy”. The first theory, proposed by Michael Braungart, chemist, and Bill McDonough, architect, introduces the 3 Rs, “Reuse, Reduce and Recycle” concept, thus moving from eco-efficiency to eco-effectiveness (McDonough & Braungart, 2010). In the book “Blue Economy. Report to the Club of Rome. 10 years, 100 innovations 100 million jobs”, entrepreneur Gunter Pauli proposes the “Blue Economy” theory. According to his economic thinking, production processes must behave like natural ecosystems: when designing company activities, it is necessary to consider how the different natural flows, such as air, light, water, energy, sound, matter, and people, relate to each other (Pauli, 2010).

All these different theories are now the basis of the modern concept of CE.

1.2 The current Circular Economy concept

There is no clear definition of CE today, but there are several. Such a plethora of views is probably because it is a young line of research, as published by Rocca (Rocca, 2020) in his book “Towards the Circular Economy - Definitions, policies and good practices”, which, after having analyzed for a period ranging from 1995 to 2017, concluded that it is a recent and constantly evolving concept.

In a literature review, Kirchherr et al. (Kirchherr et al., 2017) found and analyzed 114 definitions of CE. At the end of the review, they then provided their definition of CE, indicating it as an economic system that modifies the concept of “end of life" with the reuse, recycling, and recovery of materials in the production, distribution, and consumption processes. This system operates at the micro, meso, and macro-economic levels to achieve sustainable development and simultaneously create conditions that ensure environmental quality, economic prosperity, and social equity for current and future generations.

One of the best-known, most established, and shared definitions of CE (Haas et al., 2015; Hobson, 2016; Niero et al., 2017) is that provided by the Ellen MacArthur Foundation (2013), according to which it is a model of the restorative and regenerative industrial economy by intention and design. The foundation's vision is summarized in the following image (Image 1), known as a butterfly wing diagram.

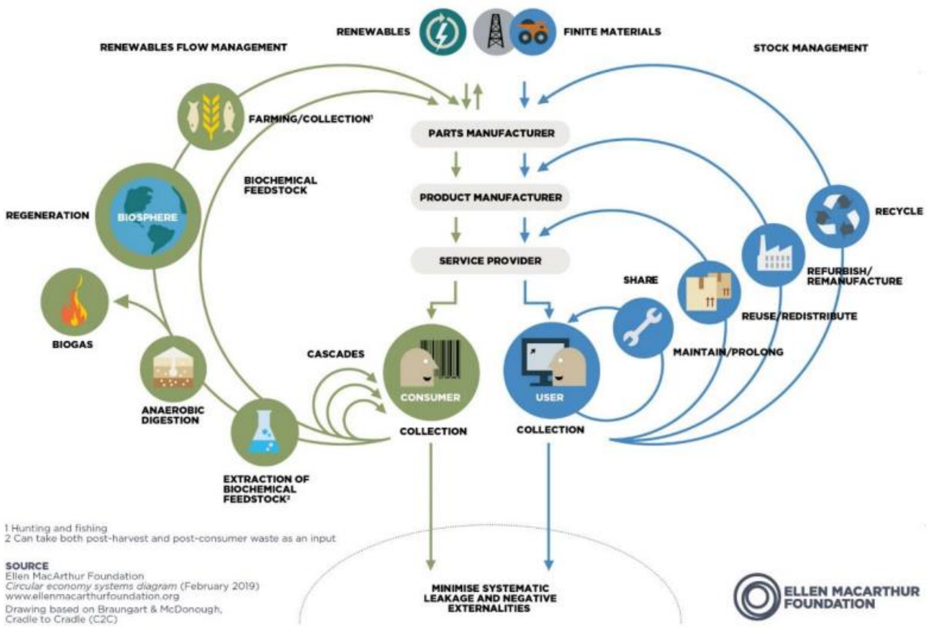

Image 1. Ellen MacArthur Foundation butterfly wing diagram. Source: Ellen MacArthur Foundation

This diagram comprises two parts: On the right side, technology and industrial production processes are represented, while on the left, we find the biosphere and natural resources. This model aims to create value through a dynamic and continuous flow of biological and technical resources based on three principles:

1) Management of material stocks through waste collection, recycling, and correct management of process outputs;
2) Maximize the use of materials, reducing to a minimum the so-called "unused value", i.e., the time in which products and services are not used, through sharing processes;
3) Minimize the negative externalities of the processes.

Geissdoerfer et al. (2017) define CE as a regenerative system in which resource input, waste, emissions, and energy losses are minimized through slowing, closing, and reducing energy and material cycles. This closure can be achieved by *a*) long-lasting products, *b*) maintaining products, materials, and resources in optimal condition, and *c*) reusing, repairing, remodeling, recycling, and renewing.

It is important to underline that CE is, first and foremost, an economic strategy that suggests ways to go from the linear consumption model to a regenerative system that achieves economic sustainability (Arru et al., 2022).

The concept of CE was promoted primarily by politicians, entrepreneurs, and non-profit organizations; the result is that many authors indicate the concept of CE as a set of vague and separate ideas deriving from different fields with few scientific concepts (Korhonen et al., 2018; Millar et al., 2019). The thinking of Homrich et al. (2018) also goes in this direction, who define CE as an "umbrella concept" under which various definitions address the issue from different perspectives (Borrello et al., 2020).

There are also several criticisms of this paradigm. The first is formulated against the key principle of CE, i.e., that the system must be closed. As suggested by Georgescu-Roegen (2013), the second law of thermodynamics says that the recycling process will always require energy and produce waste and by-products due to entropy growth. Therefore, closed systems are practically and theoretically impossible.

Beyond the law of thermodynamics, which indicates the impossibility of having closed systems, Haas et al. (2015) distinguished two barriers that limit the possibility of having closed systems. The first is given by the fact that a large quantity of materials is stored in construction, durable goods, and infrastructures, and this trend is destined to increase, especially in developing countries. The second limit constitutes the large quantity of raw materials, especially fossil fuels, used to produce energy: as long these materials are used for this purpose, they will reduce the ability to close the systems.

According to Allwood (2014), no evidence exists that secondary production can completely replace primary production. Furthermore, using current technology, reducing waste production, or eliminating toxic substances from some products is impossible. If technology can make these interventions possible in the future, a high quantity of energy will still be required, higher than that needed for primary production, with negative environmental consequences.

Although the literature on this paradigm has steadily increased in recent years (Schöggl et al., 2020), very few studies have focused on proposing evaluation methods regarding circular practices. If we want to define the actual transition from the linear to the circular model, the evaluation of the degree of circularity is essential (Saidani et al., 2019; Secco et al., 2020; Chiaraluce et al., 2021), both at a macro- and meso-economic level, but above all at micro-economic and product levels (Linder et al., 2017). This fact represents a limit to the application of CE practices but is especially an issue for those who must evaluate their effective convenience.

1.3 The concept of Circular Economy in the primary sector

CE aims at economic and social prosperity and environmental protection, and its application in agriculture can contribute to reducing the use of resources and negative externalities of this sector by improving economic performance. Given these objectives, through the application of this paradigm, the primary sector can *a*) become a pillar of the economy, ensuring economic sustainability, *b*) guarantee the conservation of biodiversity and productivity of agroecosystems, ensuring the environmental sustainability, and c) contribute to food supply and food security, improving social and health conditions, thus ensuring social sustainability.

There is only one definition of CE applied to agriculture provided by Velasco-Muñoz et al. (2021), according to which CE in agriculture can be defined as the "*set of activities aimed at ensuring not only economic, social and environmental sustainability through practices that pursue efficiency and the effective use of resources along the value chain but also ensure the regeneration of biodiversity in the agroecosystems and ecosystems that underlie them*" (p.4).

Starting from this definition, the principles of the CE, according to those proposed by the Ellen MacArthur Foundation (2013), can also be defined in the agricultural sector. The first principle is "*designing out waste and pollution*", according to which the system's effectiveness is favored by eliminating negative externalities. In the agricultural sector, these externalities are mainly linked to the adverse effects of the inappropriate use of agrochemical products. The second principle of CE is "*keeping products and materials in use*", so the value of products, co-products, and by-products should be maximized at each step of the chain and also at the transition between different chains, with the possibility of maintaining these resources to their maximum usefulness. This principle is pursued in agriculture through the production of bioenergy, soil improvers and fertilizers, and the use of by-products in animal feed. The "*regenerating natural systems*" principle includes preserving and enhancing ecosystems using renewable resources. It is implemented in the primary sector through the so-called regenerative agriculture.

CE strategies for the primary sector originate from these principles and are:

1) *Narrowing resource loops* through eco-innovations, it is possible to reduce the intensity of the use of resources and the impact on the environment per unit of product or service;
2) *Slowing resource loops* promotes the prolongation and intensification of the use of products to improve their value over time;
3) *Closing resource loops* aims to create new value through recycling and reuse of materials;
4) *Regeneration strategies* include actions that aim to preserve and enhance natural capital.

It is important to remember that there is often no clear distinction between these strategies, which can overlap and coexist. The first strategy includes all activities that improve efficiency regarding nutrients, costs, labor, materials, energy, and capital and reducing associated negative externalities. The application of the second strategy is more complex in the agricultural field as all food goods are characterized by alteration resulting from their use and cannot be reused for the same purpose or repaired to expand their useful life; this strategy can be understood as a series of actions aimed at extending the lifespan of products within the agri-food system, such as raising the shelf-life of food products. The closing resource loops strategy includes the production of bioenergy, composting, or reusing co-products or waste in animal feed. The critical point of this strategy is that the marginal cost of reuse must be lower than using virgin material, and the reused material must have the minimum technical characteristics required by the process in which it is inserted.

The latest strategy includes actions aimed at preserving and improving natural capital, such as using organic fertilizers, sowing cover crops during periods in which the soil would otherwise remain bare and exposed to atmospheric agents, the minimum tillage, and the improvement of biodiversity. This strategy incorporates different practices such as agroecology, rotational grazing, agroforestry, silvopastoralism, and permaculture.

Animals bred according to CE principles can play an essential role in feeding the ever-growing world population. Farming is a potential contributor to the spread and realization of the CE as animals recycle resources by nature, although in different ways depending on the context in which they are placed (Díaz de Otálora et al., 2021). Currently, a perfect circular agri-food system remains a utopia due to its natural openness and complexity, associated with the fact that losses of materials and nutrients cannot be eliminated (Van Zanten et al., 2019).

1.4 The Circular Economy and the Sustainable Development

Over the last decade, growing attention has been paid to the concepts of sustainability and CE, which were used in different contexts with different purposes. In a review, Geissdoerfer et al. (2017) identified 59,464 articles on the topic of sustainability and 295 on the theme of CE. As with the CE, there is no single definition for sustainability, as demonstrated by Johnston et al. (2007), who identified around 300 of them.

The most known definition of Sustainable Development (SD) was provided by The Brundtland Report in 1987, which defines it as "*development that meets the needs of the present without compromising the ability of future generation to meet their own needs*" (Brundtland, 1987). This document, developed by the United Nations during the World Commission on Environment and Development in Tokyo, identifies the three dimensions that compose SD: environmental, economic, and social.

The first modeling of the SD is provided by Young (1997), representing the three dimensions as three pillars, underlining how these must be equally balanced with each other to achieve long-term sustainability. This model was contested because it implies that the dimensions are separate from each other. In 2008, Lozano proposed a representation of the three dimensions using a Venn diagram (Image 2), which could highlight how one dimension affected the other two and how they had to be interconnected to achieve the SD.

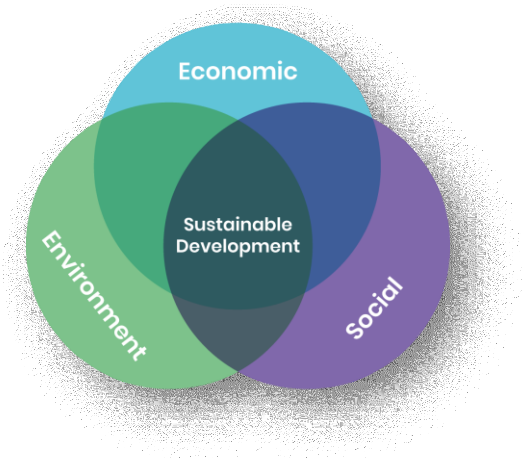

Image 2. Venn diagram of the three dimensions of Sustainable Development. Source: (Lozano, 2008)

Recently, the use of the three dimensions, economic, environmental, and social, has been criticized, proposing to replace them with *a*) satisfaction of human needs, *b*) guaranteeing social equity, and *c*) respecting the limits of the environment (Holden et al., 2017).

In 2015, during the United Nations conference in New York, the 2030 Agenda for SD was defined as an action program for people, planet, and prosperity, signed by 193 countries. The 2030 agenda contains the "Sustainable Development Goals" (SDGs), 17 objectives identified to solve the main environmental, political, and economic problems affecting the planet. In line with this global aim, the European Commission prepared in December 2015 a document entitled "Closing the loop: An EU action plan for the Circular Economy", from which emerges the idea that there is a strong relationship between the CE and the SDGs, and that this new paradigm can contribute to achieving SDG 12 aimed at promoting responsible production and consumption models (European Commission, 2015).

It is commonly accepted that the linear development model, characterized by environmental pollution and poor social equity, is not the right tool to achieve SDGs. (Andersen, 2007). Although CE is often associated with and identified as a method to achieve Sustainable Development (European Commission, 2015; Ghisellini et al., 2016; Kirchherr et al., 2017; Korhonen et al., 2018; Saidani et al., 2019; Schroeder et al., 2019), the relationship between these two concepts is ambiguous and is not well defined (Geissdoerfer et al., 2017; Millar et al., 2019; Schöggl et al., 2020).

The idea that CE is a tool to reach SD is based on the following reflections (Rodriguez-Anton et al., 2019; Schroeder et al., 2019):

1) CE aims to separate economic growth from the overuse of resources, thereby reducing pressure on the environment;
2) Promoting reuse, recycling, and re-manufacturing should lead to creating new jobs, thereby increasing social equity;
3) Applying this production and consumption model should lead to economic growth.

However, from the analysis carried out by Kirchherr et al. (2017), it emerges that among the 114 definitions of CE analyzed, 11% include explicit notions linked to SD, 13% refer to the three dimensions, and only 1% reference future generations. Often, the concept of CE does not consider the three dimensions of sustainability as a whole, focusing more on economic and environmental aspects to the detriment of social ones (Murray et al., 2017; Schöggl et al., 2020) and does not present a temporal dimension, limiting its vision to the here and now without caring about intergenerational equity (Lieder & Rashid, 2016; Geissdoerfer et al., 2017). For example, Borrello et al. (2020) indicate CE as a tool that can contribute to achieving economic and environmental sustainability objectives by pursuing an eco-effectiveness approach. However, even in this case, only two of the three dimensions of sustainability are considered.

We all agree on one thing: to pursue sustainable development, the achievement of the objectives of one dimension must not be pursued to the detriment of the other two and vice versa. When defining the CE and the practices proper for ensuring SD, it is fundamental to consider the possible compromises that can occur to the detriment of one or more dimensions of sustainability (Blum et al., 2020; Schöggl et al., 2020).

Based on this, if CE aims to provide a new model of economic development that achieves SD, it is necessary to formulate definitions that consider the three dimensions and the time frame. A first attempt was made by Kirchherr et al. (2017), but if there is no common agreement to use the definition he proposed, the impact on CE application will remain minimal. Another attempt to integrate the SD concepts into the CE framework was made by Blum et al. (2020), which propose the Sustainable Circular Economy (SCE), made up of 4 different dimensions:

1) *Material circularity*, based on the use of materials at their maximum qualitative value for the longest possible time;
2) *Economic sustainability*, which requires the generation of economic value;
3) *Environmental sustainability*, based on the reduction of environmental impact;
4) *Social sustainability*, which requires the improvement of living conditions for all humanity.

According to the authors, if an activity satisfies all the dimensions mentioned above, it can be said to have positively applied CE to SD objectives.

Ultimately, there is currently no certainty about how CE can be used as a tool to achieve SD, but this is certainly a more sustainable development model than the linear development model (Millar et al., 2019).

1.5 The Sardinian Dairy sheep sector

There are approximately 1,200 million sheep globally, generally located in sub-tropical areas and concentrated in the Mediterranean and Black Sea regions. According to FAOSTAT (2022), sheep milk is produced in Asia (46.8%), followed by Europe (29.5%), Africa (22.8%), and America (0.9%), and its production is expected to increase by approximately 3 Mt by 2030 (Pulina et al., 2018).

European sheep farming is an important sector, playing sociocultural, economic, and environmental roles, ensuring livelihoods for vulnerable populations in rural and marginal areas (Paraskevopoulou et al., 2020). Indeed, the agricultural economy of various regions of Mediterranean Europe is strongly related to this production, for which Greece, Spain, Italy, and France contributed about 31.8%, 19.0%, 16.6%, and 10.8%, respectively (FAOSTAT, 2022). This may be because dairy products are typical ingredients of the human diet in these regions, where there was a relevant Greek or Roman cultural heritage (Caja, 1990).

Sardinia is the principal region of the EU for sheep milk production, which reaches approximately 320,000 t per year (ISTAT, 2020), contributing about 40% of the regional total gross agricultural production value and about 69% of Italian production (Laore Sardegna, 2020) As for the livestock consistency, in the last decade, the number of sheep raised in Sardinia has increased by about 289.652 heads, in respect to the total amount of 2010, while the number of farms was similar to the 2010, with an increment equal to 211 units (ISTAT, 2022).

The Sardinian dairy sheep sector plays a considerable role in the regional economy (Rete Rurale Nazionale, 2018), ensures job occupation for thousands of people, and is a primary source of livelihood for several communities. Furthermore, this sector has been at the heart of local cultural identity for millennia and provides multiple ecosystem services, such as landscape maintenance and safeguarding vegetal and animal biodiversity (Furesi et al., 2013; Mattalia et al., 2020; Atzori et al., 2022) and, social services (Madau et al., 2022).

However, this sector generally operates with low-profit margins (Idda et al., 2010; Vagnoni et al., 2015), and profitability often depends on the amount of financial aid made available by the Common Agricultural Policies (Cerrato et al., 2023). This circumstance jeopardizes the medium-long-term survival of the Sardinian dairy sheep sector, which translates into severe impacts for most of the social, economic, and environmental benefits that people obtain from agro-pastoral activity, an even more powerful situation given that this region is located in one of the most underdeveloped areas of the EU (CRENoS, 2020).

The peculiarities of this sector, the multiple ecosystem and social services it provides, and no less importantly, the economic role it plays in the Sardinian region, make it a privileged observation point to evaluate particular aspects of sustainability, and it is for this reason that we have chosen to use it in our studies.

Image 3 represents a typical Sardinian ewe whit her lambs.

Image 3 – Sardinian ewes whit lambs. Source: personal archive

1.6 The objective of the Thesis

This work is structured into a general introduction, three chapters of experimental contributions, and general conclusions. The widespread introduction aims to provide an overview of the literature on the nature of CE and SD and seeks to answer the following questions:

1) What are the points of contact and differences between sustainability and circular economy concepts?
2) How are these paradigms expressed in the agricultural and livestock sector?

These two general objectives arise from the need to clarify some gaps in the literature. The two concepts are often used interchangeably and there few studies have been focused on how these are declared in the primary sector.

Furthermore, the following sections of the doctorate thesis will be aimed at giving empirical answers to the questions below:

a. What is the degree of circularity of agriculture?
b. What services provided by dairy sheep farming can be used to improve sustainability and ensure the durability of this sector
c. What is the relationship between economic and environmental sustainability on Sardinian sheep farms?

The answers to the above questions are divided into three chapters.

The first, focusing primarily on agriculture and the agri-food sector, answers the first question, and uses one of the possible methodologies to evaluate circularity. The degree of circularity in agriculture in the 27 EU countries was assessed using data on the EXIOBASE database (Merciai & Schmidt, 2016, 2018) and applying the Aguilar-Hernandez et al. (2019) framework with specific reference to agriculture. To our knowledge, it would be one of the first attempts to measure circularity – by indexes such as Circularity Index (CI), Circularity GAP (CG), and Circularity Gap Index (CGI) – in agriculture.

Subsequently, in Chapters 2 and 3, the focus was exclusively on the Sardinian dairy sheep sector.

As part of assessing the sustainability of the Sardinia dairy sheep system, the positive externalities it provides, called Ecosystem Services (ESs), were analyzed in Chapter 2. ESs are defined as "*the direct and indirect benefits that ecosystem provide* *to humanity*" (Millenium Ecosystem Assessment, 2005, p. 26) and social services, here intended as the livelihood's protection in inland areas and depopulation averting. This Chapter aimed to assess how different target populations perceive Sardinia dairy sheep farming and the important services it performs, representing a first attempt in the literature to evaluate these aspects deriving from practices. In Chapter 3, a set of indicators starting from the Farm Accountancy Data Network (FADN) was used to define the relationship between economic and environmental dimensions of sustainability in dairy sheep farms. After that, through the trade-off analysis (Phillips, 1958), the existence and magnitude of synergies or trade-offs between the two sustainability dimensions were assessed. Finally, we used regression analysis to investigate whether there is a relationship between economic and environmental sustainability indicators and structural profiles of the farms and socio-demographic variables of farmers. Evaluating the relationships between economic and environmental dimensions of sustainability is useful for making choices that do not pursue one of the two spheres to the detriment of the other.

Finally, the general conclusions reported in Chapter 4 offered a short overview of the main results obtained during the Ph.D.

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CHAPTER 1

The Circular Economy in the Agri-food system: A Performance Measurement of European Countries

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ABSTRACT

Agriculture and the agri-food industry are central to fostering economic growth and the Sustainable Development Goals' targets. However, to meet the world's future development, it is necessary to make the agri-food system more resource-efficient. The transition towards the circular economy (CE) paradigm is commonly seen as a promising strategy to overcome the critical issues affecting the sector. However, different theoretical and practical problems still need to be solved. Specifically, the CE performance measurement of specific sectors or national systems is crucial as it helps to identify and correct any deviation from the vision set out for achieving the sustainable development objectives. This article aims to contribute to CE research, focusing on European agriculture and the agri-food sector. Drawing on the EE-MRIO database EXIOBASE v3.7, this paper estimates the level of circularity in the European Union countries and the role of agriculture and agri-food in determining circularity. Results showed that circularity in the EU is low and significant differences between countries exist. Agriculture contributes to 80.5% of the entire amount of recycled materials in Europe. Vice versa, the contribution provided by the agri-food sector is limited to 1%. Some policy implications derive from this study.

Keywords: Circularity index, Circularity Gap, Index, Agriculture, Waste recycling, Exiobase.

1. Introduction

Following the industrial revolution, the world economy has grown through the “extraction–production–consumption–disposal” model, based on easily denied assumptions (European Environment Agency, 2016), such as the abundance of available resources and economic convenience of their procurement. However, it is a common opinion that this linear “take-make-waste” model is not sustainable in the long term, requiring an urgent evolution to remedy the massive, negative impacts of humanity on society and the environment (Brandão et al., 2020; Edgeman, 2020).

The circular economy (CE) stands in stark contrast to the linear model as it concerns an economy capable of reconstituting and regenerating itself, using renewable energy, and minimizing waste due to the design of products that can be subsequently repaired, recycled, and finally reused. In this perspective, CE is an approach to sustainable development that is gaining ever more attention among academics, politicians, and people in business (Ghisellini et al., 2016; Golebiewski et al., 2019; Kirchherr et al., 2017; Korhonen, Honkasalo, et al., 2018; Xue et al., 2010; Yuan et al., 2006). Although CE studies are still in their initial phase and there are numerous fields to be explored yet (Korhonen, Nuur, et al., 2018), several scholars agree that it is “an idea and an ideal” (Gregson et al., 2015, pag. 218) to redirect the path of economic development and enable cyclical thinking towards the creation of a zero-waste economy (Homrich et al., 2018; Zwier et al., 2015).

The CE has been defined as an "umbrella concept" (Homrich et al., 2018) under which there are various definitions that address the issue from different perspectives (Borrello et al., 2020; Korhonen, Nuur, et al., 2018), although numerous are the authors (e.g. Blomsma & Brennan, 2017; Haas et al., 2015; Haupt et al., 2017; Hobson, 2016; Moreau et al., 2017; Naustdalslid, 2014; Niero et al., 2017; Singh & Ordoñez, 2016) who have relied on the definition provided by the Ellen MacArthur Foundation: "a CE is regenerative by design and aims to gradually decouple growth from the consumption of finite resources".

The CE consists of a continuous positive development cycle that preserves and enhances the natural capital, optimizes the yields of the resources, and minimizes system risks by managing finite stocks and renewable flows. According to the European Commission (2008), the CE is based on four principles (4R) – Reducing, Reusing, Recycling and Renewing –, which implies the review of all stages of production - that must comply with the fundamental criteria of eco-design, modularity and versatility, use of renewable energies, eco-systemic approach and recovery of materials (Ellen MacArthur Foundation, 2021) – and the supply chain involved in the production cycle.

However, it must be underlined that CE is first an economic strategy. In this sense, CE suggests innovative ways to switch from the current predominantly linear consumption system towards a material savings and resources regeneration system to achieve economic sustainability. With a specific reference to agriculture and the agri-food industry, it is pivotal to ensure the transition of this sector toward the CE paradigm to foster and achieve global development (De Pascale et al., 2021).

Those key sectors for human wellness will face significant scenario changes and are called to solve issues such as resource scarcity, food loss and waste generation. The FAO (2019) estimated that in 2019, along the world's supply chain, was generated approximately 1.3 billion tons annually of waste with a cost of more than 1000 billion dollars per year. However, the agriculture and agri-food problems do not exhaust themselves in the mismanagement of resources and processes, that is, food production dependence on fossil fuel, non-renewable mineral resources, the exhaustion of groundwater reserves and excessive soil loss (Muscio & Sisto, 2020). Just think about how consumers' unsustainable consumption patterns is a major accomplice of agriculture in terms of its pressure on the environment and influence on climate change (Esposito et al., 2020; Taghikhah et al., 2019).

In this scenario, CE is seen as a possible and promising strategy to overcome the critical issues that affect those sectors (Esposito et al., 2020; Hamam et al., 2021), making the entire agri-food system more resource-efficient, with positive food security implications (Jurgilevich et al., 2016; Muscio & Sisto, 2020). In effect, numerous are the expected benefits, that is, use a minimal amount of external inputs, reduce negative discharges to the environment, close nutrient loops, increase farming efficiency, improve the nexus into the food supply chain and among productivity sectors, increase competitiveness, stimulate innovation, boost economic growth (European Parliament., 2015; Ward, 2017).

However, these benefits can be overshadowed by some critical issues that affect not only the agriculture and the agri-food sectors, such as theoretical (i.e., too multiple definitions), political and practical, also in terms of design, logistic, scale (i.e. processes, industrial site, business dimension, regions and economics) (Corvellec et al., 2021; Muscio & Sisto, 2020; Walmsley et al., 2019), and measurement (Circle Economy, 2021).

Especially the latter requires particular attention since the relevance of the CE into the actual economic strategies. Borrowing the phrase attributed to Peter Drucker, "if it cannot be measured, it cannot be managed", the CE performance measurement of specific sectors or national economies is crucial. Firstly, because it is the first step in moving toward a circular food production system, a process that requires proper tools for effective measurement to support robust decision-making (Velasco-Muñoz et al., 2021). Secondly, because of it helps to identify and correct any deviation from the vision set out for achieving several SDGs of the 2030 Agenda for sustainable development. In effect, the CE is seen as an engine of sustainability that improves traditional sustainability approaches based on eco-efficiency to reach a greener economy by promoting more appropriate, eco-friendly resource use and innovative business models (Hamam et al., 2021). According to Xue et al. (2010, pag. 1298) the CE "is the outcome of over a decade's efforts to practice Sustainable Development by the international economies and is the detailed approach towards Sustainable Development". In this vein, the current European Commission's target to close material loops and change the European economy towards a circular economy reveals the key role played by CE in reaching SD goals (European Commission, 2015;

Geissdoerfer et al., 2017). Moreover, CE contributes directly to several SDGs, such as SDG6, SDG7, SDG 8, SDG12, SDG15 (Schroeder et al., 2019).

At the same time, research on agriculture and agri-food sustainability transitions toward the CE paradigm is still poor, especially concerning the measurement of circularity into the system (Hamam et al., 2021; Muscio & Sisto, 2020).

This article aims to contribute to CE research, addressing the recent calls for research in CE in the agri-food sector (Hamam et al., 2021). Specifically, the study focuses on the European context, which is among the world's leading producers and net exporters of agri-food products (European Commission, 2021b). Moreover, already from 2014, the concept of CE has become a strategic key to the development of the EU (see EU/COM/2014/0398 final) and to make it cleaner and more competitive (European Commission, 2021a). By the new Circular Economy Action Plan adopted in 2020, the EU reaffirmed the importance of the change towards the circular economy, also for the agricultural and agro-food sectors, highlighting how the food value chain is accountable for significant resources and environmental pressure. However, the EU economy is still largely linear, and the agricultural sector is a major user of natural resources (European Environment Agency, 2017, 2020; Muscio & Sisto, 2020).

Despite previous research at the macro level and few previous studies focused on some agri-food chains, such as pasta (Principato et al., 2019) and tomato (Boccia et al., 2019), as far we know, there are no studies that currently measure the circularity of the agricultural and agro-industrial sector of individual European countries.

Therefore, this paper aims to fill this literature gap by answering the following research question: “What is the level of circularity of the agricultural and agri-food sector of the European countries?”. In particular, drawing on Aguilar-Hernandez et al. (2019) research and Environmentally extended multiregional input-output (EE-MRIO) database EXIOBASE v3.7, this paper intends to measure the circularity of European countries and the role of agriculture and agri-food in determining their circularity.

The paper is organized as follows: Section 2 presents the methodology employed. Section 3 presents the results. The final Section presents discussions and conclusions and outlines the implications for practitioners, academics, and policymakers and makes recommendations for future research.

2. Background

The performance measures are pivotal for guiding and reviewing CE policies (Ekins et al., 2019), as the look forward indicators provide guidance, and backwards ones give feedback and review performance. Moreover, indicators importance arises from the fact that their choice is a critical determinant of the behavior of a system (Meadows, 1998). Recently, some authors (i.e. De Pascale et al., 2021; Saidani et al., 2019) have provided an overview of the CE indices, classifying them into three levels, micro, meso and macro. Nevertheless, the attempts to globally assess the current circularity of the system are thin, perhaps due to the great challenge required and several data limitations (Ekins et al., 2019). Grounded in Material Flow Accounting, Haas et al. (2015) estimate the global economy circularity as the "share of actually recycled materials in total processed materials". Mayer et al. (2019) based their study on previous contributions (Haas et al., 2015; Nuss et al., 2017) and used the material flow approach to investigate the degree of circularity of the EU.

An important contribution to this direction has been provided by the Circle Economy (Circle Economy, 2021) approach aimed to estimate the degree of circularity of the global economy. The first document – the Circularity Gap Report - was published in January 2018, and the assessment of circularity was based on the Material Flow Accounting. The reports published every year "provide high-level insights into the global metabolism and key levers for transitioning to circularity" (Circle Economy, 2021), and measure the circularity as 'cycled materials' as a share of the total resources entering the economy. The Circularity Gap Report (Circle Economy, 2021) revealed that at present, our world is only 8.6% circular, leaving a massive Circularity Gap. This report relies on the EE-MRIO database EXIOBASE v3.7.

The Environmentally Extended Input-Output Analysis is a particularly useful framework that fits with the economic outlook used in CE and allows considering diverse measures for improving circularity, that is residual waste management, loop-closing in supply chains, product life extension and resource efficiency (Aguilar-Hernandez et al., 2018; Walmsley et al., 2019). In particular, according to Harris et al., (2021), EXIOBASE is the dominant database in the CE literature and has been used to assess the generation and recovery of waste, depletion of stocks and the circularity gap. Moreover, although previous authors have raised some problems regarding the completeness of EXIOBASE (Tisserant et al., 2017), the reliability of the entire database is not affected, and MRIO analysis was demonstrated to be capable of quantifying global and regional flows of material and estimating the quantity of it that is recycled (Aguilar-Hernandez et al., 2019).

Relying on the EE-MRIO database EXIOBASE v3.7, other authors used the same database to analyze the mitigation of environmental impact related to food consumption in Denmark (Osei-Owusu et al., 2022) or to test the implementation of the strategies of the product lifetime extension and resource efficiency (Donati et al., 2020). In the same vein, Aguilar-Hernandez et al. (2019) first have estimated and compared the material circularity gap of more nations (43 nations and 5 global regions in 2011) in a consistent framework. They quantify the Circularity Gap (CG), a measure of the waste materials that are theoretically available for circularity resulting from "the generated waste, plus old materials removed from stocks and durable products disposed of (i.e. stock depletion), minus recovered waste". In other terms, for the circularity gap calculation, they proposed the use of a metric that considers how much of the unrecovered waste can be turned into the economy as products or materials. Their approach differs from previous studies since they made an explicit mathematical distinction between the added materials to stocks and the ones dispersed in the environment as dissipative emissions or other combustion residues, allowing to determine the actual fraction of waste that is circular in a given period. From the GC, the authors drew up two other indicators, the Circularity index (CI) and the Circularity gap index (CGI).

Based on these considerations, the Aguilar-Hernandez et al. (2019) framework is suitable for our research purpose.

3. Materials and methods

Building upon the work of Aguilar-Hernandez et al. (2019), Image 1.1 shows the system's boundaries of national material flow inputs, outputs and stocks according to the data contained in EXIOBASE.

In the material flow diagram, the solid boxes depict the socio-economic processes, and the solid circles represent the material stocks. The formers consider the intermediate activities and final demand (I&C), the waste treatment sectors (T), and the rest of the world economy (RoW).

The second are the stock of natural resources (N), the material in-use stocks (S), and the stock of nature from domestic processed outputs (DPO). The lines constitute the flows. The solid ones consider the imports (*m*), domestic resource extraction (*r*), recovered or secondary materials (w_{rec}), exports (*e*), waste generation or supply (w_{sup}), additions to stocks (s_{add}), and stock depletion (s_{dep}).

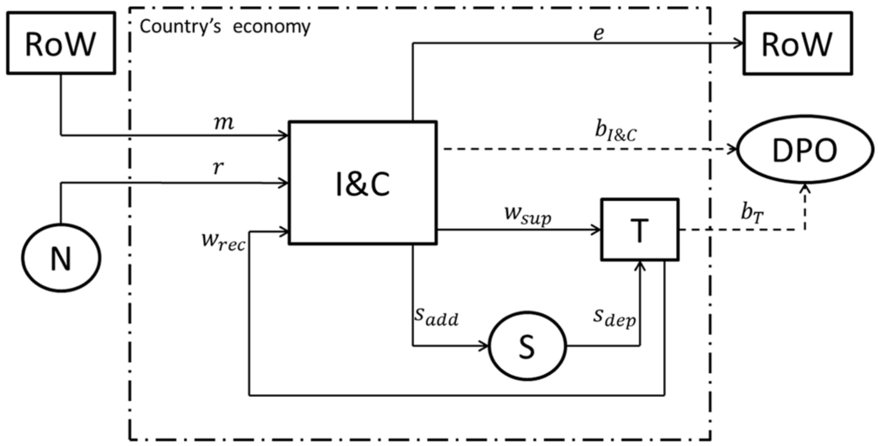

Image 1.1 - System definition of national material flow inputs, outputs and stocks, own elaboration based. Source: Aguilar-Hernandez et al. (2019)

The dashed ones pose the flow of dissipative emissions and other combustion and biomass residues caused by intermediate activities and final demand (bI&C) and waste treatment (bT). According to the authors, as the analysis looks at a system boundary for the global economy, the imports (*m*) exports (*e*) are not considered, as well as the RoW sectors, that, due to physical trade balance to other regions, does not occur in this context.

The Circularity Gap (CG) refers to all waste generated ruled out the recovery waste, which means the amount of waste not used in a circular way. In other terms, it is the difference between the entire volume of waste and the quota re-used or re-cycled. It arises from three main outflows linked to the waste material: w_{sup}, s_{dep}, and w_{rec}. The CG can be expressed as follow:

$$CG = w_{sup} + s_{dep} - w_{rec} \quad (1)$$

Image 1.2 indicates the kinds of viable intervention (signaled by the white square with dots line border) to reduce the circularity gap by acting on stock depletion, material recovery, and waste generation, depicted in squares 1, 3 and 4. The up arrow indicates an increase in material flow, while the down arrow shows a decrease or delay in waste flow.

The Circularity Index (CI) for a specific country takes into account the import (*m*) – imports to EU and non-EU countries were considered for all 27 countries present in the study, as required by the CI formula, whereas the exports are not considered as not required by CI calculate – and domestic resource extraction (*r*), which together indicate the domestic material input of I&C.

In other words, this index shows the proportion of material that, after being introduced into the economy, is destined for reuse, and can be expressed as:

$$\mathrm{CI} = \frac{w_{rec}}{r+m} \times 100 \tag{2}$$

In the same vein, the country Circularity Gap Index (CGI), which reports how much material, compared to that potentially reused, is not addressed to recycling, can be calculated as

$$\mathrm{CGI} = \frac{CG}{w_{sup}+s_{dep}} \times 100 \tag{3}$$

and it indicates the weight of all waste generated ruled out the recovery waste with respect to the total weight produced. The level of circularity is, therefore, inversely proportional to the CGI (the circularity increases with the decrease of CGI).

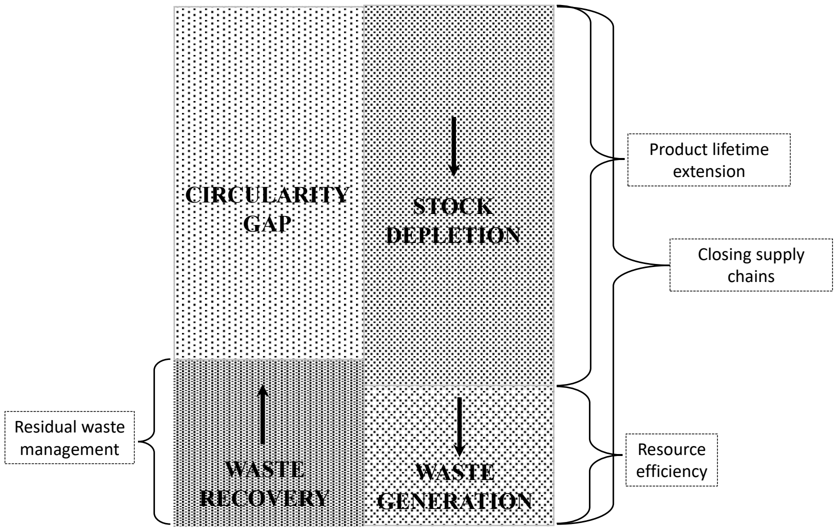

Image 1.2 - A circularity gap reduction through four intervention types. Source: Aguilar-Hernandez et al. (2019)

Data to estimate the circularity in the entire economic system (European Union and its single countries) and the role of agriculture and agri-food in determining circularity were delivered from the input-output tables shown by the EXIOBASE database. It arises from three EU-funded projects, CREEA, EXIOPOL and DESIRE, and includes data on global production recipes and demand by households, firms and government for different products and services.

EXIOBASE database is a global environmentally extended monetary and hybrid multi-regional supply and use/input-output table (MR SUT/MR IOT) for

164/200 industries/products, 44 countries (28 EU countries, 16 non-UE countries and five rest of world regions), and 2000–2011 years (Merciai & Schmidt, 2018). It uses different units measure: physical mass (e.g., tons for tangible goods and waste), joule (for energy and electricity flows) and currency/economic value (for services).

This study uses version 3.3.17 of hybrid EXIOBASE's data sources, which includes national reports, the Food and Agriculture Organization (FAO, 2021), International Energy Agency (IEA), Eurostat, International Fertilizers Association (IFA) and Ecoinvent databases.

The algorithm of EXIOBASE multi-regional hybrid supply and use tables is divided into general and sectorial modules. The latter is "a self-standing block that delivers results to the general part" (Merciai & Schmidt, 2018, p. 519), such as the agriculture module, which aims to determine the mass balance for all the agricultural activities. Image 1.3 represents the input-output table of the EXIOBASE agriculture module.

<table>
<tr><td rowspan="4">CROPS</td><td colspan="2">INPUT</td><td rowspan="4">LIVESTOCKS</td></tr>
<tr><td>– Carbon dioxide
– Minerals
– Nutrients from fertilisers and manure</td><td>– Oxygen from animal respiration
– Market and non-market feed
– Grass</td></tr>
<tr><td colspan="2">OUTPUT</td></tr>
<tr><td>– Harvested crops *
– Emissions
– Manure excreted***
– Crop residues</td><td>– Animal growth**
– Emissions
– Manure excreted***</td></tr>
</table>

Image 1.3 - The EXIOBASE Agriculture module schema. Source: Authors elaboration.

* Paddy rice, wheat, cereal grains nec, vegetables, fruit, nuts, oil seeds, sugar cane, sugar beet, plant-based fibers, crops nec.

** Cattle, Pigs, Poultry, Meat animals nec, Animal products nec, Raw milk, Wool, silk-worm cocoons, Fish and other fishing products, services incidental of fishing.

*** Conventional treatment, biogas treatment.

Concerning the crop activities, in the EXIOBASE, the input comprises the carbon dioxide, minerals, and nutrients from chemical fertilisers and manure, while the outputs (i.e., the productions of activities) include the harvested crops, emissions, manure excreted and the use of crop residues. Regarding the livestock activities, the inputs include oxygen for animal respiration, marketable and non-marketable feed, and grass, while the outputs involve the animal growth, emissions, and manure excreted.

The use of this version of EXIOBASE required some adjustments for calculating the index variables. Since there were no extension accounts of waste supply/use and stock depletions, these flows were calculated using the MR-SUT e MR-IOT. To identify the w_{sup}, both for the activities and the final demand, we considered 22 activities related to incineration, biogasification and land application, composting and land application, waste-water treatment, and landfill. The s_{dep} was estimated by the Gross fixed capital formation item presented in the final demand. The w_{rec} were identified considering 20 activities related to re-processing, recycling, biogasification and composting products. The r was represented by 18 activities related to wool and silk, forestry products, fishing activities and extraction of metals, fossil fuels, stone, sand, clay and other mining and quarrying products. The m are indicated by all material flows from other countries, except those related to waste recovery. The w_{sup} and s_{dep} were derived by MR-SUT. The w_{rec}, r and m have been calculated from the MR-IOT (please see Appendix 1 for details on the list of items included in the variables of CI and CGI indexes).

Finally, two linear regression analyses across the 27 countries were applied to estimate if the general Circularity Index – that for its inherent nature represents the most relevant index in our study because provides a measure of the level of circularity - would depend on the domestic level of economy and on the economic weight of agriculture:

$$CI_i = \alpha + ß_1\ GDP_i \quad (4)$$

$$CI_i = \alpha + ß_1\ AEV_i \quad (5)$$

where CI_i is the Circularity Index by each *i*-country, α is a constant, ß is the coefficient related to the independent variables, GDP_i is the pro-capita Gross Domestic Product by each *i*-country, AEV_i is the pro-capita Additional Economic Value of agriculture by each *i*-country.

The choice of applying two regressions was suggested by the need of prevent possible interdependency between the two variables. In this term, we would highlight not only the magnitude and the statistical significance of each variable, but also the degree of relation between each variable and the level of circularity (dependent variable).

Data on national GDP and AEV were extracted from the Eurostat database and represent annual average values with reference to the period 2011-2020.

4. Results

A preliminary analysis was carried out to offer a snapshot of what is occurring in the entire economic system of Europe. The findings on circularity in the whole economic system of Europe are shown in Table 1.1.

Firstly, the analysis shows that Europe is very far from the global average of the circular economy. Although it pains to say it – while using different versions of the database and methodological approaches – the fact is that Europe is only 4.1% circular, almost half of the already shallow global value of 8.6% (Circle Economy, 2021). However, it must be underlined that the different ways of calculation and versions of the database can affect magnitudes. Therefore, obtained results are not fully comparable with those shown in the Circularity Gap Report. Basically, the level of circularity related to the entire EU system is found to be low.

The best country is Ireland, equal to approximately three times the European average. Although at levels not comparable to this score, Denmark and France also show a good rate of circularity, placing themselves in second and third place, respectively.

However, 11 out of 27 countries re-employ less than 3% of material introduced into the economic system, with Malta, Bulgaria, and Greece representing the three worst countries, respectively.

Concerning the amount of materials that are not addressed to recycling compared to that potentially reused, Europe shows an average of 72.3%. Specifically, 24 out of 27 countries reveal a CGI above 50%, of which 13 are above 70%. Given the nature of these indexes, the country ranking by CGI reflects that by CI – in an inverted way – with only two countries (Denmark and Ireland) showing a score below 50%.

Finally, looking at the amount of waste not used circularly, European countries show an average of 27.5 million tons with sharp differences among them. The worst country is Bulgaria, followed by France and Germany, whereas the best one is Slovenia, followed by Croatia and Lithuania.

To answer our research question, firstly, we analyzed the circularity degree in the EU agricultural (Table 1.2) and the agri-food sectors (Table 1.3). Secondly, we measured the weight of latter compared to the circularity recorded in each country and estimated the weight of agriculture on agri-food (Table 1.4).

Looking at the European agricultural sector, the results highlight the role of this sector in determining European circularity. In fact, on average European countries recycle 3.4% of the materials introduced into the economic system, equal to 80.5% of the entire amount of recycled materials in the EU. Also specifically in this sector, the most striking countries in this area are Ireland, Denmark, and France, whereas Greece, Finland and Malta represent the less virtuous.

Table 1.1 – Analysis of the circularity degree of the entire European economic system

EU Country	CI (%)	CGI (%)	CG (M tonnes)
Austria	3.6	74.0	14.8
Belgium	4.4	61.0	12.4
Bulgaria	1.7	98.8	143.0
Croatia	3.3	65.4	2.0
Cyprus	2.2	98.5	23.8
Czech Republic	2.5	54.6	5.3
Denmark	8.3	42.1	5.0
Estonia	2.5	92.3	10.4
Finland	2.4	91.4	33.0
France	6.6	76.0	123.9
Germany	3.6	58.0	57.9
Greece	2.1	93.3	57.3
Hungary	6.0	85.0	23.9
Ireland	13.0	33.6	4.8
Italy	3.3	68.4	42.5
Latvia	5.0	83.5	4.9
Lithuania	5.6	62.3	2.9
Luxembourg	2.6	98.5	26.1
Malta	1.5	99.7	15.0
Netherlands	5.5	51.0	14.9
Poland	3.7	58.0	28.4
Portugal	2.6	64.8	7.2
Romania	5.0	54.7	10.3
Slovak Republic	2.2	78.0	5.7
Slovenia	5.1	55.5	1.5
Spain	5.0	62.9	37.0
Sweden	2.1	89.5	28.6
EU-27	**4.1**	**72.3**	**27.5**

Regarding materials that are potentially recyclable but have not been sent for recycling, the average value of the agricultural sector is equal to 43.3% (CGI). However, slightly more than half of these countries are below this average. The average CG of the agricultural sector is equal to 4.4 million tons. The surprising fact is that as many as 9 countries have a value of less than one million and 13 less than 2 million.

The amount of waste not used in a circular way by the 5 worst countries (Poland, Germany, Italy, France, Spain) is compressively bigger more than two times that of the other 22 countries.

Table 1.2 – Analysis of the European agricultural sector circularity degree

EU Country	CI (%)	CGI (%)	CG (M tonnes)
Austria	2.7	49.8	3.9
Belgium	3.4	36.4	3.5
Bulgaria	1.5	50.9	1.6
Croatia	2.9	48.3	0.9
Cyprus	2.1	51.0	0.4
Czech Republic	2.0	38.3	2.2
Denmark	7.0	15.2	1.0
Estonia	1.6	48.6	0.5
Finland	1.4	66.9	3.6
France	5.7	32.2	15.9
Germany	2.5	43.9	23.0
Greece	1.2	59.5	3.6
Hungary	4.6	34.3	1.7
Ireland	12.7	9.3	0.9
Italy	2.4	56.0	18.2
Latvia	4.2	37.5	0.5
Lithuania	5.3	29.2	0.7
Luxembourg	2.0	40.1	0.2
Malta	1.5	89.6	0.4
Netherlands	4.4	32.5	5.5
Poland	2.9	32.2	7.6
Portugal	2.2	44.4	2.6
Romania	4.1	41.1	4.9
Slovak Republic	1.7	54.7	1.5
Slovenia	4.1	36.4	0.5
Spain	3.8	33.7	8.5
Sweden	1.8	56.4	3.6
EU-27	**3.4**	**43.3**	**4.4**

Table 1.3 – Analysis of the European agri-food sector circularity degree

EU Country	CI (%)	CGI (%)	CG (M tonnes)
Austria	2.7	49.0	3.8
Belgium	3.5	34.8	3.3
Bulgaria	1.5	50.9	1.6
Croatia	3.0	47.6	0.9
Cyprus	2.1	50.9	0.4
Czech Republic	2.1	37.8	2.2
Denmark	7.0	14.9	1.0
Estonia	1.6	48.2	0.5
Finland	1.4	66.3	3.6
France	5.7	31.4	15.5
Germany	2.6	42.6	22.3
Greece	1.2	59.4	3.6
Hungary	4.7	32.9	1.6
Ireland	12.7	9.1	0.9
Italy	2.5	54.6	17.8
Latvia	4.2	37.2	0.5
Lithuania	5.4	28.7	0.7
Luxembourg	2.0	39.9	0.2
Malta	1.5	89.6	0.4
Netherlands	4.6	29.8	5.0
Poland	3.0	30.1	7.1
Portugal	2.2	44.2	2.6
Romania	4.1	41.0	4.9
Slovak Republic	1.7	54.3	1.5
Slovenia	4.1	36.2	0.5
Spain	3.9	31.8	8.0
Sweden	1.8	55.5	3.5
EU-27	**3.4**	**42.6**	**4.2**

The circularity analysis on the agri-food sector traces the agricultural sector data partially. Even in this case, the recycling percentage of materials introduced into the sector is 3.4%, and the most virtuous countries are Ireland, Denmark, and France.

Compared to that potentially reused, the average of material not addressed to recycling is slightly lower than that of the agriculture sector (CGI equal to 42.6%). Only Ireland reports a score of less than 10%.

Concerning the amount of waste not used in a circular way in the agri-food sector, European countries show an average of 4.2 million tons. One of the most noteworthy data is that the three worst countries (Germany, Italy and France) record together almost the same value (55.6 million tons) deriving from the sum of the other 24 countries (58.4 million tons).

The impact of the agricultural and agri-food sector on the CE in individual countries is showing the Table 1.4. It should be noted that the calculated scores mean how much a single economic sector contributes to the entire country's circularity and not the circularity solely inherent to that given sector. This occurs because the nature of the input-output matrix does not allow us to enucleate a single production sector as a closed system, as each sector is characterized by exchanges of materials with the rest of the economy. This means it is impossible to arrive at circularity measures referable to a single sector. Still, we can calculate the level of circularity in the entire economic system that derives from the processes of a given sector.

The findings showed that:

1) The agriculture contributes, on average, to determine 80.5% of the total circularity in the European countries. This percentage varies from 57.4% of Finland to 97.7% of Malta. It means that agriculture plays a predominant role in determining circularity in all EU countries.

2) Looking at the agri-food sector leaving out its upstream phases, it results that it affects circularity by about 1% (the difference between the agri-food and

agriculture CIs). Indeed, the agriculture weights for about 99% on the agri-food index, highlighting how the weight of the other phases along the supply chain is little more than insignificant in promoting circularity processes.

Table 1.4 – Impact of agricultural and agri-food sector on the circularity of each country

EU Country	CI agricultural sector/ CI country (%)	CI agri-food sector/ CI country (%)	CI agricultural sector/ CI agri-food sector (%)
Austria	74.5	75.7	98.4
Belgium	76.9	78.8	97.5
Bulgaria	89.1	89.2	99.9
Croatia	88.3	89.5	98.7
Cyprus	97.5	97.7	99.8
Czech Republic	81.1	81.7	99.2
Denmark	84.0	84.3	99.6
Estonia	64.9	65.4	99.2
Finland	57.3	58.4	98.2
France	85.6	86.5	98.9
Germany	70.1	71.6	97.9
Greece	59.2	59.4	99.6
Hungary	77.0	78.7	97.9
Ireland	97.4	97.6	99.9
Italy	73.1	75.5	96.9
Latvia	84.7	85.0	99.6
Lithuania	95.3	95.9	99.4
Luxembourg	76.4	76.6	99.7
Malta	97.7	97.8	100.0
Netherlands	79.7	82.9	96.2
Poland	78.2	80.7	96.9
Portugal	84.9	85.2	99.6
Romania	82.2	82.3	99.9
Slovak Republic	79.4	80.1	99.2
Slovenia	80.6	80.8	99.7
Spain	76.7	78.8	97.3
Sweden	82.3	84.1	97.8
EU-27	**80.5**	**81.5**	**98.8**

However, we investigated to understand if and how much a possible improvement of the Gross Domestic Product and/or agricultural production value would affect national CI. Therefore, the general CI was separately regressed on two variables: the pro-capita Gross Domestic product, the pro-capita Additional Economic Value of Agriculture (AEV) according to the formulas (4) and (5).

The regression model was tested to estimate if the preferable model is with or without the constant term. As a testing procedure, we adopted the Generalised likelihood-ratio test, which allows us to evaluate a restricted model with respect to the adopted model. Findings suggest that the preferred model is without the α term.

Results of both regression analyses are reported in Tables 1.5 and 1.6.

Table 1.5 – Estimation of the linear regression model – Independent variable: GDP

Variables		**Coefficient**	**S.E.**	**z**	**p-value**	
Constant	α	-	-	-	-	
GDP	β_1	0.001	0.001	3.904	0.001	***
$R^2 = 0.641$						
			Test on regression			
LL value	*LL' value**	$\chi2$	*d.f.*	$\chi2$ *(0.95)*		
-60.8	-61.6	1.6	1	3.84	0.000	***

*Alternative model without the constant term

Table 1.6 – Estimation of the linear regression model – Independent variable: AEV

Variables		**Coefficient**	**S.E.**	**z**	**p-value**	
Constant	α	-	-	-	-	
AEV	β_1	0.005	0.001	10.9	0.000	***
$R^2 = 0.908$						
			Test on regression			
LL value	*LL' value**	$\chi2$	*d.f.*	$\chi2$ *(0.95)*		
-48.3	-48.7	0.9	1	3.84	0.000	***

*Alternative model without the constant term

Results suggest that Circularity Index is positively and significantly related to the per capita Gross Domestic Product even if the magnitude is shallow. The correlation between the two variables is not much high (R2 = 0.641), but this analysis can depend on the differences in economic structure across regions (Aguilar-Hernandez et al., 2019).

The Circularity Index also results positively and significantly related to the per capita Additional Economic Value of agriculture. The magnitude of the coefficient is about five times higher than that estimated for the GDP, and the standard coefficient of determination is high (R2 = 0.908). These findings imply that the elasticity of CI with respect to the only agricultural sector income is remarkably higher than the entire domestic income of each country.

5. Discussion and conclusions

The role played by agriculture and the food sector in the natural resources sustainable use and preservation is undisputed. The European Commission (2020) intends to make European food the global standard for sustainability (Corrado & Zumpano, 2021) and sees the food sector as one of the most strategic in guiding the transition to a circular economy (Chiaraluce, 2021; Rocchi et al., 2021). To that end, it promotes the more efficient use of resources, that, in turn, contributes to economic growth, new market opportunities development and the mitigation of climate change.

Bearing in mind that CE principles can be deployed as a “toolbox” to attain several SDGs (Schroeder et al., 2019) and Green Deal, the centrality of the agri-food sector, in Europe as in worldwide, emerges strongly, even in light of emergencies linked to the COVID19 pandemic.

Given the above, and since the use of indicators is essential for monitoring the progress of sectors and countries towards a circular model (Poponi et al., 2022), the purpose of this study was to estimate the circularity level of the agricultural and agri-food sector in European Union countries.

First, we examined the overall level of circularity of the 27 European countries, finding that the average of the countries differs from the values previously observed by Aguilar-Hernandez et al. (2019) and stands at a much lower level (-4.5 points of difference) than the world average of 8.6 % as it stands in the last Circularity Gap Report (Circle Economy, 2021). This is despite a series of ambitious CE policies adopted by the European Commission, e.g., its "Circular Economy Package" (launched in 2015 and subsequently updated in 2018).

By focusing on the agri-food sector, although circular agriculture is still a new concept (Mor et al., 2021), the data clearly showed how relevant it is in pursuing the transition to an CE in the EU because the agriculture sector recycles 80% of the entire amount of recycled materials in Europe. However, there are major differences between countries.

A significant finding is the scarce contribution of agri-food to the CE of countries. This data reflects the amount of food waste generated in Europe, estimated at 88 million tons, equal to about 20% of the total food produced (Eurostat, 2018; Stenmarck et al., 2016). It is an absurd situation that odds with economic and ethical principles since it means to lose 143 billion euros, and 33 million Europeans cannot afford a quality meal every second day (Eurostat, 2018). Furthermore, the waste of food also depletes the environment of limited natural resources, clashed with SDG 12 aimed at ensuring the population's well-being by reducing the excessive consumption of natural resources, and SDG 2 that fosters the sustainability of food production systems and achievement of food security.

Further noteworthy results concern the relationships between CI and, by a hand, the additional value of the agricultural production and, by another hand, the GDP of each EU country: the first positive and significant, the second negative and significant. Therefore, increasing the domestic value of the agricultural production increases the circularity provided by the agriculture sector and the whole countries.

Therefore, it emerges that agriculture - given the state of technology nowadays and the nature of the inherent technical and economic processes - is the sector that contributes most to determining the level of CI in European countries – as confirmed by the incidence of the CI by agriculture on the global CI – and a possible increase of the additional value of agricultural production can affect CI more than can happen with a proportional improvement of the entire GDP. In other terms, an increase in the level of circularity of the EU economy passes primarily by the development of agriculture rather than by a general improvement of the performance of the entire economic system due to the relative high elasticity of this sector.

Basically, the marked ability of agriculture to be a leverage for fostering circularity would derive from the physiological propensity of the sector to resort to technical practices based on the regeneration of natural resources and the re-use of waste materials even within the same farms that generate waste. On the other hand, it should be emphasized that more than in other sectors, there is a widespread tendency on the part of farmers to use the resources at their disposal with caution – i.e., efficiently - and this predisposes, among other things, to naturally seek forms of management of crops or livestock that are partly based on the re-use of waste.

In the light of these considerations, some policy implications can derive in terms of quality and quantity improvement of agriculture.

Although not acting on resource circularity enhancing and agricultural quality side (thus keeping the technological frontier unchanged), policies aimed at increasing agricultural production will increase the agricultural circularity and country circularity. This would occur even without necessarily rethinking the agricultural model to be promoted in the direction of greater circularity given the natural propensity of agriculture to resort per se to practices already centered on the re-cycle of the used resources. Obviously, the eventual introduction of virtuous processes that increasingly apply the CE principles and better integration, in this sense, with the upstream and downstream sectors of agriculture can increase the sector's ability to affect the overall circularity of the economic system.

Furthermore, new practices and innovation based on the CE approach have proved economically feasible as they create additional income and paid employment by the local population, lead to social benefits such as better living conditions and new openings, and ecological benefits, such as better waste management, less natural contamination and fewer fossil fuel by-products (Mor et al., 2021).

To summarize, since the elasticity of the agricultural sector is greater than that of all the entire economy, qualitative and quantitative interventions on the agricultural sector will generate a more than proportional return to the benefit of the circularity of all the EU countries.

The food sector, in contrast, requires policy expressly oriented to the quality side. Indeed, the scarce contribution that the sector today, without the primary phase, provides to the economic system in terms of circularity is very limited. This suggests that it would be not enough to improve the sector's performance if, at the same time, the processes and the farms' organization are not rethought towards practices with a high rate of circularity. It implies that a remarkable effort needs to be made to promote innovations in different fields such as prevention of packaging waste, eco-design and end-of-life packaging management, food waste prevention and food surpluses management. This is one of the better ways to increase food quality and security, environmental sustainability, and the economic well-being of countries (Fiore et al., 2019).

On the other hand, this paper presents some limits that can open up prospects for further studies.

First, findings are grounded in material flow accounting, but, as the CE is an economic strategy, future research can replicate our analysis on Monetary EXIOBASE.

Second, results are focused on the entire agriculture and food sector; future research can investigate differences among industries.

Third, according to Ellen MacArthur Foundation (2021) "A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times". Because the Aguilar-Hernandez et al. (2019) framework employed in this study considerers the mass of recycled waste but not "how much energy is required to restore the recovered material back to the desired material or product" (Cullen, 2017, pag. 483), future research can investigate the material losses and energy inputs associated with recycling that can affect the environmental benefits deriving from the agribusiness transition toward a circularity paradigm.

Fourth, previous research highlighted the pivotal role of biomass in the circularity economy analysis (Allain et al., 2022; Erb & Gingrich, 2022; Paes et al., 2019). In the European Union (EU), the importance of biomass feedstocks has been boosted by policies that promote renewable energy and biobased products, and being a source of material goods and energy, biomass is of critical importance in a circular economy (Sherwood, 2020). Since changes in time of vegetation biomass per unit area (biomass density) is an essential climate variable that directly measures the sequestration or release of carbon between terrestrial ecosystems and the atmosphere (FAO, 2009), to realize the transformative potential of the circular economy unsustainable biomass production must be eliminated (Haas et al., 2020). Future research can investigate how such a variable affects the circularity of the agribusiness industry in the European countries. Finally, analyses on different versions of the EXIOBASE database can lead to results hardly comparable among scholars. The hope is that an increasingly accurate database will be available in the future, also to allow a more sophisticated computational procedure of circularity indicators.

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7. Appendix 1 List of items included in the variables of CI and CGI indexes.

Table 1.7 - Waste Supply (considered both for Activities and Final demand sheets)

- Food waste for treatment: biogasification and land application
- Food waste for treatment: composting and land application
- Food waste for treatment: incineration
- Food waste for treatment: landfill
- Food waste for treatment: waste water treatment
- Inert/metal/hazardous waste for treatment: landfill
- Intert/metal waste for treatment: incineration
- Manure (biogas treatment)
- Manure (conventional treatment)
- Oil/hazardous waste for treatment: incineration
- Other waste for treatment: waste water treatment
- Paper and wood waste for treatment: composting and land application
- Paper for treatment: landfill
- Paper waste for treatment: biogasification and land application
- Paper waste for treatment: incineration
- Plastic waste for treatment: incineration
- Plastic waste for treatment: landfill
- Sewage sludge for treatment: biogasification and land application
- Textiles waste for treatment: incineration
- Textiles waste for treatment: landfill
- Wood waste for treatment: incineration
- Wood waste for treatment: landfill

Table 1.8 - Stock Depletion (derived from the voice "Gross fixed capital formation" from the Final Demand sheet)

- Air transport services (62)
- Aluminium and aluminium products
- Aluminium ores and concentrates
- Animal products nec
- Ash for treatment, Re-processing of ash into clinker
- Basic iron and steel and of ferro-alloys and first products thereof
- Beverages
- Biogas an other gases nec.
- Bottles for treatment, Recycling of bottles by direct reuse
- Bricks, tiles and construction products, in baked clay
- Cattle
- Cement, lime and plaster
- Ceramic goods
- Cereal grains nec
- Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.
- Chemicals nec; additives and biofuels
- Coal, lignite and peat
- Coke oven products
- Collected and purified water, distribution services of water (41)
- Computer and related services (72)
- Construction work (45)
- Copper ores and concentrates
- Copper products
- Crops nec
- Crude petroleum and services related to crude oil extraction, excluding surveying
- Dairy products
- Distribution and trade services of electricity
- Distribution services of gaseous fuels through mains
- Education services (80)
- Electrical machinery and apparatus n.e.c. (31)
- Electricity by biomass and waste
- Electricity by coal
- Electricity by gas
- Electricity by Geothermal
- Electricity by hydro
- Electricity by nuclear
- Electricity by petroleum and other oil derivatives
- Electricity by solar photovoltaic
- Electricity by solar thermal

Table 1.8 - Continuous

- Electricity by tide, wave, ocean
- Electricity by wind
- Electricity nec
- Extra-territorial organizations and bodies
- Fabricated metal products, except machinery and equipment (28)
- Financial intermediation services, except insurance and pension funding services (65)
- Fish and other fishing products; services incidental of fishing (05)
- Fish products
- Food products nec
- Food waste for treatment: biogasification and land application
- Food waste for treatment: composting and land application
- Food waste for treatment: incineration
- Food waste for treatment: landfill
- Food waste for treatment: waste water treatment
- Foundry work services
- Furniture; other manufactured goods n.e.c. (36)
- Glass and glass products
- Health and social work services (85)
- Hotel and restaurant services (55)
- Inert/metal/hazardous waste for treatment: landfill
- Inland water transportation services
- Insurance and pension funding services, except compulsory social security services (66)
- Intert/metal waste for treatment: incineration
- Iron ores
- Lead, zinc and tin and products thereof
- Lead, zinc and tin ores and concentrates
- Leather and leather products (19)
- Machinery and equipment n.e.c. (29)
- Manure (biogas treatment)
- Manure (conventional treatment)
- Meat animals nec
- Meat products nec
- Medical, precision and optical instruments, watches and clocks (33)
- Membership organisation services n.e.c. (91)
- Motor vehicles, trailers and semi-trailers (34)
- N-fertiliser
- Natural gas and services related to natural gas extraction, excluding surveying; inclulding liquid gas
- Nickel ores and concentrates
- Nuclear fuel

Table 1.8 - Continuous

- Office machinery and computers (30) - Oil seeds - Oil/hazardous waste for treatment: incineration - Other business services (74) - Other Hydrocarbons - Other land transportation services - Other non-ferrous metal ores and concentrates - Other non-ferrous metal products - Other non-metallic mineral products - Other services (93) - Other transport equipment (35) - Other waste for treatment: waste water treatment - P- and other fertiliser - Paddy rice - Paper and paper products - Paper and wood waste for treatment: composting and land application - Paper for treatment: landfill - Paper waste for treatment: biogasification and land application - Paper waste for treatment: incineration - Pigs - Plant-based fibers - Plastic waste for treatment: incineration - Plastic waste for treatment: landfill - Plastics, basic - Post and telecommunication services (64) - Poultry - Precious metal ores and concentrates - Precious metals - Printed matter and recorded media (22) - Private households with employed persons (95) - Processed rice - Products of forestry, logging and related services (02) - Products of meat cattle - Products of meat pigs - Products of meat poultry - products of Vegetable oils and fats - Public administration and defence services; compulsory social security services (75) - Pulp - Radio, television and communication equipment and apparatus (32) - Railway transportation services

Table 1.8 - Continuous

- Raw milk
- Real estate services (70)
- Recreational, cultural and sporting services (92)
- Refined Petroleum
- Renting services of machinery and equipment without operator and of personal and household goods (71)
- Research and development services (73)
- Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)
- Retail trade services of motor fuel
- Rubber and plastic products (25)
- Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
- Sand and clay
- Sea and coastal water transportation services
- Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium
- Secondary construction material for treatment, Re-processing of secondary construction material into aggregates
- Secondary copper for treatment, Re-processing of secondary copper into new copper
- Secondary glass for treatment, Re-processing of secondary glass into new glass
- Secondary lead for treatment, Re-processing of secondary lead into new lead
- Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
- Secondary paper for treatment, Re-processing of secondary paper into new pulp
- Secondary plastic for treatment, Re-processing of secondary plastic into new plastic
- Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals
- Secondary raw materials
- Secondary steel for treatment, Re-processing of secondary steel into new steel
- Services auxiliary to financial intermediation (67)
- Sewage sludge for treatment: biogasification and land application
- Steam and hot water supply services
- Stone
- Sugar
- Sugar cane, sugar beet
- Supporting and auxiliary transport services; travel agency services (63)
- Textiles (17)
- Textiles waste for treatment: incineration

Table 1.8 - Continuous

- Textiles waste for treatment: landfill - Tobacco products (16) - Transmission services of electricity - Transportation services via pipelines - Uranium and thorium ores (12) - Vegetables, fruit, nuts - Wearing apparel; furs (18) - Wheat - Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51) - Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20) - Wood material for treatment, Re-processing of secondary wood material into new wood material - Wood waste for treatment: incineration - Wood waste for treatment: landfill - Wool, silk-worm cocoons

Table 1.9 - Waste recovery

- Ash for treatment, Re-processing of ash into clinker - Bottles for treatment, Recycling of bottles by direct reuse - Food waste for treatment: biogasification and land application - Food waste for treatment: composting and land application - Manure (biogas treatment) - Manure (conventional treatment) - Paper and wood waste for treatment: composting and land application - Paper waste for treatment: biogasification and land application - Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium - Secondary construction material for treatment, Re-processing of secondary construction material into aggregates - Secondary copper for treatment, Re-processing of secondary copper into new copper - Secondary glass for treatment, Re-processing of secondary glass into new glass - Secondary lead for treatment, Re-processing of secondary lead into new lead - Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals

Table 1.9 - Continuous

- Secondary paper for treatment, Re-processing of secondary paper into new pulp - Secondary plastic for treatment, Re-processing of secondary plastic into new plastic - Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals - Secondary steel for treatment, Re-processing of secondary steel into new steel - Sewage sludge for treatment: biogasification and land application - Wood material for treatment, Re-processing of secondary wood material into new wood material

Table 1.10 - Resource extraction

- Aluminium ores and concentrates - Biogas an other gases nec. - Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c. - Coal, lignite and peat - Copper ores and concentrates - Crude petroleum and services related to crude oil extraction, excluding surveying - Fish and other fishing products; services incidental of fishing (05) - Iron ores - Lead, zinc and tin ores and concentrates - Natural gas and services related to natural gas extraction, excluding surveying; includding liquid gas - Nickel ores and concentrates - Other Hydrocarbons - Other non-ferrous metal ores and concentrates - Paddy rice - Precious metal ores and concentrates - Products of forestry, logging and related services (02) - Sand and clay - Stone - Uranium and thorium ores (12) - Wool, silk-worm cocoons

Table 1.11 – Imports

- Aluminium and aluminium products
- Aluminium ores and concentrates
- Animal products nec
- Basic iron and steel and of ferro-alloys and first products thereof
- Beverages
- Biogas an other gases nec.
- Bricks, tiles and construction products, in baked clay
- Cattle
- Cement, lime and plaster
- Ceramic goods
- Cereal grains nec
- Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.
- Chemicals nec; additives and biofuels
- Coal, lignite and peat
- Coke oven products
- Copper ores and concentrates
- Copper products
- Crops nec
- Crude petroleum and services related to crude oil extraction, excluding surveying
- Dairy products
- Electrical machinery and apparatus n.e.c. (31)
- Fabricated metal products, except machinery and equipment (28)
- Fish and other fishing products; services incidental of fishing (05)
- Fish products
- Food products nec
- Foundry work services
- Furniture; other manufactured goods n.e.c. (36)
- Glass and glass products
- Iron ores
- Lead, zinc and tin and products thereof
- Lead, zinc and tin ores and concentrates
- Leather and leather products (19)
- Machinery and equipment n.e.c. (29)
- Meat animals nec
- Meat products nec
- Medical, precision and optical instruments, watches and clocks (33)
- N-fertiliser
- Natural gas and services related to natural gas extraction, excluding surveying; includding liquid gas
- Nickel ores and concentrates

Table 1.11 – Continuous

- Office machinery and computers (30) - Oil seeds - Other Hydrocarbons - Other non-ferrous metal ores and concentrates - Other non-ferrous metal products - Other non-metallic mineral products - P- and other fertiliser - Paddy rice - Paper and paper products - Pigs - Plant-based fibers - Plastics, basic - Poultry - Precious metal ores and concentrates - Precious metals - Printed matter and recorded media (22) - Processed rice - Products of forestry, logging and related services (02) - Products of meat cattle - Products of meat pigs - Products of meat poultry - products of Vegetable oils and fats - Pulp - Radio, television and communication equipment and apparatus (32) - Raw milk - Refined Petroleum - Rubber and plastic products (25) - Sand and clay - Stone - Sugar - Sugar cane, sugar beet - Textiles (17) - Tobacco products (16) - Uranium and thorium ores (12) - Vegetables, fruit, nuts - Wearing apparel; furs (18) - Wheat - Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20) - Wool, silk-worm cocoons

CHAPTER 2

Public perception of ecosystem and social services produced by Sardinia extensive dairy sheep farming systems

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ABSTRACT

Dairy sheep farming systems provide a great range of Ecosystems Services (ESs) and Social Services (SSs). These are Agro-pastoral Secondary Outputs (ASOs), the promotion of which can help the survival of the systems and the rural regions in which they exist. However, little attention has been paid to understanding which ASOs are recognized by the public, which is the first step to adequately promote them. This study first aims to review previous literature on ASOs relating to livestock in general and dairy sheep farming systems in particular. The literature review, conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework, revealed significant gaps. Second, the research provides evidence of public perception of ASOs of a given dairy sheep sector – i.e., that developed on the region of Sardinia (Italy) – via a questionnaire distributed to a composite sample of 525 stakeholders. We found that cultural and landscape services are the most appreciated services. Multiple Correspondence Analysis suggests that appreciation of a specific secondary output would imply the appreciation of all the other outputs. Furthermore, we ran a set of Logit Regressions where each ASO was related to several socioeconomic variables. Findings showed, among others, that the 'subjective knowledge' of the Sardinian agro-pastoral reality positively and significantly affects appreciation of all the ASOs. Several implications for practitioners, academics and policymakers are derived from these findings.

Keywords: systematic qualitative literature review; agro-pastoral secondary outputs (ASOs); multiple correspondence analysis; logit regression; Sardinia

1. Introduction

Ecosystems provide a range of services that significantly impact human well-being, health, livelihoods, and survival (MEA 2005a; TEEB 2010; Costanza et al. 2014). Several ways of defining Ecosystem Services (ESs) have been developed, such as 'the benefits people obtain from ecosystems' (MEA 2005a, p. 26) or as contributions of ecosystem structure and function (in conjunction with other inputs) to human well-being (economic, social, and personal well-being) (Burkhard et al. 2012; Burkhard and Maes 2017). In this context, it is important to emphasize that ecosystems provide benefits to people only because of the presence of individuals (human capital), their communities (social capital) and their built environment (built capital). Therefore, the benefits of ESs flow from natural capital to human well-being only through interaction with the other three forms of capital (Costanza et al. 2014).

The Millennium Ecosystem Assessment (MEA) (2005a) classified ESs into four categories: provisioning (material or energy outputs), regulating (biophysical processes providing benefits such as climate regulation or water purification), supporting (processes that allow the functioning of other ecosystems that, in turn, provide other services, such as nutrient cycles, soil formation, photosynthesis or pollination) and cultural (recreational, aesthetic and spiritual benefits). Scientists and policymakers use ESs extensively to highlight the importance of the environment in supporting human livelihoods. Therefore, the term is broadly used, and ES research has made advances in many areas, from theoretical conceptualization to practical applications (Potschin et al. 2016; La Notte et al. 2017). Numerous studies have investigated how the concept can be used in an agricultural context. In doing so, however, the few ES assessments aimed at decision support appear to be mainly limited to theoretical reflections. Few studies have focused on specific agricultural practices and the gap between ES research and information required to support decisions persists (Holt et al. 2016; Olander et al. 2017; Dendoncker et al. 2018).

However, one cannot ignore the existence of a variety of disservices to and from agriculture (Zhang et al. 2007; Herd-Hoare and Shackleton 2020). Ecosystem disservices (EDs) highlight the negative economic and non-economic effects of nature on human well-being within social-ecological systems (Blanco et al. 2019). The EDs generated by agroecosystems, i.e. “the ecosystem generated functions, processes and attributes that result in perceived or actual negative impacts on human wellbeing” (Shackleton et al. 2016), in many cases, can lead to impact production and economic losses, compromising food security, income, and thus well-being (Herd-Hoare and Shackleton 2020). The breadth and depth of EDs depend on management practices because, if they are appropriate, can improve and mitigate many agricultures negative impacts (Power 2010). Considering the livestock farming systems, utilization of resources and intensity of the production system can determine disservices; landscaping, hydrology, and environmental damage are some examples (FAO 2006; Montrasio et al. 2020).

The present work is focused on the ESs commonly provided by dairy sheep farming systems. Sheep farming represents a traditional activity in many world regions, although the main product (milk, meat, wool, or a combination of the three) may vary depending on the geographical context or the breed raised. The breeding for milk production assumes considerable economic importance in many areas (Pulina et al. 2018). Sheep milk production accounts for about 10.6 Mt, of which 29.5% is from Europe (FAOSTAT 2022), with growth forecasts of around 3 Mt by 2030 (Pulina et al. 2018).

Sheep farming is especially practiced in temperate and sub-tropical areas, concentrated in the Mediterranean and the Black Sea regions and accounting for approximately 211 million sheep (FAOSTAT 2022). In the Mediterranean areas, sheep breeding systems for milk production have traditionally developed in economically and physically disadvantaged areas (Ripoll-Bosch et al. 2012) and strongly affect the agricultural economy of several regions, where it is often practiced using a low-input system. It is important to note that, in general, low-input farming systems are associated with many agricultural practices that provide a greater range of ESs than intensive farming systems (Cooper et al. 2009). Dairy sheep farming is no exception to such rule. Furthermore, the sheep farming systems also produce other externalities of public relevance in terms of social benefits. In other words, production of Social Services (SSs) in connection with ESs can be recognized from these practices; one example is the role of pastoralism in safeguarding the livelihoods of populations located in disadvantaged and/or rural areas, by ensuring jobs or preventing depopulation. These are public functions that can counteract elements that strongly affect the economic marginalization of rural areas and from which many adverse social, economic, and environmental effects derive (O'Rourke et al. 2016; Nori et al. 2017; Quaranta et al. 2020). Pastoralism is commonly recognized as having a multifunctional dimension as it produces a wide range of environmental and social goods and services alongside food (Ripoll-Bosch et al. 2012; Nori et al. 2017; Bernués et al. 2019), thereby providing a valuable opportunity for sustainable development (Meloni et al. 2015). Overall, these externalities can be considered as Agro-pastoral Secondary Outputs (ASOs).

A significant research challenge concerns the evaluation of ASOs produced by dairy sheep farming systems, since 'the true contribution of agro-pastoralism to societal objectives is not fully accounted for, which provides an explanation for its decreasing role on Mediterranean islands over time' (Nori et al. 2017, p. 138). The ASOs are not properly valued and priced through market mechanisms, which means that these externalities are 'lost' across the value chain and often unrecognized by the final user (Nori et al. 2017). To that and, it is necessary to understand how the public perceives the relationships between such agriculture practices and ASOs and identify those that are the most requested (Bernués et al. 2016, 2019). However, a necessary condition is that the population are aware of such agro-pastoral outputs and appreciate them (Montrasio et al. 2020). The assessment of the values and perceptions of ASOs is of great importance because it is the first step towards developing a shared understanding of the agro-landscape, support change paths in terms of sustainability and understand how agricultural practices affect ASOs that, in its turn, influence agricultural productivity and society (Dendoncker et al. 2018).

In the context described above, this paper evaluates the perception of ASOs generated by the dairy sheep farming system in Sardinia, the second-largest Mediterranean island. Sardinia is one of the main European producers of sheep's milk and contributes to about 67% of Italian dairy sheep production (Autonomous Region of Sardinia 2020) (Italy accounts for 19% of total European milk production - FAOSTAT 2022). Sardinian dairy sheep breeding is usually pasture-based and quite extensive (Vagnoni et al. 2015; Vagnoni and Franca 2018). It uses traditional and low-input practices and maintains the semi-natural habitats they helped create (Ripoll-Bosch et al. 2013; Pulina et al. 2018; Faccioni et al. 2019). Moreover, the Sardinian shepherding model has been at the basis of local cultural identity, provides landscape maintenance and care, contributes to the protection of territory and animal and vegetable biodiversity, and ensures jobs for thousands of people (Furesi et al. 2013; Mattalia et al. 2020).

Despite the growing appreciation of primary and processed sheep dairy products (Nori et al. 2017, p. 136), and its role in the regional economy, the dairy sheep sector operates with low profit margins (Idda et al. 2010). Currently, its profitability often depends on the amount of financial aid made available by the Common Agricultural Policy (CAP) (Idda et al. 2010; Vagnoni et al. 2015; O'Rourke et al. 2016; Quaranta et al. 2020). Sardinian dairy sheep sector is facing a serious threat to its medium- to long-term survival since if the business is scarcely profitable, current and future generations of stock farmers would not be encouraged to continue operating. The resulting impacts could be severe on most social, economic, and environmental benefits people obtain from the agro-pastoralism contribution to societal objectives. The scenario presented here could worsen a critical situation already in place because Sardinia is one of the European Union's (EU) most underdeveloped areas and suffers from a lower Gross Domestic Product (GDP) and industrialization rate than the peninsula (ISMEA 2019). Consequently, it appears to be pivotal to foster sector durability, here understood as the ability to cope with chronic endogenous stress (Dawson et al. 2010), through the sustainability defined by Hodge as 'the persistence over an apparently indefinite future of certain necessary and desired characteristics of both the ecosystem and the human subsystem within' (Hodge 1997, p. 9).

The present paper focuses on this area of interest and has two aims. First, it aims to explore the state of knowledge of ESs and SSs related to both zootechnical activities on the whole and to dairy sheep farming systems specifically. A qualitative systematic review of world literature was performed using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework. Second, it aims to evaluate the most recognized ASOs of the extensive Sardinian dairy sheep system. Building on qualitative systematic review findings, the ASOs were identified, and a qualitative survey of residents and non-residents was carried out to ascertain perceptions of the benefits of ASOs. Data were first analyzed with a descriptive analysis, followed by a Multiple Correspondence Analysis (MCA) to cluster perceptions of the relevance of ASOs. Finally, the relationship between preferences stated for each secondary output and sociodemographic variables was evaluated using a set Multinomial Logit Regression (MLR).

The paper makes several contributions to the literature, for policymakers and stock farmers. First, as far as we know, this is the first economic study that considers both environmental and social secondary outputs provided by an extensive sheep farming system. Second, this paper helps to bridge the gap both between the growing scientific research on perceptions and values of ESs and the few studies on ES perception concerning specific agricultural practices, and between ES research and information required to support decisions (Bernués et al. 2016; Olander et al. 2017; Dendoncker et al. 2018). It does so by investigating the ESs provided by the Sardinian dairy sheep farming system and overcoming the limitations of previous research by including the assessment of perception of SSs. Third, it addresses recent calls for research on the complex relationship between pastoral activity and rural landscape in the Mediterranean region (Mattalia et al. 2020). As the paper highlights which socioeconomic, cultural and environmental outputs of the Sardinian dairy sheep sector are most appreciated, it raises awareness of the agro-pastoral contribution to the pattern of sustainable development in the Sardinian region. Fourth, the paper highlights the appreciation of ASOs and recognizes the existence of supply and demand for a public good that is inadequately remunerated in the market. As a result, the financial aid provided by the CAP as a welfare contribution non-configurable and can make stock farmers aware of their role in maintaining territory and producing public goods.

The paper is structured as follows: Section 2 describes the research methodology and sample; Section 3 presents the results; Section 4 discusses the results and provides a conclusion, outlining the implications for practitioners, academics and policymakers, and recommendations for future research.

2. Methodology

In order to achieve the aims of this paper, two-step research methodologies were used: a qualitative systematic review on the secondary outputs produced in breeding and an empirical analysis – by submitting a structured questionnaire - aimed to evaluate the perceptions of secondary outputs in extensive dairy system by part of society. Image 2.1 provides a visual representation of the aims and methods used in the different stages of the research and the output of the first phase used in the second one.

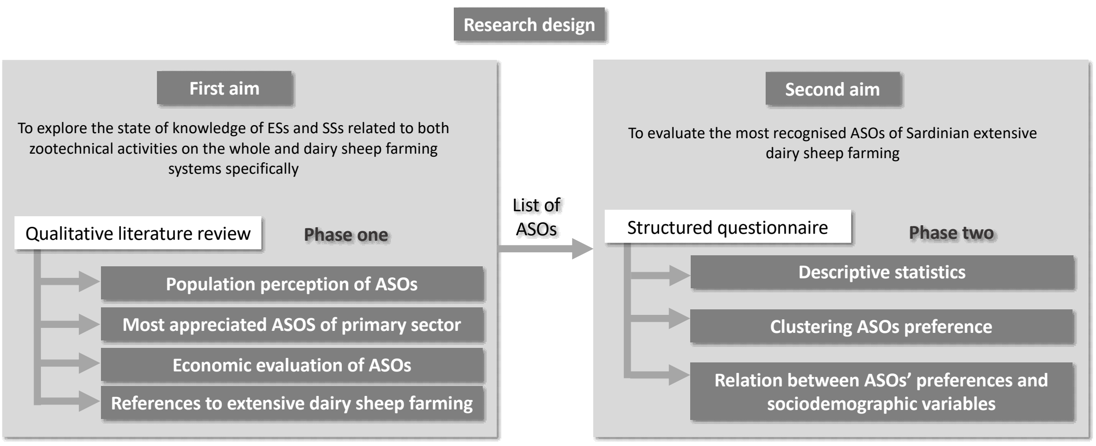

Image 2.1– Graphical representation of the research model

2.1 Systematic review

To explore the first aim, we conducted a qualitative systematic review. Quantitative reviews usually produce meta-analyses and find applications in the case of selected studies that share a highly standardized procedure, centered on similar topics, analyses or research designs, allowing for a direct comparison of results that can be contextualized in terms of effect size (Borenstein et al. 2009). The available scientific literature on the ESs and SSs of zootechnical activities do not fulfil all these conditions. A qualitative literature review based on narrative surveys overcomes problems arising from the wide differences in the literature in terms of methods and results and the relatively limited number of relevant studies available (Baumeister and Leary 1997; Jahan et al. 2016).

We followed one of the approaches to qualitative survey proposed by Baumeister and Leary (1997) and drew up a survey aiming to explore the state of knowledge of the ASO-related aspects of livestock activities. While the literature on ESs in a broad sense has developed in recent years, the same does not apply to zootechnical activities. As our aim was to investigate if sheep farming systems can survive giving value to positive externalities, our review addressed the following research questions:

1. Has previous literature analyzed the population's perception towards ASOs in the context of agroecosystems?

2. Is there evidence for which ASOs provided by the primary sector are most appreciated?

3. Has the previous literature provided an economic evaluation of primary sector ASOs, especially concerning breeding systems?

4. Are there any references to extensive dairy sheep farming systems?

The review focused on scientific, English-language, peer-reviewed publications after 2010. We used the most common online database, Scopus (Moher et al. 2009), which has previously been used across a wide range of studies because of its uniqueness, its reputable publisher (Elsevier Co.) and because it indexes over 14,000 journals in numerous fields, including social, environmental and economic. The literature search considered all countries and was performed on 8th March 2021. The PRISMA framework procedure (Moher et al. 2009) was adapted for our purposes. The PRISMA statement highlights four steps: identification, screening, eligibility and inclusion criteria.

Concerning the keyword identification process to retrieve as many articles as possible in the target research fields, data were acquired by searching publications in agriculture, business and economy areas, whose title, abstract or keywords contain the following words: ("ecosystem service*" OR "agroecosystem*" OR "multifunctional*" OR "agroecosystem service*" OR "socio-economical system*") AND ("economic valuation" OR "socio-cultural valuation" OR "perception" OR "socio-economic valuation" OR "social preferences" OR "stakeholder involvement" OR "service value" OR "ecosystem services value" OR "agroecosystem*" OR “agrienvironmental payment*” OR “agri-environmental payment*” OR “choice experiment” OR “survey” OR “agrienvironmental polic*” OR “agri-environmental polic*”) AND ("agriculture” OR “farm*” OR “livestock” OR “landscape” OR “silvopasture” OR “pastoralism”). The truncation symbol “*” covers the variations of the selected terms.

After the screening process to include or exclude based on the criteria previously defined, the eligibility step involved two researchers who examined titles, abstract, methods, results and discussion to verify the articles’ relevance to the study’s research questions and compliance with the inclusion criteria. A third researcher conducted an independent evaluation in case of doubts about inclusion criteria satisfaction. Articles that fulfilled all requirements were analyzed.

2.2. Clustering of Sardinian extensive dairy sheep system secondary outputs

To investigate the societal awareness and appreciation of social and environmental benefits obtained by Sardinian agro-pastoralism externalities, we first specified a list of ASOs. Based on the findings of a previous systematic qualitative review, a list of ESs relating to other livestock realities suitable to the Sardinian sector was identified and classified as ‘regulating’, ‘supporting’ and ‘cultural’. The ‘provisioning’ services were excluded since they were outside the research scope. The list of externalities of SSs counts the outputs referring to the means of subsistence provided in inland areas (e.g., employment for indigenous people and immigrants), the avoidance of depopulation and the provision of social agriculture activities. Twenty secondary outputs were identified and used to answer our second research question (see Table A2.1 of Appendix).

A structured questionnaire was created in Google Forms in the Italian language and disseminated across social networks. Online surveys are increasingly used to collect data for research purposes, as they are cheap, fast, and efficient in collecting valid data, removing geographic limitations and costs (Wright 2005; Vecchio et al. 2020). Recruitment was based on non-random criteria and influenced by the use of social networks, creating a potential selection/sampling bias, as respondents' beliefs, interests and strength of feelings about a topic can influence their willingness to participate in a survey (McAleese et al. 2016; Burruss and Johnson 2021). However, since no respondents received incentives for participating in this study, the voluntary response sample allowed us to investigate who has a strong opinion (positive, negative, or neutral) about ASOs, therefore understanding genuine appreciation for ASOs.

The form was sent to a sample of Italian people, with a sub-category represented by Sardinian residents and was in the field for one month (18th March – 18th April 2021). By the closing date for responses, 525 answers were recorded, all valid as the questionnaire could only be sent if all questions were answered. According to Kline (2015), there should be at least 10 valid responses per parameter. Therefore, given the numbers of the final sample (525) and the items (20), the research meets the above prior condition.

The questionnaire comprised three parts. After being welcomed into the study and reassured about the reliable and anonymous use of the data provided, respondents were first given a brief overview of the economic role of sheep farming in Sardinia, as well as how its environmental, social and cultural functions—if preserved and well-valued—can contribute to guaranteeing not only the sustainability of the sheep system but also generating well-being in the populations and the vitality of the territories concerned.

The second part collected the sociodemographic data of respondents. The third aimed to investigate two constructs that influence people's perception: past professional or family experience and subject knowledge. The latter reflects the self-confidence that an individual has in the adequacy of their knowledge (Brucks 1985; Carlson et al. 2009), and within the environmental behavior context, is of substantial importance for the individual's formation of perceptions and behaviors (Kaiser and Fuhrer 2003; Frick et al. 2004).

In the last part, respondents were asked to express their appreciation for the ASOs of the Sardinian extensive sheep sector, indicating what level of benefit (none, moderate or high) they recognize from each of them. In other words, respondents valued ASOs based on their individual subjective (group-, time- and location-dependent) assessment (Spangenberg et al. 2014; Spangenberg and Settele 2016).

Data were analyzed with three methods. First, descriptive statistics were calculated to summarize the data and provide background information about the variables in the dataset. Afterwards, based on the perception of the relevance to the community of the secondary outputs, we clustered preferences using MCA.

In so doing, will be possible to highlight the most recognized agro-pastoralism ESs and SSs and, especially, to estimate the connections among agro-pastoralism amenities. MCA is an exploratory, multivariate analysis technique considered particularly suitable for categorical data description (Greenacre 1984, 2017; Le Roux and Rouanet 2004; Greenacre and Blasius 2006). It is a technique of interdependence used for dimension reduction of qualitative variables (Benzécri 1992), considered as a multivariate extension of simple correspondence analysis and principal component analysis between quantitative variables, enabling the visualization of perceptual maps.

We used an MCA biplot (Greenacre 2010) to visualize the pattern of relationships of several categorical dependent variables in a two-dimensional plot. An orthogonal rotation of the principal axes was performed to improve the interpretation. MCA is obtained using a standard correspondence analysis on an indicator matrix (X). It is a J x M matrix where Jk is the vector of the levels (three levels: null, moderate, elevate attributed importance) for each K nominal variable (with $\sum Jk = J$ and where k = 20 nominal variables represented by the considered secondary outputs), and M is the number of observations (525 respondents).

Performing MCA on X will provide two sets of factor scores, one for the rows and one for the columns. These factor scores are, in general, scaled such that their variance is equal to their corresponding eigenvalue.

The analysis should allow us to provide evidence for the relationship between the 20 individuated ASOs by a representation in a low-dimensional space – designed based on few principal components – in order to define some clusters (profiles).

Finally, we evaluated the relationship between preferences stated for each ASO and the sociodemographic variables using an MLR model set. MLR is a highly efficient probability estimation method that can be used to address binary, ordinary or multinomial problems. It is an extension of binary logistic regression that can be used to forecast the probabilities of the different possible outcomes of a multi-way categorical dependent variable (in our case, the variable can assume three levels) given a set of independent variables that can be either dichotomous (i.e., binary) or continuous (i.e., interval or ratio in scale). Using MLR, we can see the influence of sociodemographic variables in determining trends in appreciation of ASOs arising from the Sardinian extensive dairy sheep system. Specifically, each ASO was regressed on the set of variables reported in Table 2.1.

Table 2.1 – List of the independent socioeconomic variables involved in the regressions

Independent variable	**Description**	**Scores**
Residence	Region of residence	1 = Sardinia; 0 = Other regions
Gender	Gender of the respondent	1 Male; 0 = Female
Past-Prof-Experience	Past employment in agriculture	1 = Yes; 0 = NO
Education	Level of education	1 = Secondary school; 2 = High school; 3 = Graduation; 4 = Post-graduate
Sheep breeder	Working as sheep breeder	1 = Yes; 0 = NO
Farmer	Working as farmer	1 = Yes; 0 = NO
Past-Fam-Experience	Coming from a peasant family	1 = Yes; 0 = NO
Age	Age of the respondent	1 = ≤ 17; 2 = 18-29; 3 = 30-39; 4 = 40-49; 5 = 50-59; 6 = ≥ 60
Subject knowledge	Knowledge of the Sardinian agro-pastoral reality	From 1 to 7
Frequency	Frequency in consuming Sardinian sheep dairy products	0 = never; 1 = about one a year; 2 = about one a month; 3 = about once a week; 4 = about every day

3. Results

3.1 Qualitative literature review

Using the PRISMA framework procedure (Moher et al. 2009), 12 papers were considered relevant to our research questions. Image 2.2 shows the flow diagram of the selection of relevant records.

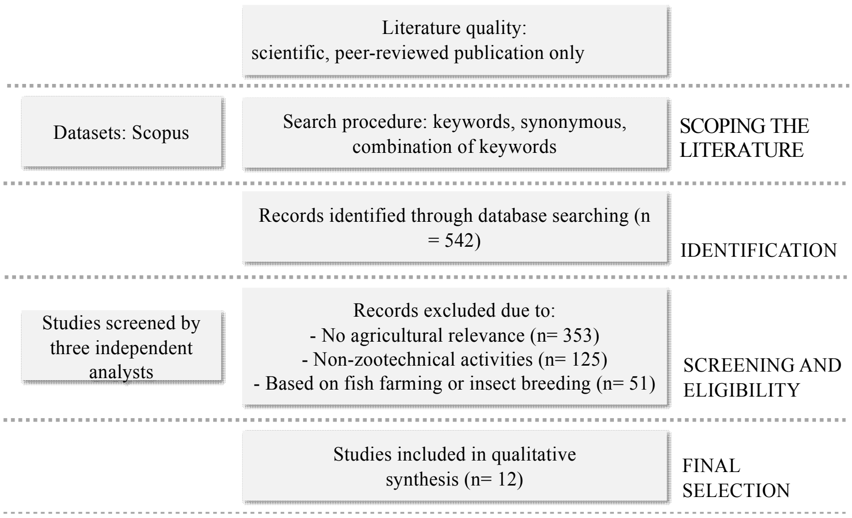

Image 2.2 - Systematic review of ecosystem services using PRISMA in Scopus database

Table A.2 of the Appendix reports a summary of the results for the selected studies according to the research questions. Findings shown that only five studies have previously examined the population's perception towards some ESs in the context of agroecosystems (RQ1), only three provided early indications on preferences among some ESs provided by the primary sector (RQ2), and only four studies provided an economic evaluation of primary sector ecosystem output (RQ3). Four out of 12 articles are attributable to Bernués A. and Ripoll-Bosch R.

Four papers have been published in the Land Use Policy journal and three in Ecosystem Services. The main results are in the literature gaps detected. First, none of these studies investigated the social benefit generated from breeding in general. Second, no previous research focused on the secondary output of extensive dairy sheep farming systems on the whole. Third, there is a lack of studies on the economic benefits generated by extensive dairy sheep farming systems. These literature gaps validated the opportunity and importance of the second part of our research.

3.2 Sample profile

The 525 Italian respondents, mainly residents, were 48.8% males and 51.2% females; 32.4% were aged between 50 and 59 years old, 24% were under 40 years old, about 23% were aged between 40 and 49 years old, and 7.1% were over 60 years old. Only 5.5% had a lower secondary school education, whereas 23.1% had an intermediate education level, 44.8% had a university degree and 26.7% had a postgraduate degree.

These percentages may result from the voluntary response sample. Regarding occupations, most respondents had a desk job (24%), 15.4% were students, 12.8% were shepherds and 1.7% were farmers. Almost half of the sample stated that they had previously been employed in the agricultural or livestock sector (45.9%) and come from a family with a peasant tradition (54.3%). The subject knowledge was high, since on a scale of one to seven, 65.1% rated themselves at five and above.

The purchase frequency of Sardinian products was also very high, as 38.1% and 39.6% declared that they consume Sardinian products at least once a day or once a week, respectively. The data are reported in Table 2.2.

Table 2.2 – Profile of the sample

	Total n = 525	%
Gender		
Male	256	48.8
Female	269	51.2
Age		
≤ 17	1	0.2
18-29	125	23.8
30-39	108	20.6
40-49	170	32.4
50-59	84	16.0
≥ 60	37	7.1
Resident		
In Sardinia	450	85.7
In other regions	75	14.3
Education		
Lower middle school	29	5.5
High school	121	23.1
University	235	44.8
Post University	140	26.7
Occupation		
Farmer	9	1.7
Househusband/housewife	9	1.7
Pensioner	11	2.1
Unemployed	22	4.2
Director	31	5.9
Teacher	48	9.1
Others	53	10.1
Breeder	67	12.8
Freelance	68	12.9
Student	81	15.4
Desk Job	126	24.0
Prior employed in the agricultural or livestock sector		
Yes	241	45.9
No	284	54.1
Coming from a family with a peasant tradition		
Yes	285	54.3
No	240	45.7
Subject knowledge about pastoral reality in Sardinia		
1	6	1.1
2	24	4.6
3	62	11.8
4	91	17.3
5	126	24.0
6	122	23.2
7	94	17.9
Frequency of Sardinian sheep products consumption		
Never	7	1.3
Everyday	200	38.1
Once a week	208	39.6
Once a month	74	14.1
Once a year	36	6.9

3.3 Descriptive analysis

The average of the responses for each ASO showed a moderate recognition of the externalities generated by the Sardinian extensive dairy sheep farming system (Table 2.3). The fact that the standard deviation was slight compared to the mean value demonstrated that the data were concentrated around the mean.

The tendency to recognize a moderate level of benefit generation from ASOs arose also when analyzing the frequency, with two exceptions: the culture and landscape (enhancing cultural identity of Sardinia and safeguard of typical landscape). Most respondents recognized that extensive dairy sheep farming generates high benefits in terms of these two secondary outputs.

Previous studies found differences between residents and non-residents concerning the perception of ESs (López-Santiago et al. 2014; Bidegain et al. 2019; Montrasio et al. 2020). As our sample mainly included residents, we wanted to investigate the possible differences between the respondents. The results showed that non-residents had a higher perception of ASOs than residents. In fact, in addition to the ‘cultural’ and ‘landscape’ ESs, non-residents demonstrated a high perception of the other six ESs (‘biodiversity’, ‘habitats’, ‘fires’, ‘insects’, ‘invasive’, ‘arts’) and also of three SSs (‘territory’, ‘employment of local inhabitants’, ‘employment of immigrants’). It is striking that residents demonstrated a moderate perception of opportunities for social activities (i.e., social farming), which represents a form of resilience and innovation within rural systems and a tool to support the competitiveness of the production system (Nicolosi et al. 2021), and of employment of the foreign workforce, which has a growing relevance, especially in rural and marginal areas (Marongiu 2021).

Table 2.3 – Descriptive analysis of ASOS's perception level by residents and non-residents

Variable	**Score**		**Frequency (%)**								
			Residents n. 450			**Non-residents n. 75**			**Total n. 525**		
	Mean	**S.D.**	**Null**	**Mod.**	**Elevate**	**Null**	**Mod.**	**Elevate**	**Null**	**Mod.**	**Elevate**
FERTILISERS	2.09	0.59	14.7	62.7	22.7	5.3	73.3	21.3	13.3	64.2	22.5
BIODIVERSITY	2.44	0.57	4.4	49.6	46.0	1.3	38.7	60.0	4.00	48.0	48.0
HABITATS	2.10	0.71	21.1	51.3	27.6	16.0	34.7	49.3	20.8	49.0	30.7
FIRES	2.25	0.69	13. 8	47.8	38.4	16.0	38.7	45.3	14.10	46.5	39.4
INSECTS	2.26	0.67	13.1	49.1	37.8	13.3	38.7	48.0	13-1	47.6	39.2
GHG	1.90	0.68	28.7	53.1	18.2	26.7	53.3	20.0	28.8	53.1	18.5
CARBON	1.99	0.65	22.2	57.6	20.2	18.7	60.0	21.3	21.7	57.9	20.4
EROSION	1.91	0.73	32.0	47.6	20.4	29.3	38.7	32.0	31.6	46.3	22.1
INVASIVE	2.20	0.67	15.6	51.6	32.9	8.0	45.3	46.7	14.5	50.7	34.9
WATER	1.89	0.65	26.2	56.7	17.1	33.3	57.3	9.3	27.2	56.8	16.0
CULTURE	2.54	0.65	8.9	30.4	60.7	6.7	17.3	76.0	8.6	28.6	62.9
ENV_EDUCATION	2.16	0.71	20.2	46.4	33.3	9.3	49.3	41.3	18.7	46.9	34.5
ARTS	2.14	0.72	20.9	46.9	32.2	16.0	37.3	46.7	20.2	45.5	34.3
RECREATION	1.93	0.70	29.6	51.1	19.3	22.7	44.0	33.3	28.6	50.1	21.3
LANDSCAPE	2.41	0.68	12.0	38.4	49.6	4.0	30.7	65.3	10.96	37.3	51.8
HERITAGE	2.08	0.68	19.8	55.3	24.9	14.7	45.3	40.0	19.1	53.9	27.1
TERRITORY	2.12	0.79	26.2	38.9	34.9	21.3	22.7	56.0	25.5	36.6	37.9
LOC_EMPLOYMENT	2.10	0.72	22.9	47.8	29.3	12.0	41.3	46.7	21.3	46.9	31.8
IMM_EMPLOYMENT	1.95	0.73	29.6	48.9	21.6	26.7	34.7	38.7	29.1	46.9	24.0
SOCIAL	1.90	0.69	29.8	53.6	16.7	25.3	42.7	32.0	29.1	52.0	18.9
Mean	**2.12**	**0.71**									

3.4 Multiple correspondence analysis

Two main dimensions were detected to represent the results within the Cartesian plane. Image 2.3 shows the plot of component loadings for the survey data. Dimension one showed a Cronbach alpha of 0.910 and explained 37% of the total variance, while dimension two showed a Cronbach alpha of 0.69 and explained 15.5% of the total variance. Overall, about 50% of the variability was explained by the first two-component model.

The biplot allows us to investigate how well variables separate groups of objects. Findings indicated that observations were clustered based on the degree of relevance attributed by respondents. By examining the graph, it emerged that the first dimension (the horizontal axis) separated respondents who gave a moderate judgement of ASOs from those who gave more polarized opinions, i.e., null or elevated. Furthermore, ‘biodiversity’ was located much further from its origin than other variables, suggesting that taken as a whole, the others did not share many characteristics of it.

The second dimension (the vertical axis) separates the respondents who did not perceive a contribution from the Sardinian extensive dairy sheep farming system to the ASOs from those who detected a high contribution. The graph shows that the first and second dimensions involved perfect discrimination between the variables. Therefore, the overall picture shows that recognizing the importance of one service involves recognizing the importance of all services provided by the Sardinian system. It was therefore concluded that multifunctionality as a whole was recognized.

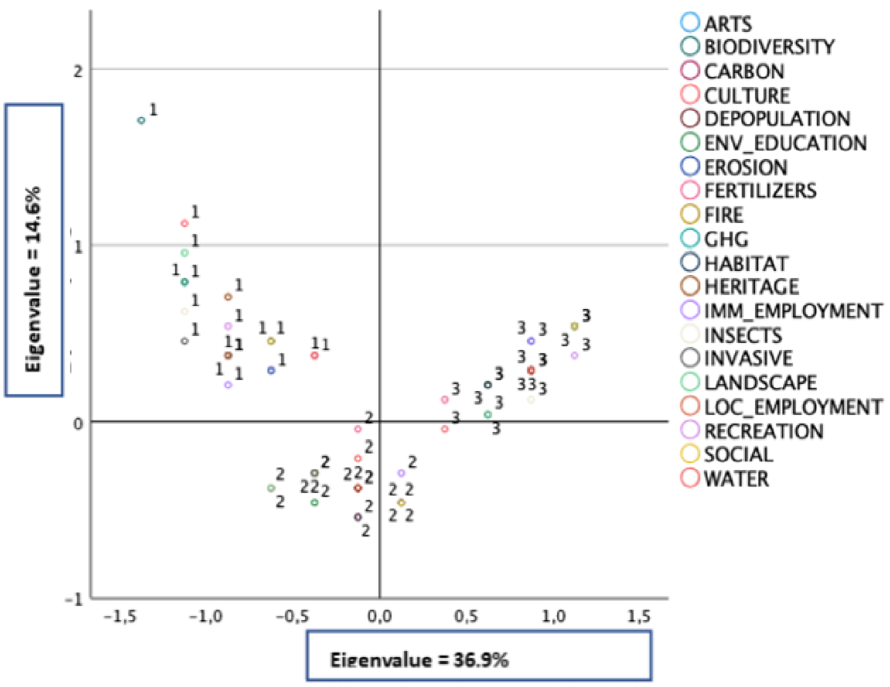

Image 2.3 – Multiple correspondence analysis biplots

3.5 Set of logit Analysis

Before running a set of MLRs, the multicollinearity test among sociodemographic variables was performed. All 10 sociodemographic variables reported a Variance Inflation Factor (VIF) of less than 2 and a tolerance greater than 0.5. Therefore, there is no risk of multicollinearity or independent variables that are highly correlated and provide the same information in the present study (Hair et al. 2010; Tabachnick et al. 2013).

Each ASO (a trichotomic variable taken as dependent variables) was regressed to the bundle of sociodemographic variables (taken as independent variables) (see Table A3 of the Appendix). Findings showed that all 20 regression models led to significant results, although not all variables were significant in all regressions. In no case did coming from a family with a peasant tradition affect the perception of the Sardinian system over ASOs. Age and gender were rarely estimated among significant findings. In contrast, others variable, such as education level and regional residence, were often significant, although magnitude and sign can vary among the secondary output considered. Only three sociodemographic variables appeared noteworthy, past professional experience, residence and subject knowledge, which were found to be highly significant and positively correlated with all ASOs.

4. Discussion

The concept of ESs, as well as the research field, are ingrained in strong sustainability thinking (Jacobs et al. 2013) and provides a framework that unravels the complex feedback loops of how pasture affects ESs flows and how, in turn, these ESs are perceived (Lamarque et al. 2014). The multifunctional character of pasture-based sheep farming systems and thus their economic, environmental and social roles are recognized by policymakers and society (Ripoll-Bosch et al. 2012). Nevertheless, the literature analysis through the PRISMA framework confirmed the need to broaden the research on ESs to meet decision-makers' and practitioners' information needs (Olander et al. 2017). Despite recognizing the pivotal role of sheep farming systems and their basis of the rural economy of Sardinia (Agris Sardegna 2017), there is a lack of studies on the secondary production of extensive dairy farming systems as a whole. Likewise, research on the economic benefits generated by extensive dairy sheep farming systems is missing. The lack of scientific relevance can only have repercussions on the ability of local, national and community policymakers to make informed decisions based on reliable information.

Moreover, the lack of studies focused on social benefits generated from breeding as a whole is surprising. Indeed, extensive dairy sheep farming systems are essential for the social fabric in rural areas. Due to the need to directly breed the sheep, people must live and work in these areas, avoiding depopulation and guaranteeing the defense of the territory. In addition, the rural decline is a global issue; extensive dairy sheep farming systems can tackle such problems by offering job opportunities to foreign workers, who in turn contribute actively to the process preservation of the above traditional practice (Nori et al. 2017).

Previous research (Ripoll-Bosch et al. 2013; Furesi et al. 2013; Leroy et al. 2018; Mattalia et al. 2020) has shown that the dairy sheep breeding system performs various functions which have given rise to several services and, in turn, benefits, for humans, who give a value of those services (Hansen and Pauleit 2014). This work recognizes that the economic value analysis of ESs is a methodology that has been criticized because of a conceptual controversy surrounding the use of economic approaches applied to ecosystems (e.g. Pimm 1997; Pearce 1998; Toman 1998; Viglizzo et al. 2012). The economic approach is anthropogenic and evaluates ecosystems according to human utility. Accordingly, the concept of ESs outlines the various contributions of ecosystems to human well-being, which are the main target of the analysis (MEA 2005b). It is acknowledged in this work that, under the ecological approach, every ecosystem has its own intrinsic value, independent of its benefits for humanity and of what people happen to like, want, or need (Sagoff 1997). However, the anthropogenic definition of ESs proposed by the MEA (2005b) originated from the aim of making natural capital relevant to society and decision-makers; moreover, making an economic evaluation allows for the comparison of the different benefits received by ESs by measuring them and expressing them in a common denominator, also including ESs not traded on the market, and which do not directly produce monetary benefits (Ottaviani 2020).

This work recognizes both the need to give value to externalities of the Sardinian extensive dairy sheep farming system and the anthropocentric nature of the framework of ESs (D'Ottavio et al. 2018) and SSs, which requires the assessment of their perception by stakeholders (Leroy et al. 2018). The assessment of ES perceptions is the first step to develop a shared understanding of the agro-landscape and support change paths in terms of sustainability (Dendoncker et al. 2018). Thus, the interviewees' perceptions of the ASOs were estimated, shedding light on possible paths to foster the durability and sustainable development of the target areas. While respondents generally showed a moderate perception of benefits generated by ASOs, significant findings emerged by analyzing the differences among residents and non-residents. In effect, because the 'subjective values are attributed based on the (individual and social) perception of real-world objects' (Spangenberg and Settele 2016, p. 102), different groups with different worldviews and different relationships with an ecosystem may recognize diverse potential services (Spangenberg et al. 2014; Bidegain et al. 2019).

Our results showed that the residence of the interviewees influenced the perception of SSs and ESs, confirming previous studies (López-Santiago et al. 2014; Bidegain et al. 2019; Montrasio et al. 2020). Non-residents, compared to residents, gave great value to ASOs, especially to those related to supporting and social services. There may be many explanations for this finding. Overall, residents recognized – more than other ASOs - the importance of pasture for the regional economy and society to enhance Sardinia's cultural identity and safeguard its typical landscape. In effect, shepherding is Sardinia's traditional and stereotypical representation (Ferrari 2009). Pasture has been at the focus of Sardinia's cultural identity for millennia and the agro-pastoral landscape, with its product, is one of the major attractions for tourists (Mattalia et al. 2020). Perhaps, it is the reason why residents placed a high value on the landscape and cultural 'noticeable' variables. In contrast, they may take for granted all other positive externalities of pasture, unlike the non-residents who make a conscious and targeted territory-use choice (Montrasio et al. 2020). Moreover, residents could also acknowledge several pasture problems associated with economic and environmental implications, such as out-migration and changes in ecologies because of shifts in grazing patterns (Nori and Scoones 2019). Idda et al. (2006) found a sense of social hostility towards the professional category of shepherds and a negatively oriented mentality towards sheep farming entrepreneurs by a portion of residents who carry out other activities that can overshadow all the other benefits generated by the Sardinian dairy-sheep system.

It could be that some of the residents may not look beyond these problems, resulting in a lack of knowledge that limits their ability to evaluate ASOs (Gundersen et al. 2017). A lack of information on an ASO may involve its 'unperception' and, in turn, render its consideration as not important (Bingham et al. 1995).

Another fact worthy of reflection is the cultural ESs 'that are usually directly experienced and intuitively appreciated' (Hermes et al. 2018, p. 296). In addition to the 'culture' appreciated by all, and 'art' appreciated more by non-residents, it was surprising that there was a moderate value attributed to 'heritage' (safeguard of cultural heritage) and 'recreation'. In reference to the first, we need only think of the 'canto a tenore', which developed in the pastoral culture of Sardinia and 'the paths of transhumance', keepers of a rich social, cultural, and environmental heritage, which the shepherds protect with their own activities. Both of these are forms of heritage inscribed in the United Nations Educational, Scientific and Cultural Organization (UNESCO) lists. The findings may mean that most people do not perceive that the Sardinian dairy sheep farming system is a vector for maintaining culture by carrying on traditions that have been going on for centuries.

These findings all highlight the need for a greater narrative effort to challenge the vision of pastoral activity, which too often is seen as old-fashioned and with negative connotations in terms of social environment and living conditions (Pastomed 2007, p. 8). There is a need to favor an increase in knowledge of the role of dairy farming systems and in the handing down of the centuries-old traditions that mark the regional cultural identity.

The moderate perception of the ES 'recreation' suggests the need for greater attention both to the management and to the promotion of the areas dedicated to pastoral activity. The durability and sustainable development of the Sardinian extensive dairy sheep systems, and the areas in which they are present, can be achieved by leveraging sustainable tourism, especially that based on natural and cultural assets. In fact, it can favor the exploitation of the territorial capital – meaning as historic and artistic capital, agricultural, pastoral and forest systems, territorial protection, know-how and craftsmanship – which can be a lever to revitalize those territories (Garrod et al. 2006; UVAL 2014) and foster local development (Maretti and Salvatore 2012; Sechi et al. 2020). However, if 'only human activities and presence can maintain this huge capital' (Sechi et al. 2020, p. 2), the territorial capital exploitation may be challenging since most Sardinian tourism is concentrated along the coasts and only a small part is in the inner area (ISTAT 2020). The increase of coastal tourism matches a decrease in population of the inner areas of the island (Onni and Cannaos 2017). The role of local policymakers in the implementation of policies to attract people towards these is essential.

Another noteworthy fact is the 'one for all' tendency, i.e., that the appreciation of one ASO involves the appreciation of all ASOs. These data can be very useful for policymakers looking to stimulate public recognition of ASOs provided by the Sardinian extensive dairy sheep farming system. The increase of information on ASOs deemed unimportant could lead to their perception and, in turn, appreciation of their importance.

Our results showed that personal provenance from a family with a peasant tradition does not affect perception of ASOs, but previous employment in the agricultural or livestock sector affects three ASOs (‘insect’, ‘territory’ and ‘local employment’). Similarly, being a shepherd or a farmer affects only four ASOs positively (‘biodiversity’, ‘habitats’, ‘carbon’ and ‘invasive’) and affects provision of social agricultural activities negatively. These data align with previous studies that see Sardinian shepherds as ‘unaware gardeners’ who build, maintain, and save the landscape unwittingly and play, albeit without knowing it, a social role related to cultural production and re-elaboration (Pitzalis and Zerilli 2013; Mattalia et al. 2020). Local organizations in conjunction with policymakers could adopt actions to raise the shepherds' awareness of the multifunctionality of their activity. On the demand side there is a recognition of the ASOs produced by the Sardinian extensive dairy sheep farming system, which could create value within the company and ultimately increase its involvement in the production of ASOs.

Given the descriptive analysis results regarding other sociodemographic variables, it is not surprising that residence significantly influences perceptions of almost all ASOs. The educational level of the interviewees affects the perception of seven benefits generated by the Sardinian extensive dairy sheep farming system. A strongly significant result concerns the variable ‘subject knowledge’, particularly given previous studies that have found a positive relationship between subject knowledge and objective knowledge, which refers to accurate stored information that an individual possesses (Radecki and Jaccard 1995; Carlson et al. 2009). These data confirm the need to increase public awareness of the role of pastoralism in generating environmental, humans' health and social well-being.

5. Conclusion

Shepherding is a primary source of livelihood for several communities in Sardinia and other Mediterranean areas. It has been at the heart of local cultural identity for millennia, provides landscape maintenance and care, and contributes to the protection of the territory and the safeguarding and enhancement of vegetal and animal biodiversity. A performing and sustainable agro-pastoral sector is seen as 'the best ticket to the future of most Mediterranean islands' (Nori et al. 2017, p. 145). Along the same lines, this study focused on the demand side, offering an overview of how the public perceives the relationships between the dairy sheep farming system and the territory's environmental and social aspects, demonstrating which ASOs are most appreciated by different beneficiaries and on which strategic policy choices should focus. This is the first step to value these positive externalities that are largely involuntary (UVAL 2014). The assessment of perception and valuation of ASOs could also allow for the setting of an effective communication strategy towards local and general communities about the positive externalities of dairy sheep farming systems.

Sardinian stock farmers provide maintenance and care of the territory almost unconsciously. Recognizing the value and contribution of their secondary products can turn them from unaware to aware territory keepers and voluntary public goods providers (Mattalia et al. 2020) and lay the foundation for 'bring together territorial protection, development and (living) labor, and ensure that territorial protection evolves from precondition to development process' (UVAL 2014, p. 42). This study, highlighting the appreciation of ecosystems and social public goods provided by stock farmers that are not adequately valued through the market mechanism, offers an answer to those who see the EU's agricultural policy support for livestock farming as excessive. The perception of ASOs makes it possible to give them a value and determine the magnitude of the benefits that the Sardinian dairy sheep farming system provides, thus supporting policymakers to make effective, informed decisions and to justify investments and actions. Our findings suggest the possibility to switch from the traditional concept of subsidies to payment for ES provision, which links payments to market demands (i.e., the values attributed to ASOs by society) and can target policy towards specific ASOs (Plieninger et al. 2012; Faccioni et al. 2019).

Finally, to our knowledge, this is the first economic study on secondary outputs provided by extensive sheep farming systems, and it considers a large number of secondary outputs. The voluntary response sample that has tilted the balance of sample in favor of resident, limits the generalizability of findings, although it allowed an insight into the views of people who have a strong feeling about the topic. Further research based on stratified sampling could validate our findings. Comparative studies would also allow us to understand the change in perception and how this relates to characteristics of the agricultural landscape and its users. Given the importance of the issue to support the decisions of public and private actors to foster the survival of the dairy sheep sector in Sardinia and other

Mediterranean regions, further research is needed to deepen the relationship between pasture and the rural landscape in the Mediterranean region. Such evidence could support rural policies aimed at safeguarding primary sector activities in the European landscape.

This study focused on SSs and ESs provided by dairy sheep farming systems. According to (Blanco et al. (2019) and Herd-Hoare and Shackleton (2020), an integrated assessment of ESs and EDs could offer further perspectives for proper management approach and the definition of innovative sustainability policies that consider and integrate the social, economic, and environmental dimensions of livelihoods and land use. Future research may expand our research by identifying EDs arising from dairy sheep farming systems, investigating people's reactions to them, and assessing whether the information obtained offers significant contributions to rethinking sustainability policies towards greater effectiveness and equity.

Finally, further research needs to be conducted in the field of economic evaluations of secondary production of the extensive dairy sheep farming system, such as the monetary valuation of key ASOs and preferences and willingness-to-pay of different groups of people.

6. Appendix

Table A2.1 – List of secondary outputs

Services	Variable	Description
Regulating	FERTILISERS	Production of natural fertilisers
	HABITATS	Maintenance of natural habitats
	INSECTS	Presence of useful pollinating insects
	GHG	Greenhouse gas mitigation
	CARBON	Preservation of carbon in the soil
	EROSION	Reduction of soil erosion caused by rain
	INVASIVE	Control of invasive species of flora and fauna
	WATER	Ensuring good quality of water
	LANDSCAPE	Safeguard of the typical landscape
Cultural	CULTURE	Enhancing cultural identity of Sardinia
	ENV_EDUCATION	Promotion of environmental education
	ARTS	Inspiring arts and culture
	RECREATION	Supply of recreational and cultural activities
	HERITAGE	Safeguard of cultural heritage
Supporting	BIODIVERSITY	Safeguard of animal biodiversity (local breeds)
	FIRES	Fire prevention
Social	TERRITORY	Avoid depopulation and ensure the defence of the territory
	LOC_EMPLOYMENT	Job supply for the local population
	IMM_EMPLOYMENT	Job supply for immigrants
	SOCIAL	Providing social agricultural activities

Table A2.2 – Description of selected studies

RQ 1: Has previous literature analysed the population's perception towards ASOs in the context of agroecosystems?										
	Authors	**Title**	**Year**	**Journal**	**Sector considered**	**Reference Area**	**Type of farming considered**	**Aim of the analysis**	**Ecosystem services considered**	
1a	Balázsi Á., Dänhardt J., Collins S., Schweiger O., Settele J., Hartel T.	Understanding cultural ecosystem services related to farmlands: Expert survey in Europe	2021	Land Use Policy	Agriculture	Europe	-	To assess the understanding and perceptions on the usefulness and acceptance of the cultural ecosystem services concept by experts working in the science-policy-implementation interface related to agricultural landscapes of Europe.	*Cultural*:	Recreation and ecotourism; aesthetic, spiritual, religious, educational, cultural heritage values, inspiration, sense of places, knowledge systems, social relationships, and cultural diversity.
1b	Bernués A., Rodríguez-Ortega T., Ripoll-Bosch R., Alfnes F.	Socio-cultural and economic valuation of ecosystem services provided by Mediterranean mountain agroecosystems	2014	PLoS ONE	Farming	Guara Natural Park, northeast Espana	Meat sheep farming	Determine the economic, social, and cultural value of ecosystem services derived from mountain agro-ecosystems in the Euro-Mediterranean region.	*Cultural*: *Supporting*: *Provisioning*:	Maintenance of the agricultural landscape. Conservation of biodiversity; fire prevention. Production of quality food linked to the territory.
1c	Leroy G., Hoffmann I., From T., Hiemstra S.J., Gandini G.	Perception of livestock ecosystem services in grazing areas	2018	Animal	Farming	42 countries (53.7% European e 46.3% extra-European)	General	Investigate how ecosystem services (except provisioning) related to livestock grazing are perceived across countries.	*Regulating*: *Cultural*: *Supporting*:	Habitat; water quality; cycling regulation; clime and air; erosion and avalanche; bush encroachment; fire control; pest and disease; control of crop residues and eradication of weeds; seed dispersal. Cultural-historical and natural heritage; knowledge systems, educational, landscape, recreational, spiritual, and religious values. Nutrient cycling; support of primary production.
1d	York E.C., Brunson M.W., Hulvey K.B.	Influence of Ecosystem Services on Management Decisions by Public Land Ranchers in the Intermountain West, United States	2019	Rangeland Ecology and Management	Farming	Intermountain West - Western United States	Cattle (95%) and sheep (7%)	Identify which ES drive pasture management decisions	*Regulating*: *Cultural*: *Provisioning*: *Supporting*:	Control of crop residues and eradication of weeds, bush encroachment and fire, erosion, and avalanche; regulation of climate and air quality, pest and disease, quality and cyclin water; seed dispersal. Cultural, historical and natural heritage; knowledge systems; educational, landscape, recreational, spiritual and religious values. Habitat; nutrient cycling. Support of primary production.
1e	Boeraeve F., Dufrêne M., Dendoncker N., Dupire A., Mahy G.	How are landscapes under agroecological transition perceived and appreciated? A Belgian case study	2020	Sustainability (Switzerland)	Agriculture and farming	Hainaut - Belgium	Cattle	Assess the extent to which locals (local inhabitants and Farmers) appreciate and view landscapes undergoing agricultural transitions	*Regulating*: *Cultural*: *Supporting:* *Provisioning:*	Water pollution, flood, and erosion protection; pest control; landscape aesthetics; soil fertility. Recreation and education inspiration; heritage; social cohesion. Biodiversity. Food production.

Table A2.2 – Continuous

RQ 1: Has previous literature analysed the population's perception towards ASOs in the context of agroecosystems?							
	Preliminary phase	**Users interviewed (preliminary phase)**	**Type of users interviewed (preliminary phase)**	**Users interviewed (secondary phase)**	**Type of users interviewed (secondary phase)**	**Methodology**	**Results**
1a	Only this	81	Experts from the following areas of activity formed our target group: a) sustainable agriculture, landscape ecology, grassland management; b) nature conservation, cultural heritage conservation (i.e., conservationist profile); c) ecosystem services research; d) policy on environment and rural development.	-	-	Social analysis through questionnaires by mail and post	The results show a wide knowledge and acceptance of the cultural ecosystem services concept within such expert communities. Especially the aesthetic, cultural heritage, educational and recreational values were considered the most relevant CES subcategories.
1b	Yes	88	Five Focus Groups (FG): two with livestock farmers (n=11) that used pastures within the park, and three with citizens (n=22) residents in neighbouring cities.	504	102 citizens of Guara Natural Park, 402 inhabitants of the Aragon region	Choice experiment	Cultural services (particularly the aesthetic and recreational values of the landscape), supporting services (biodiversity maintenance) and some regulating services (particularly fire risk prevention) were clearly recognised by both farmers and citizens. The prevention of forest fires (≈50% of total willingness to pay) was valued by the general population as a key ecosystem service delivered by these agroecosystems, followed by the production of specific quality products linked to the territory (≈20%), biodiversity (≈20%) and cultural landscapes (≈10%). The value given by local residents to the last two ecosystem services differed considerably (≈10 and 25% for biodiversity and cultural landscape, respectively). The Total Economic Value of mountain agroecosystems was ≈120 € person−1 year−1, three times the current level of support of agro-environmental policies.
1c	Yes		Qualitative pilot survey by FAO in 2013	44 Europeans and 38 non-Europeans	Scientists and other experts working in grassland-related fields from 42 countries	Case study analysis	A large proportion of respondents reported either positive or very positive impacts for some cultural ES, namely cultural, historical and natural heritage (84%), knowledge systems and educational values (77%), landscape values (74%), and for some supporting and regulating ES, namely habitat provision (66%), nutrient cycling (65%), and bush encroachment/fire control (66%). Depending on the ES, between 0%, for spiritual and religious values, and 17%, for water quality and cycling regulation, respondents reported a negative or very negative impact. Respondents reported those impacts as more positive in Europe, in protected areas and where several species were present in the grazing area.
1d	Yes	11	Professionals in cooperative state agencies	287	Ranchers	Qualitative analysis through data-gathering through semi-structured “key informant interviews” before and large-scale survey after	The analysis identified services ranchers believe rangelands provide. The most frequently selected were provisioning or cultural services: forage for livestock (98.4%), demonstrating good stewardship to the public or other ranchers (95.9%), and maintaining a family legacy for future generations (93.8%). The least frequently selected were oil and gas production (11.4%), renewable energy production (21.9%) and income from tourism, recreation experiences and hunting leases (22.3%).
1e	Only this	37	9 local inhabitants, 2 local farmers, 2 agroecological, 2 ES experts	-	-	Qualitative analysis by questionnaire and mixed linear model	Both locals and experts see the agroecological scenario as delivering more ES and the conventional scenario as delivering the least ES. The agroecological scenario was seen as the most appreciated and the one delivering the most ES, while the conventional one was the least appreciated and seen as the one delivering the least ES.

Table A2.2 – Continuous

RQ 2: Is there evidence for which ASOs provided by the primary sector are most appreciated?										
	Authors	**Title**	**Year**	**Journal**	**Sector considered**	**Reference Area**	**Type of farming considered**	**Aim of the analysis**	**Ecosystem services considered**	
2a	Bernués A., Tello-García E., Rodríguez-Ortega T., Ripoll-Bosch R., Casasús I.	Agricultural practices, ecosystem services and sustainability in High Nature Value farmland: Unraveling the perceptions of farmers and nonfarmers	2016	Land Use Policy	Farming	Mountains of the Spanish Northeast (Central and pre-Pyrenees)	Meat cattle and sheep farming	Analyse the perceptions of farmers and nonfarmers regarding the relationships between agriculture and the environment in areas of naturalistic interest and the environment	*Regulating:* *Cultural*: *Supporting*: *Provisioning*:	Air quality, water flows, and climate regulation; disturbance (forest fires) and soil fertility/erosion prevention; water purification/waste management; pollination; biological control (pests). Aesthetic; recreation/tourism; culture/art; spiritual experience; education/cognitive dev. Lifecycle maintenance; gene pool protection. Food (meat and milk); water; raw materials (firewood, forage, mushrooms); genetic, medicinal, and ornamental resources.
2b	López-Santiago C.A., Oteros-Rozas E., Martín-López B., Plieninger T., Martín E.G., González J.A.	Using visual stimuli to explore the social perceptions of ecosystem services in cultural landscapes: The case of transhumance in Mediterranean Spain	2014	Ecology and Society	Agriculture and farming	Conquense Drove Road - Espana	Cattle and Sheep farming	Compare the perception of ES deriving from two different landscapes (pine forest and cultivated fields); investigate the perception of ES in landscapes with or without drove road dedicated to transhumance; analyse the links between the perception of ES and the socio-cultural and demographic characteristics of the sample.	*Regulating:* *Cultural*: *Provisioning*:	Air purification; plant regeneration; fire prevention; soil erosion control; habitat for species; connectivity. Aesthetic values; cultural identity; tourism; hunting; tranquillity/relaxation. Feed for animals; gathering; food from agriculture; wood and timber; livestock.
2c	Montrasio R., Mattiello S., Zucaro M., Genovese D., Battaglini L.	The perception of ecosystem services of mountain farming and of a local cheese: An analysis for the touristic valorisation of an inner alpine area	2020	Sustainability (Switzerland)	Farming	Valli di Lanzo, Piedmont	Dairy cattle farming	Evaluate the community's perception towards livestock farming in the Lanzo Valleys and the typical product; investigate the consumers' habits and preferences to detect possible positive impacts on mountain tourism	*Regulating*: *Cultural*: *Supporting*: *Provisioning*:	Control of fire, invasive species, and soil erosion; Improvement of water quality; pollination. Cultural identity; environmental education; inspiration for arts and culture; maintenance of landscape; recreational opportunities; religious experiences. Habitat maintenance; maintenance of local breeds. Food production; maintenance of biodiversity; production of fertilizers, wool, and leather.

Table A2.2 – Continuous

RQ 2: Is there evidence for which ASOs provided by the primary sector are most appreciated?							
	Prelimi-nary phase	**Users interviewed (preliminary phase)**	**Type of users interviewed (preliminary phase)**	**Users interviewed (secondary phase)**	**Type of users interviewed (secondary phase)**	**Methodology**	**Results**
2a	Only this	88	Five Focus Groups (FG): one with farmers of meat-sheep, mixed agriculture-sheep, one with farmers of cattle farmers with few or no agricultural crops, and three with nonfarmers.	-	-	Focus groups	The farmers were very knowledgeable of ecosystem services (particularly regulation), the interactions among them, and their relationships with agricultural practices, particularly grazing management. Nonfarmers were less knowledgeable of ecosystem services, particularly regulation, and identified fewer relationships with agricultural practices. However, nonfarmers were highly concerned about the provision of quality food products and several cultural ecosystem services.
2b	Yes		Information collected from a study by Oteros-Rozas et al. (2012)	314	191 residents and 123 non-residents	Qualitative analysis by a questionnaire that includes visual stimuli	Overall, respondents recognized the higher capacity of forests to deliver a wider range of ecosystem services to society compared with croplands. Provisioning services were mostly associated with cropland, whereas regulating services and cultural ecosystem services tended to be related to forests. All three types of ecosystem services were more perceived by respondents when a drove road was present in each landscape. However, differences in the visual perception of ecosystem services supply and preference for transhumance landscapes emerged in relation to certain socio-demographic and cultural respondent characteristics such as a previous relationship with transhumance and agriculture, rural/urban origin and identity, environmental awareness, and cultural attachment to a place.
2c	Only this	233	Residents and non-residents	-	-	Qualitative analysis by a questionnaire	The respondents had a very positive awareness of the impact of mountain livestock farming in the Lanzo Valleys. The most important perceived ESs are cultural identity and maintenance of local breeds. Women, non-residents, and respondents with an intermediate education level generally had a more positive perception of ESs. There was a very low perception of disservices derived from mountain animal farming.

Table A2.2 – Continuous

	Authors	Title	Year	Journal	Sector considered	Reference Area	Type of farming considered	Aim of the analysis	Ecosystem services considered	
RQ 3: Has previous literature provided an economic evaluation of primary sector ASOs, especially concerning breeding systems?										
3a	Bernués A., Alfnes F., Clemetsen M., Eik L.O., Faccioni G., Ramanzin M., Ripoll-Bosch R., Rodríguez-Ortega T., Sturaro E.	Exploring social preferences for ecosystem services of multifunctional agriculture across policy scenarios	2019	Ecosystem Services	Farming	Guara Natural Park (Espana), Aurland Municipality (Norway), Province of Trento (Italy)	Meat sheep farming (Espana), meat sheep farming and dairy goats farming (Norway), dairy cattle farming (Italy)	Analyse social preferences for ES and associated willingness to pay in three European multifunctional agroecosystems in Europe (Mediterranean, Atlantic, Alpine) under alternative agrienvironmental policy scenarios	*Regulating:* *Cultural*: *Supporting*: *Provisioning*:	Fire and water prevention; soil fertility in the Atlantic areas. Agricultural landscape maintenance. Biodiversity conservation. High-quality food.
3b	Bernués A., Rodríguez-Ortega T., Alfnes F., Clemetsen M., Eik L.O.	Quantifying the multifunctionality of fjord and mountain agriculture by means of socio-cultural and economic valuation of ecosystem services	2015	Land Use Policy	Farming	Aurland, southeast Norway	Meat sheep farming and dairy goats farming	Define the value of the main functions performed by fjords and mountain agroecosystems in the Nordic countries by means of the ecosystem services framework	*Regulating:* *Cultural*: Supporting *Provisioning*:	Soil fertility. Agricultural landscape. Biodiversity. Quality products linked to the territory.
3d	Bielski S., Marks-Bielska R., Novikova A., Vaznonis B.	Assessing the value of agroecosystem services in warmia and mazury province using choice experiments	2021	Agriculture (Switzerland)	Agriculture	Warmia e Mazury region - Poland	-	Assess the non-market values of agroecosystem services in an exceptionally environmentally rich area of the Warmia and Mazury region (Poland), identifying consumers' preferences for them	*Regulating*: *Cultural*: *Supporting*: *Provisioning*:	Water quality. Agricultural landscape. Biodiversity.
3e	Rewitzer S., Huber R., Grêt-Regamey A., Barkmann J.	Economic valuation of cultural ecosystem service changes to a landscape in the Swiss Alps	2017	Ecosystem Services	Agriculture and farming	Visp - Swiss	Cattle	Advance the notion that the economic valuation of cultural ecosystem services is, principally, not more problematic than the economic valuation of non-cultural ecosystem services	*Regulating*: *Cultural*: *Supporting*:	Protection against natural hazards. Agricultural heritage; aesthetic value of landscape. Biodiversity

Table A2.2 – Continuous

RQ 3: Has previous literature provided an economic evaluation of primary sector ASOs, especially concerning breeding systems?							
	Prelimi-nary phase	**Users interviewed (preliminary phase)**	**Type of users interviewed (preliminary phase)**	**Users interviewed (secondary phase)**	**Type of users interviewed (secondary phase)**	**Methodology**	**Results**
3a	Yes	-	Representative panellists	1044	Resident	Choice experiments and questionnaire	Some lessons were delivered. i) Value of ES: biodiversity and regulating ecosystem services always produce welfare gains; people, however, perceive trade-offs between delivery of agricultural landscapes and quality food products. Nevertheless, preferences are heterogeneous and vary across regions, scenarios, and ES. ii) Policymaking: society’s willingness to pay for ecosystem service delivery largely exceeds the current level of public support. Moreover, further abandonment and intensification of agriculture are clearly rejected by the public. iii) Methodological: monetary valuation is context-dependent, and extrapolation of economic values can be misleading.
3b	-			43; 312	Socio-cultural analysis: farmers (27), local businesses (9), representatives of governmental agencies (3) and non-profit organisations (4) involved in the conservation of environmental and cultural heritage. Choice experiment: Resident of Aurland (72) and inhabitant near Bergen (240)	Socio-cultural analysis and Choice experiment	The socio-cultural perceptions of multifunctionality among local stakeholders were similar, but differences in the relative importance of the functions reflected particular interests (agriculture compared with tourism). Both the local and the general populations attached great importance to the production and availability of quality foods. The general population showed very homogenous preferences among ecosystem services, but local people rated them very differently. Local people ranked a more agricultural landscape very high. The total economic value of fjord and mountain agroecosystem was 850 € per person per year. The willingness to pay for the provision of ecosystem services under a policy scenario of further development of multifunctional agriculture clearly exceeded the current level of public support. The welfare loss that society would experience in a scenario of further abandonment of agriculture was even greater
3d	-	-	-	353	Residents	Choice experiment	Residents were concerned about environmental issues that may be caused by agriculture. There was a demand for the provision of agroecosystem services. Marginal willingness to pay values were the highest for water quality (EUR 1.94), followed by wildlife population (EUR 1.02) and agricultural landscape (EUR 0.85)
3e	Yes	117	Local inhabitants	252	Local inhabitants	Pre-studies (semi-structured interviews, stakeholder workshop); pilot study (n = 117); discrete choice experiment	Citizen support was expressed for agricultural heritage and biodiversity-rich dry grasslands. Aesthetic impacts of settlement extension and grassland intensification reduced the economic value of development options impacting the Visp landscape. Estimated marginal willingness-to-pay ranged from 410 CHF (1 CHF approx. 0.8 EUR in 2013)/person/year for 60 additional ha of dry grassland to 833 CHF for the visual impact of settlement expansion (by changes of the tax bill).

Table A2.3 – Set of logit regressions

Dependent variables	FERTILIZERS				BIODIVERSITY				HABITATS				FIRE				INSECTS			
Independent variables	*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*	
Residence	-0.372	0.296	0.208		**-0.618**	**0.297**	**0.037**	**	**-0.779**	**0.286**	**0.007**	***	**-0.518**	**0.286**	**0.070**	*	-0.077	0.285	0.786	
Gender	-0.216	0.187	0.248		-0.136	0.184	0.459		**-0.344**	**0.173**	**0.047**	**	-0.284	0.178	0.111		-0.234	0.177	0.186	
Past_Prof_Experience	-0.042	0.213	0.844		0.227	0.210	0.279		-0.100	0.199	0.614		0.061	0.205	0.767		**0.488**	**0.203**	**0.016**	**
Education	-0.172	0.117	0.143		**0.269**	**0.115**	**0.019**	**	0.176	0.108	0.104		0.133	0.112	0.234		0.095	0.112	0.392	
Sheepbreader	-0.065	0.325	0.842		0.125	0.314	0.692		**0.566**	**0.299**	**0.058**	*	0.447	0.307	0.145		0.404	0.305	0.185	
Farmer	-0.376	0.728	0.605		**138122**	**0.833**	**0.097**	*	0.234	0.595	0.694		0.239	0.657	0.716		0.820	0.668	0.220	
Past_Fam_Experience	-0.019	0.208	0.926		0.241	0.202	0.233		-0.091	0.192	0.636		0.159	0.197	0.420		-0.247	0.196	0.208	
Age	-0.086	0.075	0.254		-0.012	0.074	0.868		0.017	0.069	0.805		0.079	0.071	0.265		0.053	0.071	0.450	
Subject_Knowledge	**0.135**	**0.078**	**0.083**	*	**0.198**	**0.077**	**0.010**	***	**0.191**	**0.071**	**0.007**	***	**0.346**	**0.075**	**<0.0001**	***	**0.340**	**0.076**	**<0.0001**	***
Frequency	-0.052	0.117	0.656		-0.080	0.113	0.482		-0.112	0.107	0.297		-0.088	0.107	0.409		**-0.238**	**0.110**	**0.030**	**
cut1	-272266	0.670	<0.0001	***	-222477	0.676	0.001	***	-121074	0.628	0.054	*	-0.389	0.631	0.538		0.163	0.630	0.796	
cut2	0.433	0.655	0.509		116932	0.656	0.075	*	106312	0.628	0.091	*	211045	0.638	0.001	***	277621	0.645	<0.0001	***
Log-Likehood ratio test: Chi-square (10)	104962				112456				963421				119658				127404			

Dependent variables	GHG				CARBON				EROSION				INVASIVE				WATER			
Independent variables	*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*	
Residence	-0.387	0.292	0.185		**-0.764**	**0.285**	**0.007**	***	**-0.680**	**0.283**	**0.016**	**	-0.111	0.284	0.696		**-0.694**	**0.333**	**0.037**	**
Gender	-0.125	0.181	0.487		-0.121	0.174	0.488		0.029	0.175	0.870		**-0.526**	**0.180**	**0.004**	***	0.014	0.188	0.942	
Past_Prof_Experience	0.289	0.209	0.168		**0.354**	**0.197**	**0.073**	*	-0.061	0.200	0.762		-0.122	0.205	0.554		0.205	0.222	0.355	
Education	**0.300**	**0.113**	**0.008**	***	0.057	0.108	0.595		0.098	0.110	0.371		**-0.217**	**0.113**	**0.055**	*	0.064	0.117	0.581	
Sheepbreader	0.245	0.304	0.421		0.452	0.287	0.115		-0.335	0.296	0.258		**116924**	**0.309**	**0.000**	***	-0.246	0.323	0.447	
Farmer	114495	0.699	0.101		**119250**	**0.643**	**0.064**	*	0.624	0.648	0.335		**154040**	**0.731**	**0.035**	**	0.487	0.839	0.562	
Past_Fam_Experience	-0.039	0.201	0.845		0.302	0.193	0.117		-0.057	0.196	0.772		0.214	0.200	0.284		-0.036	0.210	0.863	
Age	0.049	0.072	0.500		-0.014	0.069	0.840		-0.068	0.070	0.329		-0.051	0.072	0.478		-0.008	0.076	0.912	
Subject_Knowledge	**0.258**	**0.076**	**0.001**	***	**0.190**	**0.073**	**0.009**	***	**0.204**	**0.074**	**0.006**	***	**0.160**	**0.075**	**0.033**	**	**0.249**	**0.078**	**0.002**	***
Frequency	0.081	0.111	0.469		0.044	0.106	0.681		-0.049	0.108	0.648		0.086	0.109	0.429		-0.135	0.119	0.256	
cut1	106535	0.648	0.100		0.106	0.617	0.863		-162389	0.626	0.010	***	-0.877	0.642	0.172		-213660	0.689	0.002	***
cut2	388574	0.674	<0.0001	***	229846	0.627	0.000	***	0.844	0.624	0.176		203629	0.649	0.002	***	-0.238	0.678	0.726	
Log-Likehood ratio test: Chi-square (10)	123929				112665				92231				143348				833572			

Dependent variables	CULTURE				ENV_EDUCATION				ARTS				RECREATION				LANDSCAPE			
Independent variables	*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*	
Residence	**-0.451**	**0.273**	**0.098**	*	**-0.451**	**0.273**	**0.098**	*	**-0.528**	**0.283**	**0.062**	*	**-0.732**	**0.278**	**0.009**	***	**-0.649**	**0.298**	**0.029**	**
Gender	-0.177	0.173	0.306		-0.177	0.173	0.306		**-0.318**	**0.172**	**0.065**	*	**-0.319**	**0.173**	**0.065**	*	-0.246	0.179	0.170	
Past_Prof_Experience	0.217	0.198	0.274		0.217	0.198	0.274		-0.164	0.200	0.412		-0.127	0.199	0.523		0.176	0.206	0.395	
Education	-0.003	0.108	0.975		-0.003	0.108	0.975		0.049	0.109	0.654		-0.090	0.109	0.408		0.150	0.112	0.180	
Sheepbreader	-0.106	0.303	0.726		-0.106	0.303	0.726		-0.320	0.291	0.271		0.045	0.296	0.879		0.242	0.311	0.436	
Farmer	0.148	0.659	0.822		0.148	0.659	0.822		-0.405	0.616	0.510		0.558	0.643	0.386		0.247	0.671	0.713	
Past_Fam_Experience	0.307	0.191	0.108		0.307	0.191	0.108		0.261	0.190	0.170		0.154	0.191	0.420		0.239	0.198	0.228	
Age	0.073	0.069	0.288		0.073	0.069	0.288		**0.202**	**0.069**	**0.004**	***	**0.150**	**0.069**	**0.030**	**	-0.008	0.072	0.915	
Subject_Knowledge	**0.189**	**0.071**	**0.008**	***	**0.189**	**0.071**	**0.008**	***	**0.244**	**0.072**	**0.001**	***	**0.260**	**0.073**	**0.000**	***	**0.212**	**0.075**	**0.005**	***
Frequency	-0.157	0.105	0.136		-0.157	0.105	0.136		-0.091	0.105	0.384		-0.095	0.104	0.362		**-0.185**	**0.112**	**0.099**	*
cut1	-119579	0.616	0.052	*	-119579	0.616	0.052	*	-0.314	0.619	0.612		-0.533	0.625	0.393		-191884	0.653	0.003	***
cut2	100348	0.615	0.103		100348	0.615	0.103		181040	0.625	0.004	***	180158	0.631	0.004	***	0.208	0.646	0.747	
Log-Likehood ratio test: Chi-square (10)	916621				916621				951135				102057				952683			

Dependent variables	HERITAGE				TERRITORY				LOC_EMPLOYMENT				IMM_EMPLOYMENT				SOCIAL			
Independent variables	*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*		*Coeff.*	*S.E.*	*p-value*	
Residence	**-0.577**	**0.285**	**0.043**	**	**-0.746**	**0.290**	**0.010**	**	**-0.623**	**0.283**	**0.028**	**	**-0.471**	**0.284**	**0.098**	*	**-0.485**	**0.288**	**0.092**	*
Gender	-0.066	0.176	0.708		0.033	0.173	0.849		0.194	0.174	0.264		0.133	0.173	0.439		-0.041	0.175	0.814	
Past_Prof_Experience	-0.027	0.204	0.896		**0.377**	**0.200**	**0.059**	*	**0.338**	**0.200**	**0.091**	*	0.127	0.200	0.524		0.166	0.202	0.411	
Education	**-0.241**	**0.111**	**0.030**	**	0.080	0.108	0.457		**0.234**	**0.110**	**0.033**	**	**0.234**	**0.109**	**0.032**	**	-0.012	0.108	0.913	
Sheepbreader	0.006	0.300	0.985		-0.203	0.292	0.488		-0.130	0.299	0.665		-0.187	0.292	0.523		**-0.655**	**0.297**	**0.027**	**
Farmer	-0.333	0.694	0.632		-0.348	0.663	0.600		-0.536	0.706	0.448		-112476	0.719	0.118		-0.329	0.636	0.605	
Past_Fam_Experience	0.305	0.195	0.118		0.021	0.190	0.912		0.026	0.192	0.893		-0.082	0.192	0.668		0.308	0.194	0.112	
Age	0.086	0.071	0.225		**0.244**	**0.070**	**0.001**	***	0.105	0.069	0.131		0.087	0.069	0.202		0.010	0.069	0.887	
Subject_Knowledge	**0.163**	**0.073**	**0.026**	**	**0.370**	**0.072**	**<0.0001**	***	**0.252**	**0.072**	**0.000**	***	**0.285**	**0.073**	**<0.0001**	***	**0.120**	**0.072**	**0.095**	*
Frequency	**-0.254**	**0.107**	**0.018**	**	-0.166	0.105	0.114		**-0.184**	**0.109**	**0.091**	*	-0.145	0.108	0.178		-0.130	0.107	0.224	
cut1	-249716	0.638	<0.0001	***	0.606	0.614	0.323		-0.122	0.610	0.842		0.534	0.617	0.386		-113554	0.610	0.063	*
cut2	0.041	0.627	0.947		234727	0.623	0.000	***	209925	0.619	0.001	***	269764	0.629	<0.0001	***	127706	0.611	0.037	**
Log-Likehood ratio test: Chi-square (10)	102492				119053				112369				101822				906501			

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CHAPTER 3

Economic and Environmental Sustainability Trade-Off Analysis in Sheep Farming Using the Farm Accountancy Data Network Database

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ABSTRACT

Agriculture and livestock farming significantly contribute to the success of all United Nations Sustainable Development Goals of Agenda 2030 and are pivotal in the sustainability transition of the European agri-food sector. However, those sectors have been criticized for generating negative environmental externalities. In this context, adopting indicators able to evaluate agriculture and sheep farming sustainability is essential for fostering sustainable development in the primary sector and defining appropriate policies to support it. Such indicators are crucial for understanding if European Union policies striving to realize win–win opportunities based on synergy between farms' environmental and economic dimensions are realistic. This paper focuses on this wave of interest and has two aims. First, it intends to investigate the existence of synergies or trade-offs between those dimensions using a trade-off analysis. To this end, a significant set of economic and environmental farm indicators was selected, and two composite indicators were created. Second, it aims to investigate the relationship between those two indicators and some pivotal structural and socio-demographic variables. This study was carried out on 219 Sardinian sheep farms included in the Italian Farm Accountancy Data Network. The findings showed a low synergy between the economic and environmental spheres, a relationship between economic indicators and farmers' ages and organic production variables, and no relationships between the environmental dimension and the analyzed variables.

Keywords: livestock; synergies; Sardinia; sustainability indicators; European policy; dairy farming

1. Introduction

Agriculture and livestock farming are central to sustainable development (Atzori et al., 2022; Kanter et al., 2018) as they significantly contribute to the success of all Sus-tainable Development Goals (SDGs) of Agenda 2030 (Arru et al., 2022; Verbeek et al., 2019), and, partly, because they are circular by nature (Díaz de Otálora et al., 2021).

The European Union (EU) is committed to a comprehensive sustainability transition of the European agri-food sector. Livestock systems are not an exception, particularly in the light of the central role they play in the European primary economy (Finco et al., 2018) both in terms of the millions of workers involved and the considerable total eco-nomic output and government revenue contribution (FoodDrinkEurope, 2021; Grau & Reig, 2021; Juchniewicz & Łukiewska, 2021). Moving towards this direction, the EU has approved new policies—the European Green Deal (European Commission, 2019), the Farm to Fork (European Commission, 2020b) and Biodiversity (European Commission, 2020a) strategies, and the Next Generation EU (European Commission, 2021)—that organically operate to support the food system's transition towards a new production model. The aim is to ferry Europe's agricultural sector towards a more sustainable model and make EU the first climate-neutral continent in the world (including through the application of various measures, such as reducing both the use of fertilizers by 20% and the use of antibiotics or increasing the share of organically cultivated agricultural land). On the wave of these new strategies, agricultural activities must simultaneously meet a set of complex goals (i.e., to mitigate climate change while adapting to it and to reverse biodiversity loss as well), which would lead to safeguarding the affordability of food products, generating fairer economic returns, furthering the competitiveness of the EU supply sector, and favoring fair trade (Dell'Unto et al., 2023). The feasibility of adhering to new EU constraints while maintaining farming activities' social and economic sustainability is a very current topic. This is because the importance of ensuring the EU agricultural sector's economic vitality and competitiveness to ensure EU food security and affordability and to meet new EU environmental goals is undeniable (Dell'Unto et al., 2023).

According to Poponi et al. (2022), actions are needed in the agri-food sector and livestock production to ensure a transition to a more suitable development model (Lebacq et al., 2013; Masi et al., 2021; Pulina et al., 2022). Actually, although progress is slow, more sustainable production methods have been developed lately (Arvidsson Segerkvist et al., 2020; Masi et al., 2021). This also depends on criticism levelled at the agricultural sector, particularly livestock farming, which is argued to cause negative externalities and is indicated as one of the activities with the greatest environmental impact (Pulina et al., 2022; Zanni et al., 2022).

Specifically, sustainable livestock systems "should be environmentally friendly, economically viable for farmers and socially acceptable" (Lebacq et al., 2013), where environmental sustainability comprises the management of inputs and the use of re-sources and economic sustainability is the ability of the farming system to be profitable and to ensure prosperity for the farming community (Lebacq et al., 2013; Van Cauwen-bergh et al., 2007).

Nevertheless, the transition to a new livestock production system is contested, be-cause each solution inevitably generates positive or negative outcomes and new patterns of winners and losers among actors (Morris et al., 2021).

In this context, farmers are called to make efforts in light of the "just transition" (European Commission, 2020b) that should create synergies and avoid trade-offs among the sustainability dimensions (environment, social, and economic) embedded in multiple objectives of the European strategy. At the same time, to support the agriculture transition, policymakers need to know (i) whether the policies aimed at stimulating environmental performance improvement in agriculture (e.g., F2F, biodiversity strategies, and PNRR) come at the cost of retarding economic performance (e.g., by lowering the farm’s productivity), and (ii) whether those aimed at leveraging the potential eco-nomic benefits of transitioning to more sustainable systems realize win–win opportunities between farms’ environmental and economic dimensions.

Due to their controversial contribution to environmental change, farming systems, as well as being at the center of public and scientific debate, have led to an academic focus on their sustainability, with previous research studies on farm sustainability covering a miscellaneous spectrum of approaches and findings, which are encompassed by some dominant research fields (Masi et al., 2021; Muñoz-Ulecia et al., 2023).

One line of research includes studies aimed at understanding how livestock farming systems can improve their resilience by looking at the self-sufficiency of their inputs and by operating on their sustainability performance and strategies (Gaudino et al., 2018; Lebacq et al., 2015; Perrin et al., 2020). Studies have also examined the possibility of implementing a circular economy approach to transition to a more sustainable system (Ellen McArthur Foundation, 2020; Verduna et al., 2020). Others highlight that as a result of their wide variety of production orientations, farming practices, and modes of re-source use, livestock farming systems provide contrasting social, economic, and environmental outcomes, thus requiring a sustainability assessment that ought to take into account the farming systems' differences for a deeper understanding of specific social and environmental roles of livestock on both a global and local scale (McGee et al., 2022; Muñoz-Ulecia et al., 2023; Rivera-Ferre et al., 2016).

In order to support the sustainable development of agricultural and livestock systems, sustainability assessment is essential (Boggia et al., 2022), because sustainability is a concept without substance if it is not associated with an indicator that evaluates it (Dumanski et al., 1998). Moreover, as a multifaceted concept with various meanings for different actors (Conway & Barbier, 1990), sustainability cannot be assessed by addressing only one aspect; rather, it must be considered in its entire complexity without overlooking the interrelation among the single dimensions' components.

Despite the increasing attention paid by the theoretical and empirical literature to the study of agricultural economic and environmental performances and balancing different objectives of sustainability (Aldieri et al., 2019; Kanter et al., 2018; Sidhoum et al., 2022), previous studies were often limited to environmental issues to the detriment of economic ones (Darnhofer et al., 2010; Špička et al., 2020), or they were concentrated on only one dimension and did not provide an effective measure of the degree of sustain-ability. In addition, the results of previous studies are inconclusive, showing both a possible relationship (Bonfiglio et al., 2017; Gómez-Limón & Sanchez-Fernandez, 2010; Picazo-Tadeo et al., 2011) and a trade-off between economic and environmental goals (Briner et al., 2013; Jaklič et al., 2014; Reckling et al., 2016). In this regard, among the latest studies in the literature, Sidhoum et al. (Sidhoum et al., 2022) analyzed the relationship between economic, environmental, and social sustainability on a sample of Spanish crop farms. Their findings showed the presence of trade-off between economic and environmental sustainability and environmental and social sustainability. Špička et al. (2020) compared the compatibility of economic and environmental objectives in 1189 agricultural holdings in the Czech Republic. They found a moderately significant trade-off between the two dimensions investigated in the total sample. At the same time, in the sub-sample of milk farms, they found a positive relationship between economic and environmental dimensions. In their study, Gómez-Limón et al. (Gómez-Limón & Sanchez-Fernandez, 2010) found that the most sustainable farms were those "of large size and are managed by professional farmers, younger people, members of cooperatives and possessing a farming qualification" (p. 1073). Furthermore, they found a positive relationship between the three dimensions of sustainability. Reckling et al. (Reckling et al., 2016), in their research, found that, in general, there is a trade-off between environmental and economic goals. Still, this result may vary depending on the production system considered.

Despite this research evidence, however, there is still a need for studies that can allow us to fully understand the interrelationships between economic and environmental dimensions at the level of livestock farm analysis and levers to foster the sustainable transition of agriculture and livestock systems.

This study contributes to these discussions and has two aims. Firstly, it takes up the call of several authors who emphasize the need to provide indices assessing sustainability at the farm level (de Olde et al., 2016; van Huylenbroeck et al., 2000) using a set of indicators (Singh et al., 2012) (Aim 1a). This is for two reasons: *(i)* the farm level is the legal unit for legislative purposes, and it is the economic unit that generally receives payments for externalities, and, as such, it is the level at which most policies are directed (OECD, 2001), and it is considered the most proper unit for assessing sustainability and implementing sustainable activities (Kelly et al., 2018); *(ii)* it is through indicators that the sustainability concept is made concrete and operative, and those indicators guides the decisions at the farm level, thereby determining how food systems affect societies and the environment, all within a framework where different actors have differing perceptions of the concept (Robling et al., 2023). Moreover, this study seeks to improve our understanding of the existence and magnitude of the synergy or trade-off between the economic and environmental dimensions of the primary sector at the farm scale, where the primary focus of stakeholders is on maximizing yields and minimizing environmental impact (Kanter et al., 2018) (Aim 1b).

Secondly, because farm sustainability is affected by the farm's structural assets (Castel et al., 2003; Masi et al., 2021; Usai et al., 2006)—which mainly include the farm's land area, the number of animals raised, the farmer's age and education, and the pro-duction methods (such as organic)—this study wants to analyze the relationship be-tween the sustainability dimensions investigated and the structural profiles of farms and some socio-demographic variables of the farmers (Aim 2).

To be precise, this study intends to respond to the following research questions:

RQ1: What is the relationship between the economic and environmental sustainability dimensions in dairy sheep farming?

RQ2: What relationships exist between economic and environmental sustainability dimensions, structural profiles of farms, and socio-demographic variables of farmers?

To answer these research questions, this paper focused on 219 sheep farms located in Sardinia and included in the Farm Accountancy Data Network (FADN) database in 2019 and 2020. In more detail, this paper used trade-off analysis (Phillips,

1958) and regression analysis to answer the first and second research questions, respectively.

This paper provides pivotal food for thought for academics, policymakers, and farms for implementing new indicators to evaluate the multidimensionality of sustainability in agriculture, thus responding to previous research calls to understand the role of livestock production in the transition to a more suitable development model and to investigate which structural farm profiles and socio-demographic farmer variables can affect the economic and environmental dimensions of sustainability in a crucial sector, such as the dairy sheep farm.

The remainder of this paper is structured as follows. Section 2 introduces the live-stock sector analyzed and its peculiarity in the investigated area. The research materials and methodology are illustrated in Section 3. Section 4 outlines the results, and Section 5 presents the conclusion and discussion of the results and provides suggestions for future research.

2. Sector Characteristics and Study Area

Approximately 1200 million sheep worldwide are generally located in sub-tropical areas and concentrated in the Mediterranean and Black Sea regions. According to FAO (2022), world sheep milk production (10.6 Mt) refers first to Asia (46.8%), followed by Europe (29.5%), Africa (22.8%), and America (0.9%). In 2030, sheep milk production is expected to increase by approximately 3 Mt (Pulina et al., 2018).

European sheep farming is an important sector playing sociocultural, economic, and environmental roles and ensuring livelihoods for vulnerable populations in rural and marginal areas (Paraskevopoulou et al., 2020). As a matter of fact, the agricultural economy of various regions in Mediterranean Europe is strongly related to sheep milk production, to which Greece, Spain, Italy, and France contribute 31.8%, 19.0%, 16.6%, and 10.8%, respectively (FAO, 2022); this may be because in these regions, given their significant Greek or Roman cultural heritage, dairy products are traditional ingredients in the human diet (Caja, 1990).

Specifically, the analysis narrows in on the Sardinian region, whose peculiarities make it a good benchmark for analyzing sheep raising and the challenges this sector is facing today. In the European Union (EU), Sardinia is the most important region for sheep milk production, which reaches approximately 320,000 t per year (ISTAT, 2020). Nationwide, Sardinia sheep milk production contributes to about 69% of the Italian output (Laore Sardegna, 2020) and accounts for 10% of the total EU supply (FAO, 2022). Regionally, Sardinian dairy sheep farming plays a considerable role in the regional economy (Istituto di Servizi per il Mercato Agricolo Alimentare (ISMEA), 2018), contributing to about 40% of the total gross agricultural production value. However, it generally operates with low profit margins (Idda et al., 2010), and profitability often depends on the amount of financial aid made available by the Common Agricultural Policies (CAP) (CREA, 2021; Muñoz-Ulecia et al., 2023).

3. Materials and Methods

3.1. Data

The analysis was carried out using a quantitative research approach to examine the economic and environmental sustainability degree of the livestock sector in Sardinian dairy sheep farms.

Data were extracted from the FADN database, which has been used in recent years to evaluate the sustainability of the agri-food sector (Bazzani et al., 2021; Boggia et al., 2022; Cardillo et al., 2023; Coppola et al., 2022; Dabkiene et al., 2021; Liberati et al., 2022). Its principal purpose is to provide data for the EU Commission to assess the economic performance of farms and the impact of the Common Agricultural Policy (CAP) (Marongiu et al., 2022).

In particular, using the Italian FADN database, named Rete Italiana di Contabilità Agricola (RICA), Sardinian sheep farms that meet the following criteria were selected:

- Farms with data available for the years 2019–2020. The choice to analyze the 2019 and 2020 years derives from the need to avoid the results being influenced by conjectures depending on specific years, and they were the latest data available.

- Farms dedicated to animal husbandry whose animal heritage was composed of at least 75% dairy sheep.

A total of 219 Sardinian sheep farms were selected. This research was carried out in February 2023.

The Italian FADN survey was used because it represents the farms of a territory that can be considered professional and market-oriented and offers data concerning the region, the economic dimension, and the technical–economic issues. Specifically, the Italian FADN has nationwide coverage of 95% of the utilized agricultural area, 91% of the livestock units, 97% of the value of standard production, and 92% of labor units; it has a sample of 11,000 farms, which is representative of all of the various types of farms in the national territory, and it provides greater detail with respect to the EU FADN as it collects slightly more than 1500 variables (Turchetti et al., 2022).

3.2. Research Method

To investigate the relationship between economic and environmental farm sustainability dimensions (RQ 1) and the relationship between the latter and the structural and socio-demographic variables (RQ 2), two methodologies were used: the trade-off analysis (points I–IV, Figure 1) and the regression analysis (points V–VI, Figure 3.1).

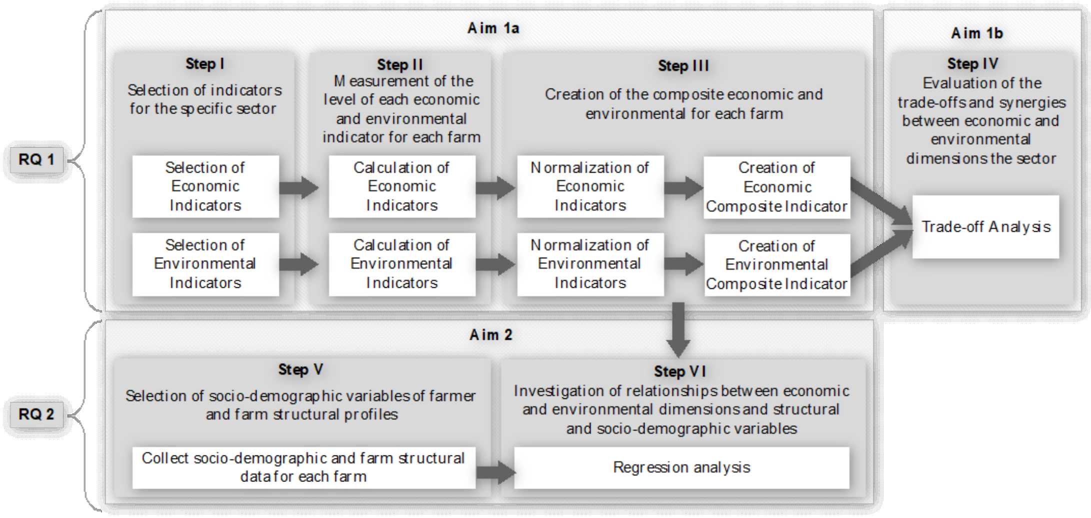

Image 3.1 - Research method regarding the economic and environmental sustainability degree of dairy sheep farms

To answer the first research question and achieve Aim 1a, a preliminary selection of specific economic and environmental indicators for the dairy sheep sector was carried out. The second step concerned measuring farms' economic and environmental indica-tors for each farm. After that, the information obtained during those phases was merged by creating a synthetic indicator for each dimension. The last step evaluated the existence and magnitude of synergy or trade-off between the two sustainability dimensions, thus allowing the achievement of Aim 1b and providing significant information to facilitate assessment and decision making by farmers and policymakers.

Subsequently, to achieve Aim 2 and answer our second research question, we selected significant structural variables of farms and socio-demographic variables of farmers and studied the relationship between these and the economic and environmental performance of farms using regression analysis.

3.2.1. Selecting Farms' Economic and Environmental Sustainability Indicators

To identify the degree of economic and environmental sustainability of each farm, economic and environmental indicators that provide reliable and relevant information for the analysis were selected. This step is crucial because selecting a well-defined indicator through a transparent procedure is necessary for the credibility and reproducibility of this study (Niemeijer & De Groot, 2008).

The economic dimension includes six indicators describing agricultural productivity, cost, and profitability, which have already been used in previous research (Bereżnicka, 2018; Coppola et al., 2022; Díaz de Otálora et al., 2021; Masi et al., 2021; Ri-poll-Bosch et al., 2012; Špička et al., 2020). The procedure for calculating points based on FADN standard output codes (specifically indicated) is shown.

- ECI1: Farm Net Value added (NVA) per agricultural work unit (AWU, the full-time equivalent of employment) (NVA/AWU) (SE425). It indicates the ability to remunerate all resources used in farm activities, and it is a source of labor, land (rent), and capital (interest) cost coverage.

- ECI2: Total output per AWU (SE131/SE010). It considers sales of individual products, in-house use, captive consumption, and changes in closing stocks from opening ones.

- ECI3: Total output livestock per total livestock units (LU) (SE206/SE080).

- ECI4: Specific livestock costs per LU (SE309). It includes direct production costs, e.g., the costs of seed, fertilizers, feed, veterinary expenses, etc.

- ECI5: Productivity of intermediate consumption (SE131/SE275). It is the ratio be-tween the total output and the total intermediate consumption. It estimates the production cost effectiveness, i.e., the ability to cover production costs without considering depreciation and externalities, make a profit, and allow expanded re-production without state intervention.

- ECI6: Return on equity (ROE) (SE420/SE501). It is calculated as the ratio of farm net income (FNI) to shareholders' equity. It measures how efficiently the company uses resources, i.e., the profitability of investments in the farm's assets.

The environmental dimension was assessed using data from eleven indicators, some of which were already used in various combinations in previous research (Cardillo et al., 2023; Díaz de Otálora et al., 2021; Liberati et al., 2022; Masi et al., 2021; Meul et al., 2009; Riera et al., 2023; Špička et al., 2020; Weltin & Hüttel, 2023). This work represents an evolution of those studies as it includes two indicators not previously used, such as animal emissions and carbon sequestration, which we consider critical in evaluating the environmental performance of farming because they complete the picture provided by a set of more generic indicators. At the European level, including an indicator that evaluates the greenhouse gas (GHG) produced by animals appears to be paramount, because the livestock sector is considered one of the main contributors to the environmental impacts of agriculture, mainly due to GHG emissions (Verduna et al., 2020). At the same time, carbon sequestration can partly counteract the livestock sector's climate impact (Knudsen et al., 2019; Moberg et al., 2020). The grasslands on which dairy farms graze their animals can increase carbon sequestration so that CO2 is captured through stable and solid forms in the soil, thus reducing farmers' carbon footprint per kilogram of milk. Therefore, adding the carbon sequestration indicator in the environmental assessments of dairy products has been demonstrated to significantly impact the conclusions when evaluating various management alternatives, such as feed strategies (Henryson et al., 2022; Vellinga & Hoving, 2011).

- ENI1: Organic fertilizers used. It was elaborated by comparing the total cost of organic fertilizers indicated in the Italian FADN (i.e., humus and manure from cattle, buffaloes, horses, granivores, sheep, goats, and other animals) to the farm's total utilized agricultural area (UAA) (SE025). The more organic fertilizers applied, the higher the farm scores.

- ENI2: Use of industrial mineral fertilizers per UAA. It was elaborated by comparing the total cost of industrial mineral fertilizers indicated in the Italian FADN (i.e., solid mineral and organic mineral solid fertilizers) to the UAA of the farm (SE025). The fewer the industrial mineral fertilizers that are applied, the higher the farm scores.

- ENI3: Use of pesticides per UAA. It was elaborated by comparing the total cost of crop protection to the UAA of the farm (SE300/SE025). The fewer the pesticides that are applied, the higher the farm scores.

- ENI4: Use of water, energy, and fuels. It was elaborated by comparing the total cost of water, energy, and fuels indicated in the Italian FADN to the total production (SE131). The lower the consumption, the higher the company's score.

- ENI5: Share of clover. Using data from the Italian FADN, the ratio between meadow hectares with leguminous crops and the farm UAA (SE025) was calculated.

- ENI6: Stocking density. It is the ratio between total livestock units and the business UAA (SE080/SE025).

- ENI7: Multiannual and perennial crops per UAA. Taking data from the Italian FADN, the ratio between multiannual and perennial crops and the farm UAA (SE025) was calculated.

- ENI8: Greening. Based on the Italian FADN database, it indicates the number of measures a farm adheres to.

- ENI9: Renewable energy. Based on the Italian FADN, the farm's presence of renewable energy sources was assessed (binary value 0 or 1).

- ENI10: Animal emissions. It is calculated as the share of animal emissions per LU (CO_{2eq}/SE080). Precisely, based on Italian FADN data and the refined Tier 1 method elaborated by the Intergovernmental Panel on Climate Change (IPCC, 2019a, 2019b), two emission types were calculated, including the enteric methane (CH_4) emissions from fermentation occurring in the rumen and from manure management, and nitrous oxide (N_2O) emissions from manure management. These emissions were converted into a single indicator that measures the animal CO_{2eq} emission for each farm. Details of the calculation methods are available in Appendix A.

- ENI11: Carbon sequestration. It is calculated as the share of carbon sequestration per UAA (CO_2/SE025). The coefficients of potential carbon sequestration were calculated based on indices set out in the previous literature (Dondini et al., 2023; Giussani, 2013; Kumar et al., 2018; Richardson et al., 2019). The calculation method details are available in Appendix B.

3.2.2. Composite Indicator Creation

Agricultural trade-off analysis and sustainability definition rely on indicators (Böhringer & Jochem, 2007; Independent Science and Partnership Council (ISPC), 2014; Van Der Werf & Petit, 2002). Sustainability is a multidimensional concept that, therefore, requires a holistic approach. Such a feature makes the assessment of sustainability one of the most complex analyses (Ikerd, 1993; Sala et al., 2015). Starting from these premises, the sustainability analysis cannot be based on a single indicator but rather on a set of indicators (Singh et al., 2012) that must be comparable and that can be aggregated (Böhringer & Jochem, 2007).

These drawbacks can be overcome using composite indicators, which, by condensing the complexity and multidimensionality of the various indicators, make it possible to evaluate and compare results arising from different realities (Munda & Saisana, 2011; Singh et al., 2012). It should also be pointed out that the use of composite indicators is a debated topic. In fact, according to some studies (Böhringer & Jochem, 2007; Sharpe, 2004), they do not provide complete information on the phenomenon under analysis and can lead to erroneous conclusions. Politicians and stakeholders nonetheless recognize them as a powerful tool for policymaking and public communication, providing information on sustainability dimensions development at various scales of analysis, and summarizing and focusing large amounts of complex information into a manageable amount of meaningful information (Nardo et al., 2005; Singh et al., 2012; Talukder et al., 2017).

A composite indicator means the mathematical combination of individual scores representing different aspects of the phenomenon under investigation (Saisana & Ta-rantola, 2002). Specifically, in this work, because the analysis was carried out over two years, an average of each value of data reported by the Italian FADN for the two years under analysis was preliminarily carried out for each farm.

The first step in creating a composite indicator requires reducing multidimensionality in favor of a standard scale through the normalization process, which can occur via different techniques. In this research, the normalization was performed in two phases. Firstly, ranking normalization was adopted, being one of the most widely employed techniques (Saisana & Saltelli, 2011), by which the single score of each indicator of the economic (ECi) and environmental (ENi) dimensions for each farm was calculated based on the distance from the maximum value. In this way, the individual values of each indicator fell within the range [0,1]. Afterwards, z-score normalization was used. Such normalization was calculated by subtracting the mean from an indicator value and di-viding it by its standard deviation. This technique provides a dimensionless output, and the differences between the normalized values are preserved thanks to a linear trans-formation. Moreover, z-score is preferred when extreme values are present in the dataset (Nardo et al., 2005). In this regard, it should be noted that other normalization techniques, such as distance from a target value or min–max normalization, cannot be ap-plied in this study due to the absence of target, minimum, and maximum values for all of the indicators considered.

After normalization, the second step involves merging singular scores into compo-site indicators. For this purpose, this work adopted the arithmetic mean, a common aggregation technique where the normalized indicators are summed to compute the arithmetic mean (OECD, 2008). This methodology may be subjected to the compensatory effect. However, this effect is negligible due to the research objective of evaluating the trade-off between the two dimensions in their entirety and not between individual indicators. In sum, the economic (EC) and environmental (EN) aggregated indicators were calculated as follows:

$$\mathrm{EC} = \frac{\sum_{n=6}^{1} \mathrm{ECI_i}}{\mathrm{N}} \quad (1)$$

$$\mathrm{EN} = \frac{\sum_{n=11}^{1} \mathrm{ENI_i}}{\mathrm{N}} \quad (2)$$

where the ECIi and ENIi indicate the single economic and environmental indices used to calculate the economic (EC) and environmental (EN) aggregated indicators.

3.2.3 Trade-Offs and Synergy Analysis

Trade-off analysis is based on two concepts: resource scarcity and opportunity cost. It determines the effect of the decrease of one or more key factors and the simultaneous increase of other key factors within a process.

In recent years, this theory, first applied to agriculture in the 1970s to define the economic impact of new agricultural technologies on the primary sector (Alston et al., 1995), has been increasingly used to assess agricultural sustainability. The reason lies mainly in the need to adequately measure the presumed mutual reciprocity of the components of sustainability and verify whether the agricultural and environmental objectives envisaged by the new European policies can be achieved without penalizing the agricultural economic sphere.

In this way, Špička et al., analyzing the compatibility of economic and environmental sustainability objectives in 1189 Czech farms through data from the FADN, found a moderate trade-off between the two dimensions in the total sample, which in-creased when analyzing farms according to their economic size. Similar conclusions arose from Masi et al. (2021), whose analyzed FADN data related to 1211 Italian dairy and buffalo farms to identify relations among all dimensions of sustainability and farms' structural profiles.

Despite the increasing relevance of the trade-off analysis in the agricultural field and the dairy sheep sector, to our knowledge, no study has previously assessed the degree of sustainability in dairy sheep farming.

This work evaluated the presence of trade-off or synergy relationships between EC and EN using the Pearson correlation analysis (r), which has been widely used in trade-off analysis in the past (Raudsepp-Hearne et al., 2010; Špička et al., 2020; Turner et al., 2014; Xiao et al., 2023). The purpose of this analysis was to describe both the direction as well as the strength of the linear relationship between two continuous variables. Pearson correlation coefficients range from −1.00 to 0.00 to +1.00. In order to interpret the descriptive significance of the magnitude of the coefficient absolute value, the following criteria were used (Hatcher & O'Rourke, 2013): (1) $r = 0.00$ implies that there is no statistical association, (2) $r \pm 0.20$ signifies weak association, (3) $r \pm 0.50$ indicates a moderate association, (4) $r \pm 80$ suggests a strong association, and (5) $r = 1.00$ indicates a perfect association. The results are tested at confidence level $\alpha = 0.1$.

3.2.4 Analysis of the Relationships between EC, EN, and Structural and Socio-Demographic Variables

The farms' structural profiles and the socio-demographic farmers' variables considered relevant are the following:

- Gender (G). It is a binomial variable taking a value of 0 if the farm manager is male or 1 if she is female.

- Age (Y). It is a binomial variable that follows the young farmer's CAP definition, according to which she/he can be a maximum of 35–40 years old (Italy set 40 years old as the age limit). Therefore, the variable is 1 if the farm manager is 40 years old or younger and 0 on the contrary.

- Education (E). This variable can assume a value that ranges from 1 to 4 as the farm manager's education level increases: 1, holding only an elementary school leaving certificate; 2, holding a lower middle school leaving certificate; 3, holding a high school diploma or a professional diploma; and 4, holding a university degree.

- Organic (O). It is a binomial variable obtained by taking a value of 0 if the farm is conventional (non-organic) or 1 if the farm is organic.

- Diversification (D). It is a binomial variable obtained by taking a value of 0 if the farm does not diversify or a value of 1 if, instead, it implements diversification.

To identify the relationships between those variables and indicators of EC and EN, regression analysis was used. This statistical tool allows for showing the significant im-pact of a set of independent variables (predictors) on the dependent variables (Hair, 2011), and the extent to which variance in a continuous dependent variable can be explained by a set of predictors. Therefore, it allows us to identify the influence of structural and socio-demographic variables on the environmental and economic performance of Sardinian dairy sheep farms. To explore the relationships between these variables and the aggregated indicators of EC and EN, two regressions were performed:

$$\mathrm{EC} = \alpha \mathrm{G} + \beta \mathrm{Y} + \gamma \mathrm{E} + \varepsilon \mathrm{O} + \zeta \mathrm{D} \quad (3)$$

$$\mathrm{EN} = \alpha \mathrm{G} + \beta \mathrm{Y} + \gamma \mathrm{E} + \varepsilon \mathrm{O} + \zeta \mathrm{D} \quad (4)$$

where α, β, γ, O, and ζ are the exposure (gradients) to the respective independent variables G, Y, E, O, and D., i.e., regression parameters for the slope.

4. Results

4.1. Sample Profile

The 219 Sardinian dairy sheep farms are run by men in 89% of cases; most of the individuals (81.7%) are over 40 years of age. As to education level, most farmers have a lower middle school degree (63.9%), almost a quarter (22.4) of the sample have a diploma from high school, and as many as 11% have no lower middle school diploma. Only five farmers have a university degree.

Concerning the geographical distribution, almost 38% of farms are located in the province of Sassari, whereas a quarter are situated in the province of Nuoro. The remaining 37% is equally distributed between the Oristano and Cagliari provinces. The sample revealed low diversification and organic management, with 7 farms and 11 farms out of 219, respectively. The data are reported in Table 3.1

Table 3.1- Profile sample of the analyzed farms. Source: Our processing based on FADN data

		Total=219	**%**
Gender	Male	195	89.0
	Female	24	11.0
Age	≤40	40	18.3
	>40	179	81.7
Resident	Province of Sassari	83	37.9
	Province of Nuoro	54	24.7
	Province of Oristano	41	18.7
	Province of Cagliari	41	18.7
Education	No lower middle school	25	11.4
	Lower middle school	140	63.9
	High school	49	22.4
	University	5	2.3
Diversification	Yes	7	3.2
	No	212	96.8
Organic	Yes	11	5.0
	No	208	95.0
Total Agricultural Area (ha)	0-100	175	80.0
	101-200	37	17.0
	>201	7	3.0
Livestock unit (LU)	0-50	159	73.0
	51-100	48	22.0
	101-150	10	5.0
	>150	2	1.0

The following Tables 3.2 and 3.3 show the economic and environmental indicator statistics and the farms' performances for each proposed indicator.

The analysis of the distribution of means and standard deviation for the economic dimensions shows that, in general, the sample of farms analyzed presents a wide variability, and it is thus rather heterogeneous.

The high values assumed by ECI1 and ECI2 could be due to the fact that these types of farms often use family work, and the entity of these work units within the AWU can vary among the farms. Concerning the ECI6 index, the results show a fairly good average ROE (0.27 ± 0.34), although there is a lot of heterogeneity between farms. However, it should be underlined that this indicator, because it considers the net income as the numerator, also includes the revenue deriving from CAP.

Regarding the environmental indicators, there is a high sample variability for the ENI 1, 2, 3, 5, and 7 variables, while the rest of the environmental indicators show more homogeneity. The first thing to highlight is the reduced use of mineral fertilizers and pesticides. These data are extremely important, as they reflect one of the objectives of European policies and emphasize the active role of sheep farming in achieving them.

As regards animal density, indicated by ENI6—which is an important parameter for defining the protection of pasture (Dumont et al., 2007; Sepe et al., 2015)—the farms analyzed, albeit with a fairly wide range (1.43 ± 0.84 LU/UAA), are within the optimal range of animal load, identified by the legislator as between the values of 0,2 (condition of undercharge) and 4 LU/UAA (condition of overload) (Sepe et al., 2015). The use of renewable energy (ENI9) in the farms analyzed is almost completely absent.

For ENI10 and ENI11, the values obtained from our analysis are higher than those presented in the literature (Atzori et al., 2015; Vagnoni et al., 2015), but these differences are due to the different calculation methods. For animal emissions, in this analysis, we chose to use the IPCC methodology, which is widely used in similar studies and universally recognized (Correddu et al., 2023). Furthermore, a different unit of measurement was used compared to most studies analyzing the impact of animal emissions, which are generally allocated per kg of Fat and Protein Corrected Milk (FPCM) (Atzori et al., 2015; Vagnoni et al., 2015). In our study, the functional unit used is LU, because data on annual milk production were not available. Regarding the carbon sequestration definition, the differences from previous studies (i.e., (i.e., Arca et al., 2021)) are due to *(i)* the species included in the calculation and *(ii)* the carbon sequestration rate used and the methodologies adopted to define these rates.

Table 3.2 - Statistic of economic indicators and farms performance. Source: Our processing based on FADN data

	ECI 1 (€)	**ECI 2 (€)**	**ECI 3 (€)**	**ECI 4 (€)**	**ECI 5 (%)**	**ECI 6 (%)**
Mean	68,245.05	108,590.89	2,705.50	1,384.02	4.96	0.27
St. dev.	40,075.49	56,905.76	899.76	618.89	4.00	0.34
N. of farms that perform better	99	100	107	123	73	74
N. of farms that perform worse	120	119	112	96	146	145

Table 3.3 - Statistic of environmental indicators and farms performance. Source: Our processing based on FADN data

	ENI 1 (€/UAA)	**ENI 2 (€/UAA)**	**ENI 3 (€/UAA)**	**ENI 4 (%)**	**ENI 5 (%)**	**ENI 6 (LU/UAA)**
Mean	20.35	97.68	0.33	0.00	4.43	1.43
St. dev.	142.82	380.81	3.47	0.03	13.45	0.84
N. of farms that perform better	17	187	217	212	32	139
N. of farms that perform worse	202	32	2	7	187	80

Table 3.3 - Continuous. Our processing based on FADN data

	ENI 7 (%)	**ENI 8 (N.)**	**ENI 9 (N.)**	**ENI 10 (ton CO_2eq/LU/yr)**	**ENI 11 (ton CO_2/UAA/yr)**
Mean	62.22	2.30	0.03	5.35	1.79
St. dev.	32.53	0.78	0.23	0.52	0.63
N. of farms that perform better	122	49	3	71	81
N. of farms that perform worse	97	170	216	148	138

4.2. Trade-Off between Economic and Environmental Performance

Table 3.4 illustrates the results of the Pearson correlation analysis, thus allowing us to evaluate the strength of the linear relationship between the economic and environmental performance in Sardinian dairy sheep farms and provide an answer to our first research question. The correlation analysis shows that the two variables considered are significantly positively correlated with each other (p-value < 0.1). Accordingly, despite the low intensity of the relationship between variables, there is a systematic relationship between these variables, and they are mutually reinforcing because they increase as one variable increases. This means that an increase in their profitability leads to an increase in the sector's contribution to achieving the environmental sustainability goals of the EU.

Table 3.4 - Relationship between economic and environmental dimensions. Source: Our processing based on FADN data

Number of farms	Correlation coefficient	P-value
219	0.1191	0.0785*

* Statistically significant for P<0.1.

4.3. Relationship between Economic and Environmental Performance and Structural and Socio-Demographic Variables of Farms.

Two models were used to analyze the relationships between the economic and environmental dimensions and the structural and socio-demographic variables considered, one with a constant and the other without. The Generalized likelihood-ratio test (λ) was used to determine which of the two models most suited our needs. For each regression analysis, the model with a constant variable was compared to that without a constant variable. The statistic associated with this test is defined as (Knoke et al., 1994):

$$\lambda = - 2\ln L = - 2 = - 2\ [\ln L(H0) - \ln L(H1)] \quad (5)$$

where L (H1) and L (H0) are the log-likelihood values of the model with or without a constant variable, respectively. The statistic parameter l has a chi-square distribution with different degrees of freedom that match the number of parameters deleted. These are assumed to be zero in the null hypothesis Ho. The null hypothesis cannot be rejected if λ is lower than the corresponding critical value for a given significance level.

The results of the Generalized likelihood-ratio test are reported in Table 3.5. In both cases, for the EN and EC models, the λ value was higher than the tabular value $\chi 2$, so we accepted the null hypothesis and used the models without the constant.

Using regression analysis, we were able to answer our second research question. The first regression analysis showed that one socio-demographic variable and one structural farm variable influence the economic performance of farms positively; these are young (p value < 0.1) and organic (p value < 0.05). The model fits the data well (p-value (F) < 0.05); however, the R2 is not high, implying that the pool of variables on the whole weakly affects the dependent variable.

Surprisingly, the environmental dimension is not linked to any of the structural profiles of farms or the socio-demographic variables of farmers considered. The model does not statistically fit the data—the p-value (F) is really high—and the R2 is extremely low, meaning these selected variables do not conditionate the environmental dimension.

The results of the regressions are reported in Table 3.6 (economic dimension as de-pendent variable) and Table 3.7 (environmental dimension as dependent variable), respectively.

Table 3.5 - Hypothesis testing for each model adopted.

Model	Restriction	$L(H_1)$	$L(H_0)$	λ	d.f.	χ2	Decision
EN	No constant variable	-35.817	-36.788	1.944	1	0.0039	Accept the null hypothesis
EC	No constant variable	-182.688	-183.030	0.684	1	0.0039	Accept the null hypothesis

Table 3.6 - Linear regression results between economic dimension and structural and sociodemographic variables. Source: Our processing based on FADN data.

Variable	Coefficient	Std. Error	P-value
Gender	0.110	0.126	0.386
Young	0.195	0.102	0.058 *
Education	− 0.022	0.021	0.298
Organic	0.353	0.176	0.047 **
Diversification	− 0.311	0.217	0.153

* Statistically significant for P <0.1; ** Statistically significant for P <0.05.

Table 3.7 - Linear regression results between environmental dimension and structural and socio-demographic variables. Source: Our processing based on FADN data.

Variable	Coefficient	Std. Error	P-value
Gender	-0.031	0.065	0.630
Young	0.001	0.052	0.985
Education	0.006	0.011	0.545
Organic	0.027	0.090	0.766
Diversification	-0.143	0.111	0.201

5. Discussion

The agricultural sector is the backbone of the economy in many developed and developing countries, and it has an essential role in achieving sustainability goals. In the vision for a more sustainable food system in the EU, farms should be more environmentally friendly and socially acceptable, and they must ensure enough income for the farm owner. To achieve these objectives, it is necessary to preliminarily define proper indicators capable of evaluating the degree of the entirety of sustainability dimensions of the farm, and policymakers should pursue policies aimed at realizing win–win opportunities between the environmental and economic dimensions of farms.

This paper focused on this issue, and it had two aims investigated by concentrating on an important sector: dairy sheep farming. Firstly, this paper aimed to respond to previous research calls to provide indices to assess the sustainability in farms and investigate the type of relationship between the environmental and economic performances of farms. Secondly, this paper aimed to investigate which structural profiles of farms and socio-demographic variables of farmers could affect the economic and environmental performances of dairy sheep farms and foster their durability and "just transition" towards a sustainable livestock system that is environmentally friendly and economically viable for farmers.

Going into the details of the sample, over 80% of the sample is represented by male farmers over 40 years of age and with a low level of education. This could be the reason for the almost complete absence of diversification, which is one of the strategies households employ to increase and stabilize income, reduce risks, and maintain food security by making use of diverse assets and opportunities provided by their environment and the markets they can access (Abdulai & CroleRees, 2001; Neudert et al., 2020). Whether diversification occurs in other sectors beyond livestock farming, such as arable farming or non-agricultural incomes, it could be a profitable strategy, especially for the pastoral regions (Henke et al., 2022; Neudert et al., 2020). Our findings confirm previous research (Abdulai & CroleRees, 2001; Wu et al., 2014), according to which a higher level of formal education and the older age of farmers affect the diversification strategy and the farm's production, the first positively and the second negatively, in addition to the adaptation and adoption of changes and new technologies.

Concerning the first aim, we preliminarily calculated the single economic and environmental indices, and then we elaborated two composite indicators used to perform the trade-off analysis (Aim 1a). In reference to the economic indicators, farms showed high variability in this, which may be due to a different specialization of the sheep farms that can be found in Sardinia. In fact, even with the same farm size and number of animals, farms with different production assets can exist in terms of infrastructure and, most importantly, genetic diversity (Simula, 2023), with differences in milk production.

Regarding the environmental indices, this study expands previous research in which farm-level sustainability indicators were considered (i.e., (i.e., Špička et al., 2020)), including some of the crucial aspects important in the evaluation of the sustainability of livestock sector performances, because they influence farms' climate impact and the choice between different management alternatives, such as feeding strategies. These aspects are the GHG produced by animals and the carbon sequestration. Actually, animal emissions represent the main source of GHG pollution in dairy sheep farms (Arca et al., 2021). At the same time, the carbon sequestration indicator contributes not only to mitigating the impact derived from livestock farming, but it also highlights the positive role that this type of farm plays in providing ecosystem services (Arca et al., 2021; Madau et al., 2022). Including these indicators calculated with specific coefficients for the type of breeding and composition of the flocks increases the degree of fidelity of the sustainability indicators to reality and makes them operative to guide decisions at the farm level, as well as highlighting how the sector affects societies and the environment.

Studying how the environmental and economic performances of farms are related (Aim 1b) by analyzing the result of the trade-off analysis, this study answered the first research question. Specifically, it identified a positive and significant synergy between the economic and environmental dimensions of dairy sheep farming, even if low. This is an important result from the political point of view as it indicates that these farms can play an active role in achieving the objectives of a fair transition dictated by the new European policies [13], and it underlines the importance of political and economic support towards this type of activity [14].

Although there are currently policies to support pastoralism, sheep farming is one of the least supported sectors and one of the least profitable activities, together with goat raising (Nori, 2022; Vagnoni et al., 2015). Often, the profitability of livestock farms is supported by the presence of public financial aid, which can represent up to 75% of the total output (Cerrato et al., 2023). The reduced profitability and the growing uncertainties that this sector has to face are leading to a reduction in the number of farms and an increasingly limited generational renewal (Nori & Farinella, 2020). Policymakers and decision makers have a double task. First of all, they must safeguard the existence of these types of farms, which are useful for achieving green objectives and represent a cornerstone for the protection of territories that, without this activity, would be subjected to abandonment and degradation (Nori, 2022). Secondly, they must make measures to support livestock farming more feasible. Indeed, if it is true that the EU recognizes the multifunctional role of this sector through targeted policies, it is also true that these are often based on complicated procedures that are inconsistent or conflicting with each other, which might discourage breeders from pursuing their activities (Nori, 2022).

In this context, our findings are a starting point for decision makers called to define measures to support the sector. Indeed, while being aware that it is not automatically achieved and that the choices need to be weighed, the synergy between the economic and environmental dimensions suggests that leveraging one dimension can favor the development of the other. It is, therefore, crucial for the sustainable development of the sector to turn the farmers' environmental care into income opportunities for dairy sheep farms (Madau et al., 2022) by developing an effective and efficient mechanism that translates farms' environmental dimension growth into their economic dimension growth and vice versa.

Moving on to the second objective of our study, the structural profiles (Diversification and Organic) and socio-demographic variables (Gender, Age, and Education) used in our analysis agree with those used in similar studies [16,17].

Using the regression between the aforementioned data and the economic dimension to answer our second research question, we identified two positive and significant relationships, one relating to the young age of the farmers and the other to the fact that the farm is organic.

The first represents an important signal, as the presence of young farmers is fundamental to face the new challenges posed to this sector [18], and the generational renewal of agriculture and livestock farming is critical for the long-term survival of these in the EU [19]. Despite this, in recent years in the EU, there has been a decreasing trend in the number of young farmers [20], which specific CAP measures have attempted to counterbalance.

The presence of a positive relationship between the economic dimension and organic animal production is a finding confirmed by the previous literature [21,22], even if it is a debated question. Often, the greater cost effectiveness of organic farms is due only to the CAP measures that favor the implementation of this production model. Moreover, according to some authors [21,23], although this production method is more environ-mentally friendly, it presents difficulties, such as high production costs, lower productivity, and excessive bureaucracy, which can discourage farmers from applying it. Therefore, it is necessary to analyze this relationship more deeply to understand the actual nature of these factors.

However, as regards the regression between the environmental dimension and the variables analyzed, no relationship was found. This fact can be attributed to two reasons: *(i)* the environmental dimension is influenced by other variables that were not considered in our analysis, and *(ii)* the economic dimension is separate and not linked to socio-demographic or structural variables.

Some limitations affect our research. The empirical evaluations can be affected by the nature of the data on which they are carried out. Although the FADN is one of the most reliable databases, you may have to deal with deficient data, which can translate into possible sample bias (European Commission. Statistical Office of the European Union., 2020). Furthermore, although similar approaches are found in the literature on this issue, our choice is characterized by a certain degree of discretion both for the se-lection of individual indicators and for the procedure for calculating the value of the synthetic sustainability indicators (EC and EN). Concerning the procedure, using other methodologies (e.g., Multi-Criteria Analysis or Fuzzy Analysis) could be an alternative proposal, as could the possibility of weighing the individual indicators rather than using the arithmetic mean. Regarding the indicators, their selection can influence the conclusions of the analysis (Lebacq et al., 2013). However, because the selected environmental and economic indicators have previously been used in other preceding studies and the greenhouse gas and carbon sequestration indicators have allowed for in-depth investigation of the sustainability performance of farms, despite these limitations, our results suggest several important academic, practical, and policy implications.

6. Conclusions

This study, to our knowledge, is the first to evaluate the relationship between the economic and environmental sustainability dimensions in dairy sheep farming and between each of them and some structural and socio-demographic variables.

Firstly, it takes up the call of several authors who emphasize the need to provide indices assessing sustainability at the farm level (de Olde et al., 2016; van Huylenbroeck et al., 2000) using a set of indicators (Singh et al., 2012).

In terms of academic implications, this study fills a gap in the literature regarding farms' sustainability assessment (de Olde et al., 2016; Singh et al., 2012; van Huylenbroeck et al., 2000) by providing a measure of economic and environmental performance at the farm level through a set of indicators that grasp different aspects of farm management. This is really relevant, because the farm (i) is the first level at which policy measures are implemented, (ii) provides us with the highest degree of detail and is, therefore, the most useful site to assess whether sustainability practices have an effect or not, and (iii) is directly affected by the negative effects of climate change and, at the same time, benefits from the green practices that are applied.

Moreover, this paper, using a set of indicators for economic and environmental dimensions, offers a more realistic view of the sector, because sustainability is a multifaceted concept that is not correctly represented using a singular indicator or by examining only one dimension.

Again, this study is the first that combines the use of FADN indicators with indicators deriving from other methodologies, such as the IPCC tier 1 (IPCC, 2019a, 2019b) for the methane and nitrous oxide calculation and the carbon sequestration definition.

Finally, because the definition of sustainability must consider structural and socio-demographic variables of farms, as they can positively or negatively influence their sustainability dimensions, this paper shows which variables to leverage to foster farms' sustainability.

With reference to policy issues, knowing the relationship between the farm's environmental and economic dimensions is fundamental because it allows politicians to understand whether the green transition they aspire to meet takes place from a win–win perspective between environmental sustainability and economic profitability. Furthermore, underlining the active role of the sector in pursuing green objectives offers a valid justification for public support, which is often defined as disproportionate.

Finally, our findings show the need to foster young breeders, who are fundamental to guarantee the durability of the dairy sheep sector, which has also been recognized to be crucial in light of the social role played by the sector to protect the territory.

As regards the implications for workers in the sector, knowing that applying more environmentally sustainable practices can also lead to better farm economic performance, it may be an incentive to move towards different production methods considered more sustainable.

This research can be extended in several directions. First, future research is war-ranted to evaluate whether, in other contexts where the structural profile of the companies and the socio-demographic variables of the farmers are different, the results of the trade-off analysis are different or not. Furthermore, it would be interesting to repeat this analysis in the same sector in other regions and states to see how the regional and political contexts influence sustainability, so that a cross-sectional research design can strengthen our research's implications. Future research can also repeat the analysis by investigating other livestock and agriculture sectors by adapting the animal emissions and carbon sequestration to the cases analyzed. Expanding this type of study to the social dimension is also important due to its pivotal role in achieving the sustainability of the sector and its increasing role in the CAP..

6. Appendix A. Calculation Method of Animal Emissions

The Enteric fermentation emissions produced by sheep are calculated as follows:

$$EF_i = EF_i * N_i \quad (A.1)$$

where:

EF_i = enteric methane emissions in sheep category (kg CH_4 yr^{-1})

N_i = number of head

EF_i = emission factor per sheep category (kg CH_4 $head^{-1}$ yr^{-1}) (the parameters are indicated in Table A3.1)

Table A3.1 - Enteric emission factor per sheep category.

Livestock categories	Emission factor EF_i (kg CH_4 $head^{-1}$ yr^{-1})	Source
Sheep	9	(IPCC, 2019a) – Table 10.10

The methane emissions from manure management produced by sheep are calculated as follows:

$$EMm_i = (N_i * VS_i * AWMS_i * EF_i)/1000 \quad (A.2)$$

where:

EMm_i = Methane emissions from manure management in sheep category (kg CH_4 yr^{-1})

N_i = the number of head

VS_i = annual average of volatile solids (VS) per head of sheep (kg VS head^{-1} yr^{-1}) (Equation A.3)

$AWMS_i$ = animal waste management systems, i.e., the fraction of VS_i for sheep category (dimensionless) (the parameters are indicated in Table A3.2)

EF_i = emission factor for direct CH_4 emissions from manure management system for sheep (g CH_4 kg VS^{-1}) (the parameters are indicated in Table A3.3)

Table A3.2 - Animal waste management systems values.

Livestock categories	$AWMS_i$	Source
Sheep	0.58	(IPCC, 2019a) – Table 10A.8

Table A3.3 - Values of emission factor for direct CH4 emissions from manure management system by sheep category.

Livestock categories	Emission factor EF_i (g CH_4 kg VS^{-1})	Source
Sheep	5.1	(IPCC, 2019a) – Table 10.14

The annual average of volatile solids (VS) per head are calculated as follows:

$$VS_i = \left(VS_{rate} * \frac{TAM_i}{1000} \right) * 365 \qquad (A.3)$$

where:

VS_{rate} = default VS excretion rate (kg VS 1000 kg animal mass^{-1} d^{-1}) (the parameters are indicated in Table A3.4)

TAM_i = typical animal mass for sheep (kg) (the parameters are indicated in Table A3.5)

Table A3.4 - Value of VS excretion.

Livestock categories	VS excretion rate (kg VS 1000 kg animal mass^{-1} d^{-1})	Source
Sheep	8.2	(IPCC, 2019a) – Table 10.13a

Table A3.5 - Typical animal mass.

Livestock species and categories	TAM (kg)	Source
Sheep		(Brandano, 2008)
Lamb	27.4	
Replacement ewe	38	
Ewe	45	
Ram	65	
Slaughter sheep	45	

The direct N_2O emissions from manure management are calculated as follows:

$$DirN_2O=\{[(N_i * Nex_i)*AWMS_i]*EF_i\}* \frac{44}{28} \qquad (A.4)$$

where:

$DirN_2O$ = direct N_2O emissions from manure management (kg N_2O yr^{-1})

N_i = the number of head

Nex_i = annual average nitrogen (N) excretion per head (kg N head^{-1} yr^{-1})

$AWMS_i$ = animal waste management systems, i.e., the fraction of fraction of total annual N excretion for sheep category (dimensionless) (the parameters are indicated in Table A3.2)

EF_i = emission factor for direct N_2O emissions from manure management system (kg N_2O-N kg N^{-1}) (the parameters are indicated in Table A3.6)

44/28 = conversion of N_2O-N(mm) emissions to N_2O(mm) emissions

Table A3.6 - Value of direct N2O emission factors.

Livestock categories	Emission factor EF_i (kg N_2O-N kg N^{-1})	Source
Sheep	0.003	(IPCC, 2019b) – Table 11.1

The annual N excretion rates are calculated as follows:

$$Nex_i = \left(N_{rate} * \frac{TAM_i}{1000}\right) * 365 \quad (A.5)$$

where:

Nex_i = annual N excretion per head (kg N $head^{-1}$ yr^{-1})

N_{rate} = default N excretion rate (kg N 1000 kg animal $mass^{-1}$ d^{-1}) (the parameters are indicated in Table A7)

TAM_i = typical animal mass (kg) (the parameters are indicated in Table A3.5)

Table A3.7 - Value of nitrogen of excretion rate.

Livestock categories	N_{rate} (kg N 1000 kg animal mass^{-1} d^{-1})	Source
Sheep	0.36	(IPCC, 2019b) – Table 10.19

The indirect N_2O emissions due to volatilisation of N from manure management are calculated as follows:

$$IndN_2O_{vol}=(N_{vol}*EF_{at})*\frac{44}{28} \quad (A.6)$$

where:

$IndN_2O_{vol}$ = indirect N_2O emissions due to volatilisation of N from manure management (kg N_2O yr^{-1})

N_{vol} = amount of manure nitrogen lost due to volatilisation of NH_3 and NO_x (kg N yr^{-1})

EF_{at} = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces (kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$ (the parameters are indicated in Table A.3.8)

44/28 = conversion of N_2O-N(mm) emissions to N_2O(mm) emissions

Table A.3.8 - Emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces.

Livestock categories	**EF_{at} (kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$**	**Source**
Sheep	0.01	(IPCC, 2019b) – Table 11.3

The nitrogen losses due to volatilisation from manure management are calculated as follows:

$$N_{vol}=[(N_i * Nex_i)*AWMS_i]*Frac_{gas_i} \quad (A.7)$$

where:

N_{vol} = amount of manure nitrogen lost due to volatilisation of NH_3 and NO_x (kg N yr^{-1})

N_i = the number of head

Nex_i = annual average nitrogen (N) excretion per head (kg N $head^{-1}$ yr^{-1})

$AWMS_i$ = fraction of total annual N excretion for sheep category managed in manure management (dimensionless) (the parameters are indicated in Table A2)

$Frac_{gasi}$ = fraction of managed manure nitrogen for sheep category that volatilises as NH_3 and NO_x in the manure management (dimensionless) (the parameters are indicated in Table A3.9)

Table A3.9 - Fraction of managed manure nitrogen that volatilises as NH_3 and NO_x.

Livestock categories	$Frac_{gasi}$	Source
Sheep	0.12	(IPCC, 2019b) – Table 10.22

The indirect N_2O emissions due to leaching from manure management are calculated as follows:

$$IndN_2O_{leach}=(N_{leac}*EF_{leach})*\ \frac{44}{28} \quad (A.8)$$

where:

$IndN_2O_{leach}$ = indirect N_2O emissions due to leaching and run off from manure management (kg N_2O yr^{-1})

N_{leach} = amount of manure nitrogen lost due to leaching (kg N yr^{-1})

EF_{leach} = emission factor for N_2O emissions from nitrogen leaching and runoff (kg N_2O-N kg N leached and $runoff^{-1}$) (the parameters are indicated in Table A3.10)

44/28 = conversion of N_2O-N(mm) emissions to N_2O(mm) emissions

Table A3.10 - Emission factor for N2O emissions from nitrogen leaching and runoff.

Livestock categories	EF_{leach} (kg N_2O-N kg N leached and $runoff^{-1}$)	Source
Sheep	0.011	(IPCC, 2019b)– Table 11.3

The nitrogen losses due to leaching from manure management are calculated as follows:

$$N_{leach}=[(N_i * Nex_i)*AWMS_i]*Frac_{leach_i} \quad (A.9)$$

where:

N_{leach} = amount of manure nitrogen lost due to leaching (kg N yr^{-1})

N_i = the number of head

Nex_i = annual average nitrogen (N) excretion per head (kg N $head^{-1}$ yr^{-1})

$AWMS_i$ = fraction of total annual N excretion for sheep category managed in manure management (dimensionless) (the parameters are indicated in Table A2)

$Frac_{leachsi}$ = fraction of managed manure nitrogen for sheep category that is leached from the manure management (dimensionless) (Table A3.11)

Table A3.11 - Fraction of managed manure nitrogen for sheep category.

Livestock categories	**$Frac_{leachi}$**	**Source**
Sheep	0.02	(IPCC, 2019b) – Table 10.22

7. Appendix B. Calculation of Carbon sequestration

The carbon sequestration value of the crops reported in Table B3.1 was estimated using data elaborated by previous studies.

Table B3.1 - Carbon sequestration rate for each crop typology.

Type of crops	Carbon sequestration rate (tons C ha^{-1} yr^{-1})	Source
Pastures	0.20	(Dondini et al., 2023)
Legumes (for grazing and grain)	0.88	(Kumar et al., 2018)
Grasses (for grazing and grain)	0.21	(Giussani, 2013)
Forage mixture of grasses and legumes	0.36	(Richardson et al., 2019)

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CHAPTER 4

General conclusions

In Chapter I, we focused on the concept of circular economy (CE), estimating the degree of circularity of the economy of the 27 European countries. In particular, we looked at how much agriculture and agri-food affect the circularity of individual countries. We found that the level of circularity into the EU economic system is pretty low, equal to 4.1%, with significant differences between the various countries. The pivotal data that emerged from this analysis is the primary sector's predominant contribution: 80.5% of recycled materials are part of this sector. Concerning the agri-food sector, his degree of circularity is almost entirely composed of the upstream phases, bringing only about 1% more circularity. Agriculture thus plays a predominant role in determining circularity in the EU, and it is the sector that best responds to political requests to increase the application of circular practices.

Basically, in this chapter, we put on evidence the importance of measuring circularity in the agricultural sector even if this measure reflects the contribution provided by the sector to the circularity of the economic system on the whole. These results, although extremely important for the primary sector, have limitations, due to the nature of the databases on which they are calculated. In the future we hope that these sources will consider not only the quantities of waste produced and sent for recycling, but also the amount of energy needed to complete this process. The energy component is particularly important because if more is required for recycling than to produce raw materials, then we are faced with a technological problem which undermines some of the principles of the CE.

In the Chapter II, the focus was shifted to the Sardinian dairy sheep sector and on sustainability. Two dimensions of his sustainability were analyzed investigating on public services provided: environmental and social. For this purpose, the perception by part of collectivity of the ecosystem and social services generated by this production activity was analyzed. This analysis is necessary to provide correct information regarding the pivotal secondary outputs provided by this sector, which in this way can be correctly evaluated. The results demonstrated that relevant services are granted by livestock farming, such as the maintenance of the landscape or the prevention of depopulation, and generally, respondents recognized the multifunctional role that pastoralism has played for centuries. The perception of these services makes it possible to give them value and highlight the environmental and social role played by Sardinian dairy sheep farming, thus supporting policymakers to make effective, informed decisions and justify investments and actions. Furthermore, the assessment of the perception and valuation of ES and SS could also allow for the setting of an effective communication strategy about these positive externalities of dairy sheep farming systems.

The Chapter III aims to highlight the type of relationship that links economic and environmental sustainability dimensions in dairy sheep farming and if these could be influenced by some farms' structural or socio-demographic variables of farmers. For the first scope, a series of economic and environmental indicators were used, some of which have already been used in previous studies, others used for the first time. Economic indicators, on the one hand, and the environmental ones, on the other, were merged into two different composite indicators, which, through the trade-off analysis, allowed us to evaluate the relationship between the two dimensions of sustainability. To assess the relationships between the two sustainability dimensions investigated and the structural and socio-demographic variables, linear regressions were carried out. The results of the trade-off analysis showed the presence of a slight synergy between the dimensions analyzed. At the same time, from the regressions, it emerged that the economic dimension is positively and significantly influenced by the young age of the farmer and by the application of organic practices. These results are pivotal to understanding whether the policies currently put into practice by the EU can be applied without damaging either the profitability of the activity or the environment. They also indicated how the presence of young people in agriculture and livestock farming is necessary to guarantee the vitality of this sector.

This thesis attempted to respond to the need to evaluate both the degree of circularity and sustainability, with its different dimensions, in a fundamental sector such as the primary one, with reference to dairy sheep farming. Their measurement needs to be promoted and necessary because without it these concepts remain abstract and besides it is impossible to identify any positive or negative effects deriving from their application.

Focusing analysis on extensive dairy sheep farming, we found that sustainability is positively perceived by population, and it suggests that environmental and social functions played by the sector are view as important by collectivity. Enhancing these public functions, however, can jeopardize the economic dimension of the activity. Indeed, literature has reported several examples of agricultural sectors and/or territorial realities in which a trade-off between the two sustainability dimensions - economic and environmental – exist. Our study suggests, on the contrary, that a synergy appears in this sector, at least with reference to the Sardinia, and therefore creation of environmental value would lead to a correspondent increase of economic value and vice versa. This is a important finding in terms of policy addresses and strategies in the sector's favor.

At the same time, how the environmental dimension can be improved in the dairy sheep farming is a challenge, especially considering the possible increase of circularity into the practices. We found that European agricultural, in general, mostly contribute to circularity in the economic system. The challenge is to understand how possible virtuous circular processes introduced in this activity can jointly improve the environmental and economic dimension but, for analyzing that, it is necessary to have methodological tools able to measure circularity at specific sector or farm level and to assess the role of circularity in affecting economic performances.

In this perspective, the measurement of circularity should be integrated in that of sustainability, for example, introducing specific indicators into the sustainability indicators. This can occur at macro- and meso-economic level but, above all, at a microeconomic level, in which the entrepreneur focuses on maximizing profits and minimizing negative externalities. Such assessments are even more necessary in the primary sector, which is the first and most directly affected by climate change and therefore needs to understand the effectiveness or otherwise of practices to reduce its effects.

However, as put on evidence in the general introduction, the two concepts are different and not necessarily complementary. To be able to combine the SD with the CE is required to *(i)* integrate the two definitions, as done by Kirchherr et al. and Blum et al., *(ii)* developing methodologies that complement the measurement of sustainability with indicators to assess circularity. This last point represents a pivotal challenge to which we are called to find a solution. If we do not arrive at a total evaluation of these two paradigms, we will always have only partial assessments, which will incorrectly influence the choices of policymakers and stakeholders and diminishes the application and effectiveness of these practices.