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Building sustainable futures: the bio-based fertilizer case-study

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Abstract. Bio-based fertilizers (BBFs) can be a solution for converting agricultural waste into new products useful for increasing organic matter in the soil, thus reducing the consumption of mineral fertilizers. This can contribute to the ecological transition launched by the European Commission for the coming decades. Scenario analysis is an effective tool to assess the factors that can affect the development of the agri-food supply chain, evaluating the effects of their possible evolutions. The aim of this work is to draw plausible future scenarios for the BBF supply chain and to strengthen the consistency evaluation process of these scenarios. We built the scenarios considering both the literature and findings from stakeholder consultations. We then verified their consistency by adopting the Cross-Impact Balances (CIB) method, along with other techniques to better evaluate the consistency and plausibility of the narratives. The analysis provides stakeholders with information to evaluate possible future trends in the BBF supply chain. Monitoring the evolution of the identified drivers and maintaining constant and periodic discussions among stakeholders constitute the prerequisites for supporting the desirable future development of BBFs.

Keywords: future scenarios, bio-based fertilizers, circular economy, sustainability, social-ecological transition.
JEL Codes: D81, E37, O33, Q16, Q57.

1. INTRODUCTION AND BACKGROUNDS

In an increasingly globalized and interconnected world, the development of socio-economic systems is influenced by a multitude of factors whose trends are difficult to predict, at least in the long term. As demonstrated by recent financial, pandemic, and climate crises, mathematical models are not always capable of producing reliable forecasts in a context where uncertainty plays a determinant role (Puy et al., 2022). The most recent big-data analysis tools and the development of artificial intelligence will certainly enhance our ability to understand the world, but they will also generate a mass of results that are not always coherent, making it difficult to identify the most reliable ones (Hariri et al., 2019). Chaos theory has demonstrated the unpredictability of complex systems, where a small change in the state of one or more factors is sufficient to produce completely different effects (Schueler, 1996).

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Future scenario analysis does not aim to predict the future but evaluates what happens if one or more factors that influence the system (driving forces) evolve in certain directions. It is not a probabilistic model but a logical approach for identifying possible evolutionary trends based on an appropriate knowledge of the initial state of the determining factors, the cause-effect relationships between them, and their impacts on the system.

There is no single definition of scenarios. In this work, scenarios are plausible narratives of how the future could develop, based on a coherent and consistent set of assumptions about the main driving forces and their relationships (Hunt et al., 2012; Boschetti et al., 2016; Guivarch et al., 2017). The narratives or storylines focus on the drivers that have greater importance and uncertainty, highlighting the main scenario characteristics, the relationships between key driving forces, and the dynamics of their evolution (IPCC, 2014). They may include quantitative data from literature, specific surveys, or mathematical models (Swart et al., 2004; Reed et al., 2013; Guivarch et al., 2017).

The literature on future studies is extensive, with several attempts at classification tracing back to the triad of possible, probable, and preferable futures. Börjeson et al. (2006), adapting previous classifications, distinguish three main categories of scenario studies based on the user's perspective (questions): predictive scenarios (what will happen?); exploratory scenarios (what can happen?); and normative scenarios (how to reach a preferred future situation?), further articulated based on more specific questions.

Different techniques can be adopted to develop future scenarios. A widespread method generates four alternative (exploratory) scenarios related to the investigated topic using the 2×2 Matrix Technique (Schoemaker, 1995; O'Neill et al., 2014; Rhydderch, 2017; Fritsche et al., 2021). For this purpose, two factors of great importance and uncertainty that influence the future of the topic are identified, with two opposed outcomes imagined for each. Placing the two factors on a Cartesian plane, they intersect at the present time to form four quadrants, with the ends of the axes indicating the possible evolution of the two factors at the chosen future horizon. Each quadrant produces a scenario whose narrative is determined by the outcomes of the factors on the axes and other relevant identified factors.

Another technique of interest is a normative scenario, participatory backcasting (Quist and Vergragt, 2006), which starts from sharing a desirable future among stakeholders and identifies possible actions (policies) that may lead to the fixed goal. Explorative scenarios and backcasting can also be combined, as Vervoort et al. (2014) experimented in the context of food security.

Numerous public and private institutions use scenario analysis for their strategic choices and policies. In some governments, it has become an institutionalized activity (as in Singapore, the United Kingdom, and Finland) (Störmer et al., 2020). The European Commission (EC) has also been using this tool for a long time. Burgelman et al. (2014) trace its history, noting that the motivation behind this choice was to improve the administration and governance of the EC through the broad involvement of stakeholders in the decision-making process. The use of foresight processes by the EC began in the late 1970s, but only in 2017 did the EC produce documents officially acknowledging the usefulness of foresight for better regulation (Störmer et al., 2020). The EC documents cited recognize four functions or benefits of applying foresight to policymaking: informing policy, facilitating policy implementation, embedding participation in the policymaking process, and supporting policy definition.

Scenario analysis has constituted an important tool for the scientific community in defining possible future paths of socio-economic development, both globally and in specific sectors and territories. Among the former, a series of future scenarios have been produced, starting from the conceptual work of O'Neill et al. (2014) and later defined in the corresponding narrative contents (O'Neill et al., 2017). These are known as Shared Socioeconomic Pathways (SSPs) and describe alternative future trajectories of several factors connected to the challenges that climate change poses to society concerning adaptation and mitigation. They represent plausible conditions that can be realized in the future (to 2050) in large regions of the world regarding human and demographic development, economy and lifestyle, policies and institutions, technology, environment, and natural resources.

Due to the general nature of the SSPs, they can be used as references for other analyses of development paths, both on issues directly related to the climate and on more specific themes, at both global and sub-national scales (e.g., Lassaletta et al., 2019; Chen et al., 2020; Mitter et al., 2020), thus distinguishing basic and extended SSPs (O'Neill et al., 2014; van Ruijven et al., 2014). Using SSP narratives, Mitter et al. (2020) defined possible future scenarios for the European agri-food system, the so-called EUR-Agri-SSPs, providing plausible references to derive storylines related to more specific contexts (sectors or areas). The EUR-Agri-SSPs have recently been used as a reference for defining future scenarios for pesticides (Nagesh et al., 2023).

Using the same context scenarios, in this work we define plausible future development pathways for the bio-based fertilizer value chain, identifying the main factors that can influence its future development.

To date, there is no unique definition of bio-based fertilizers (BBFs), but work is underway at the European level towards a standard definition (ESPP, 2023). Wester-Larsen et al. (2022) define BBFs "as materials or products derived from biomaterials (plant, animal, or microbial origin, often wastes, residues or side-streams from agriculture, industry, or society) with a content of bioavailable plant nutrients suitable to serve as a fertilizer for crops" (Wester-Larsen et al., 2022, p.1). This is the meaning of BBFs used in our work, which is consistent with the elements of the ongoing debate at the European level and the recent literature on the subject (Tur-Cardona et al., 2018; Chojnacka et al., 2020; Puglia et al., 2021; Egas et al., 2023; Kurniawati et al., 2023).

The cited literature reports how the production of bio-based fertilizers from residues and by-products of the agri-food system would contribute to solving the problems arising from the large quantities of organic waste produced and the use of mineral fertilizers, which depend on non-renewable resources. An increasing and widespread use of BBFs to replace mineral fertilizers would improve the health of natural resources by reducing the accumulation of nutrients in the soil and water. The recovery of useful materials from the waste of the agri-food system to produce fertilizers also responds to the need to make the entire system more sustainable. This need was expressed by the European Commission in the Circular Economy Action Plan (European Commission, 2015), most recently updated (European Commission, 2020), and is reiterated by the 2019 EU Fertilizer Regulation (European Commission, 2019), as well as the recent report from the European Environment Agency (2020). However, it should be considered that the use of these products is not free from problems in the current state of technology. It has been ascertained that contamination by heavy metals and pathogens represents the main problem for the use of BBFs, whose acceptability by consumers (farmers) would be hindered, among other things, by issues relating to costs (for transport and production) and the still unclear political framework (Kurniawati et al., 2023).

For the purposes of this work, the qualitative data for identifying the most important and uncertain driving forces relating to BBFs were provided by a multi-actor participatory technique. This approach was supported by data collection from official sources and literature.

Stakeholder engagement is quite common in futures studies. In the review by Fauré et al. (2017), they highlight how this approach is particularly prevalent when dealing with issues related to sustainability. More generally, Pernaa (2017) points out that anticipating the future requires more interdisciplinary and multi-perspective collaboration due to the growing complexity in our societies. The participatory approach strengthens scenarios and facilitates the activities of researchers, policy makers, and decision-makers (Borch and Merida, 2013; Mitter et al., 2020).

The participation of stakeholders also contributes to ensuring the internal consistency of the storylines (or grading them in terms of coherence) through the judgments expressed by experts on the relationships between the identified drivers. A tool to visualize these relationships is Causal Loop Diagrams (CLD), used, for example, by Mathijs et al. (2017) and Mitter et al. (2020). In this work, we adopt the Cross-Impact Balance (CIB) analysis (Weimer-Jehle, 2006), which identifies internally consistent scenarios through cross-impact matrices. More generally, the CIB method is aimed at the "systematic construction of qualitative and semi-quantitative scenarios" (Weimer-Jehle, 2023), and has been applied in many contexts to analyse the relationships between the factors of scenarios using an algorithm. In the literature, CIB has more frequently been used for the analysis of scenarios in the energy field, for climate change, and for sustainable development. There are few works about the agricultural and agri-food sector, with only one publication (Kurniawan, 2020) that used CIB together with the SSP method to evaluate the coherence of scenarios at different scales of detail. In our analysis, we adopted CIB to evaluate the consistency of scenarios of the same scale, constructed through the SSP method (BBFs scenarios).

In summary, the aim of the work is twofold. Firstly, it is intended to draw plausible future scenarios for the BBF supply chain, and secondly to verify whether CIB can be used to facilitate the consistency analysis of the scenarios, reducing the risk of outlining internally inconsistent situations. The originality of this work concerns both the study object of the scenario analysis (BBF supply chain) and the combined use of CIB and EUR-Agri-SSP methodologies to strengthen the validation process of the scenarios.

In the following paragraphs, the methodological path adopted to build plausible and consistent future scenarios for BBFs is described, followed by the achieved results. The discussion is focused on the combined use of different methods and tools. Finally, the advantages and limitations of the methodological approach are outlined in the conclusion.

2. METHODOLOGY

The methodology used to build the BBF scenarios is based on two preliminary considerations.

First, the case study represents a segment of the agri-food chain, which is itself a component of the agri-food system. This concatenation of contexts, which can be further expanded to include higher levels, implies that the driving forces influencing the development of BBFs can be internal to the sector or derived from external contexts. For example, the production cost of BBFs or their chemical-physical characteristics are internal drivers, while the prices of mineral fertilizers or the environmental sensitivity of consumers are external factors. The ability of the SSPs to nest scenarios allows for the linking of external factors to internal ones, thereby articulating higher-level narratives by incorporating specific insights and variations for the analysed sector.

The second consideration concerns the role of the multi-actor approach. Generally, building scenarios with the participation of stakeholders involves a lengthy process of exchanges with the actors, including a preparatory phase and multiple meetings in which the elements of the scenarios are progressively defined (e.g., Bock et al., 2020; Mitter et al., 2020). In our study, the approach was decidedly more concise, hampered by the restrictions linked to the COVID-19 pandemic. Due to these constraints, the participatory process was carried out through online workshops and surveys, an approach that limited the interaction between the subjects involved but sped up the collection of information.

The analysis followed the steps shown in Table 1.

2.1. Identifying and analyzing the focal issue

The case study focuses on the production and use of BBFs, considering the main aspects that can affect the organization and development of this supply chain. The goal was to outline some plausible and alternative scenarios for 2050, useful to support decision strategies for both those who want to invest in the sector and policymakers who intend to facilitate the development of BBFs.

An analysis of the available documentation focused on the fertilizer sector (Chojnacka et al., 2020; Fertilizers Europe asbl, 2021) and more generally on the development of the agri-food system (FAO, 2022) has provided the first qualitative and quantitative information. We classified this information according to the STEEP categories (society, technology, economy, environment, politics). For each category, the phenomena that characterize the sector have been summarized, with statistical and forecast data, to evaluate the current and prospective situation. In this way, the main factors (driving forces

Table 1. Synoptic diagram of the analysis path.

Phases	Methods and Tools	Outputs
1. Identifying and analyzing the focal issue (from Jan 2021 to Mar 2021)	- bibliographic review on biofertilizers and agri-food system global trends - STEEP classification analysis of main factors affecting BBF supply chain	- 18 “trend cards” summarizing the current and forecast situation of each factor (analysis and statistics)
2. Choosing the appropriate scenario-building method (from Apr 2021 to Jun 2021)	- bibliographic review on scenario methods and on European agri-food scenarios - EUR-Agri-SSPs scenarios as baseline method for BBF supply chain analysis	- selection of the method for scenario building - identification of the global agri-food framework for BBFs development
3. Identifying the drivers and organizing the information framework (from Jul 2021 to Oct 2021)	- participatory approach techniques involving 5 experts, 14 stakeholders, and 10 project partners - 1 focus group, 5 online meetings, 3 online surveys	- validation and integration of relevant and uncertain drivers for BBF development (134 final factors)
4. Building and analyzing scenarios (from Nov 2021 to Dec 2021)	- adaptation of EUR-Agri-SSPs scenarios introducing and analyzing BBF main drivers - in-depth narrative writing linked to global scenarios; synthetic narrative drafting diversified by the project pilot areas - narrative revision by experts in European agri-food development	- four main scenarios: two extreme and opposite and two intermediate ones - scenario variants for each project pilot area (4)
5. Checking the consistency of BBF scenarios (from Jan 2022 to Feb 2022)	- Cross-Impact Balances (CIB) tool for analyzing the relationships and combinations between the states of the drivers - comparison between SSP and CIB results (future situations)	- 9 consistent scenarios from 2,187 variant combinations - the 4 SSP scenarios are included in the 9 CIB scenarios (positive consistency check)

or drivers) to be considered for the development of BBFs were identified.

2.2. Choosing the appropriate scenario building method

The definition of plausible future scenarios for BBFs started with the identification of more general scenarios for the food system and the main factors that influence its evolution. To this end, academic and grey literature and research projects on the subject were examined via the web, and also retrieved from the websites of international organizations, government agencies, and private institutions. The H2020 SURE-Farm Project was identified as consistent with our objectives. SURE-Farm defined the EUR-Agri-SSPs scenarios (Mathijs et al., 2017, also described in detail in Mitter et al., 2020), which are derived from the global Shared Socioeconomic Pathways (SSP) scenarios (O'Neill et al., 2017). Mitter et al. (2020) start from the SSPs to narrate the future conditions of the farming system in Europe and use a multi-actor approach for their definition. They extend the analysis to food consumer issues and use other scenario studies to enrich the narratives. Based on the uncertainty of the main socio-economic, environmental, and technological factors, they define five alternative scenarios, the EUR-Agri-SSPs, describing plausible future conditions (up to 2050) for the European agricultural and food systems in relation to climatic challenges.

The EUR-Agri-SSPs are taken as context scenarios for the BBFs case study. Each of them defines differentiated conditions of the macro-environment (population, geopolitics, economic development, markets, technology, etc.) which in turn influence the conditions of the specific factors identified for the development of the BBF supply chain. In this study, only four of the five EUR-Agri-SSPs have been considered, excluding the EUR-Agri-SSPs No. 2 because it has intermediate characteristics compared to the other scenarios.

2.3. Identifying the drivers and organizing the information framework

The set of indicators that measure the possible trends of the drivers in the reference period of the scenarios has been defined. This information, organized by STEEP categories, formed the basis of the BBFs scenarios, built on differentiated trends and therefore outlining evolutionary trajectories that lead to alternative or opposite future situations. In this way, it was possible to evaluate which factors determine the preferable evolution of BBFs.

The set of drivers selected for the BBFs scenarios derives from the bibliographic survey (Phase 1) and the participatory process, and partially from those already identified by Mitter et al. (2020) for the EUR-Agri SSP scenarios. The main driving forces that can favour or hinder the development of fertilizers of biological origin in the European agri-food system were identified and discussed in several meetings coordinated by the research group, in which sector stakeholders participated.

For this purpose, in each of the European areas considered for the development of the case study (Almeria (ES), Flanders (B), Friuli-Venezia Giulia (IT), and Pays de la Loire (FR)), 10-15 stakeholders from the fertilizer sector were selected, including researchers, operators, associations, and policymakers, based on the following criteria: Interest, Availability, Relevance, Appropriateness, Representativeness, Broad Vision (Zawalińska et al., 2022).

The four regions were selected by the Rustica project partners because the agricultural sector significantly contributes to the deterioration of natural resources, although to different extents. The intensity of agricultural production causes widespread contamination by fertilizers (and pesticides), and considerable quantities of low-quality waste pose problems for their proper utilization/disposal, risking worsening the environmental impact. Despite local policies promoting the development of the circular economy, the use of food sector waste in the form of bio-based fertilizers is still rather limited in all regions, as results from the direct survey carried out during the EU Rustica Project. The diversity of the socio-economic contexts of the regions, through the multi-actor approach, provided elements to enrich and strengthen the prospective framework defined hereafter in the BBFs future scenarios.

Having been informed in advance about the objectives and contents of the study, the stakeholders in each area were then invited to participate in a workshop during which they were interviewed based on a work outline common to all areas. Overall, around 50 stakeholders were involved to identify and classify the most relevant and uncertain drivers of the BBF supply chain. Relevance was assessed by the power to influence the evolution of the phenomenon of interest (BBFs development), while uncertainty concerned the predictability of the trend in the period considered. At the end of the stakeholder consultation, 134 of the most relevant and uncertain factors were considered for the scenario analysis (Table A in the appendix). These factors were further analysed to classify them according to their common characteristics in terms of context and/or purpose. This slightly more detailed reclassification of the STEEP categories was helpful in identifying these seven main driving forces: sustainability awareness, political framework, fertilizers market, technological solutions, innovation uptake process, agri-environmental system, and bioeconomy patterns. These were considered the main determinant factors for the evolution of BBFs.

2.4. Building and analyzing scenarios

The BBFs scenarios were developed by associating the drivers identified for the BBFs with the EUR-Agri-SSP context scenarios. The process of adapting and deepening context scenarios into BBFs ones was long and articulated. In continuity with the context scenarios, the drafts of the BBFs narratives were elaborated, assuming four distinct future situations: two extreme and opposite (favourable/unfavourable for the BBFs development) and two with a mix of positive and negative elements (Phase 4). A fifth EUR-Agri-SSP scenario was not considered as it is intermediate between the others. In the first two scenarios, the direction of the drivers is opposite, all aimed at facilitating or hindering the occurrence of a positive context for BBFs, while the other two are characterized by diversified situations with some dominant evolutionary elements.

Each scenario is characterized by a different evolution of the drivers. For example, in the first scenario, the sustainability of agriculture is favoured by a growth in social environmental awareness, which implies a propensity to reuse agricultural waste and to eat healthier food.

The drafting of a scenario narrative is rigidly codified in the literature, and although there are margins for subjective interpretations, these must be based on objective elements such as the possible evolutions of coherent and specific drivers. The subjectivity of the interpretation can only make the narrative more interesting by avoiding a slavish commentary on the situations that outline the scenario. Nevertheless, the guidelines of the methodology adopted, the feedback from the experts, and the robustness check of scenarios limit the personal influences of researchers, experts, and stakeholders.

2.5. Checking the consistency of BBF scenarios

With the drafting of the final narratives, the analysis of the scenarios was not concluded, as it was necessary to verify that the construction and revision process had not led to inconsistent situations within each scenario and between them. For example, if a scenario considers a sharp increase in energy prices and at the same time a reduction in the prices of mineral fertilizers, a contradictory or at least unrealistic situation has occurred.

We then proceeded with a consistency check of the BBFs scenarios by analysing the relationships and combinations between the states of the drivers. While Mitter's methodology used Causal Loop Diagrams (CLD) to analytically describe the interdependencies between factors, another analysis tool called Cross-Impact Balances (CIB) (Weimer-Jehle, 2006) was chosen for BBFs. Both methods analyse the relationships of influence between drivers and are used when it is not possible to adopt a mathematical model to measure these interdependencies. The CIB method analyses the relationships between the factors through a quantitative assessment (scores), while the CLD uses a graphic language (flow charts). The CLD method should be applied to each hypothesized scenario, while the CIB method considers all possible scenarios generated by the drivers' combinations. For this reason, CIB was chosen to assess all scenarios, including those unrelated to Mitter's results.

The CIB method is based on the construction of a symmetrical matrix where the different future situations are placed by row and by column. These situations are identified by a title (descriptor) and articulated into a few possible evolutionary paths (variants). The descriptors summarize the previously identified drivers, which act in the same context, labelling the group with a title evocative of the dominant theme, while the variants are derived from the different evolutions of the drivers between the scenarios.

3. RESULTS AND DISCUSSION

3.1. The future scenarios for the bio-based fertilizers

Following the methodology described above, the first draft of the BBFs narratives was prepared by the research group and submitted for review to a panel of experts. Twelve experts from different institutions and professional backgrounds participated in the panel. The online focus group was held in July 2021. The participants were selected based on their roles and expertise in the field: Research/Academics, Stakeholders, and Policymakers.

Two experts were from The University of Bologna and CREA Agriculture and Environmental Research Centre, with technical backgrounds in fertilizers and organic farming. A representative from ENEA had expertise in biomass for energy use, and a fruit supply chain expert was from CRPV. The six stakeholders involved included representatives from the Italian Biomass Association - ITABIA, the President of the Associazione Chimica Verde Bionet-Biomass and Green Chemistry, a representative from Esco Lazio - Biogas and Digestate, a biological expert in biofertilization from BIO/INTESA, the Head of Communication for Terre d'Etruria Cooperative, and a representative from Enomondo, which focuses on the recovery of agri-food waste for bioenergy and compost. Additionally, two experts from the Italian Ministry of Agriculture and three agri-environmental technicians from three Italian regions were involved.

They were asked to evaluate the narratives' plausibility, consistency, richness, creativity, and salience, as indicated by the reference methodology (Mitter et al., 2020). These criteria aim to consolidate the texts by eliminating any inconsistencies and evaluating their degree of realism while maintaining elements of creative originality, considering unexpected and improbable situations. This is exemplified by the war in Ukraine, an extreme event not directly considered in the hypothesized scenarios, which were developed before the conflict, although one scenario describes a situation of strong territorial inequalities and social conflicts.

The experts' suggestions were useful in refining the narratives and arriving at their final version, the summary of which is reported below, while their full version is available online as supplementary material. Each of the following narratives is composed of the main elements of the context scenario (from Mitter et al., 2020, in a box in italics) and the extended BBFs narrative (in regular font).

FIRST SCENARIO: BBFs ON VALORIZATION PATH

<u>Main elements of context scenario: Agriculture on sustainable paths</u>
A strong network of small and medium-sized towns and large cities. Diversity in agricultural supply chains supported by globally connected markets with internalized costs of trade. Multi-level cooperation, policy integration, and societal participation. Pronounced technological development directed towards environmentally friendly processes and cooperation between farmers and consumers. Increasing environmental awareness, resource use efficiency, and environmental health.

BBFs narrative

Sustainability awareness is growing in agriculture, leading to the adoption of circular business models, often through vertical integration in supply chains. Growing urbanization facilitates the recovery and enhancement of biomass, thanks to infrastructure and the concentration of actors and knowledge in cities. Digital technologies ensure the dissemination of knowledge to the most remote rural areas, where technological solutions are also widespread.

There is a growing demand for safe and sustainable (organic) products, especially local products. Society's interest in food production methods directs agriculture towards more sustainable techniques and, due to strict environmental legislation, towards greater use of bio-based products from agricultural waste, such as fertilizers. This leads to competition between the possible destinations of raw materials, resulting in wide price volatility for bio-based products.

With the increase in demand for bio-based products, the supply is organized and structured into small or medium-sized networks with consortium-type biomass transformation plants spread throughout the territory, depending on the availability of local feedstock. Sustainable logistics allow for efficient biomass collection and delivery services. Within the local networks, integrated products and services adapted to the needs of farms are provided.

Policy encourages and supports the adoption of circular business models by stimulating the integration of actors. On the demand side, policy pays great attention to communication and fosters relationships based on trust.

The integration between economic subjects facilitates the adoption of technological innovations that improve the quality of the BBFs (stability of characteristics, ease of use, effectiveness). Artificial Intelligence (AI) caters to fertilization needs by powering Decision Support Systems (DSS) based on the automatic exchange of data between devices and BBFs suppliers.

The greater use of BBFs derived from the recycling of fruit and vegetable waste reduces the utilization of mineral fertilizers, avoiding the exploitation of non-renewable resources for their production.

SECOND SCENARIO: BBFs ON DIFFERENTIATION PATH

<u>Main elements of context scenario: Agriculture on separated paths</u>
Decelerated urbanization. National agricultural supply chains benefit from protectionism. National agricultural policies aim for national food and energy security. Slow agricultural technology development and uptake due to reduced investments and scepticism. High pressure on natural resources due to high national demand for agricultural commodities and limited coordination and technological progress.

BBFs narrative

A general climate of mistrust, slow generational turnover, and the degradation of infrastructure hinder the integration of economic actors and the adoption of innovative and eco-sustainable solutions. Society also lacks a culture of waste recycling.

Low environmental sensitivity creates an unfavourable climate for the spread of sustainable (organic) agriculture and the adoption of circular production processes, which are also hampered by the reduction of public support. At the farm level, the valorisation of waste is limited and often faced with ineffective techniques. This hinders the spread of bio-based productions, to which inefficient logistics contribute. Even if the price of biomass is low, the final bio-based product does not have a good quality-price ratio.

A few large producers of fertilizers (mostly mineral fertilizers) dominate the market, while the growing isolation of countries makes access to raw materials (such as phosphorus) more difficult and contributes to their price increase. The large companies cater to their country's fertilizer needs, increasing their use efficiency through customized solutions and new technologies for mineral extraction.

Environmental policy is inconsistent and unresponsive, and the bioeconomy and circular economy languish due to the closure of national economies and the lack of environmental objectives. Traditional agricultural lobbies, dominated by a few major players, increase their influence on political decision-makers, while the integration of local actors to organize integrated supply chains is not supported by adequate regional policies.

The scarcity of investments in R&D limits the development of technologies with low environmental impact. There is also a lack of technological solutions for the adequate reuse of agricultural waste. This leads to poor quality finished products, which therefore cannot compete with mineral fertilizers. Small-scale plants are present only in some areas with strong production specialization, but their diffusion is hindered by general mistrust and difficulty in establishing relationships.

On the environmental front, the inappropriate treatment of agricultural residues contributes to the pollution of natural resources.

THIRD SCENARIO: BBFs ON POLARIZATION PATH

> <u>*Main elements of context scenario: Agriculture on unequal paths*</u>
> *Territorial fragmentation. A business-oriented elite dominates agricultural supply chains. A business-oriented elite dominates European institutions and sets the policy agenda. Rapid technology development focuses on production and energy efficiency. Environmental awareness is limited to the neighbourhoods of the wealthy upper class.*

BBFs narrative

The tendency towards individualism hinders the organization of supply chains, while the lack of environmental sensitivity means that sustainable techniques remain confined to some rural areas and communities. In these areas, the lack of infrastructure produces serious logistical problems for the transport and storage of agricultural products, as well as for the distribution of inputs and the collection of production waste.

Only in peri-urban areas do a few fertilizer producers invest in bio-based products to differentiate their supply and respond to an elite demand willing to pay high prices. As a result, BBFs are more expensive than mineral fertilizers due to the absence of a market or well-structured supply chain. Furthermore, economic conditions do not support farmers adopting high-cost inputs due to low food prices.

The demand for bio-based fertilizer products is weak as environmental standards are not restrictive. This situation is also exacerbated by the lack of specific regulations on the use of organic waste. Existing regulations, which are neither coherent nor incisive, favour aspects of technological development over those of environmental sustainability. The main rules that define certifications and labels are managed and guaranteed by private bodies, leading to differences between territorial productive systems.

Subsidies for innovative technologies in agriculture favour investments only in the most developed regions/countries, where effective BBF technologies are adopted. Elsewhere, the complexity and cost of technology limit its local accessibility. Technological platforms interconnect economic actors mainly to manage trade flows while maintaining the managerial autonomy of companies.

In general, agriculture contributes to the degradation of natural resources, as the use of mineral fertilizers and chemical pesticides is intensive. Sustainable agriculture methods and circular approaches are widespread only in natural areas. Here, the use of bio-based fertilizers is mandatory as agricultural products are certified and subject to strict quality controls.

FOURTH SCENARIO: BBFs ON TECHNOCRATIC PATH

> <u>*Main elements of context scenario: Agriculture on high-tech paths*</u>
> *Metropolization. High-tech, large companies dominate globalized agricultural supply chains. European institutions foster international trade but delay environmental action. There is a high affinity for output-oriented technology. A lack of global environmental awareness.*

BBFs narrative

The environmental awareness of the population and young farmers is limited, partly because the high and generalized orientation towards using technology for all aspects of life has solved many problems related to the scarcity of non-renewable resources. However, in rural areas excluded from technological development, traditional agricultural practices remain inefficient and sometimes negatively impact natural resources.

Food waste is concentrated in cities due to increasing urbanization. Bio-based fertilizers are processed in agro-industrial districts where the plants operate on an industrial scale and are part of multinational networks. Waste from agricultural production in less urbanized areas is recycled by large high-tech farms through their own small and medium-scale plants. The mineral fertilizer industry dominates the market thanks to the development of more efficient technologies and highly effective formulations. Green chemistry is developing rapidly, but the technologies are protected by patents and are therefore not very accessible due to the competitive market environment.

Public support for the circular approach is almost absent, with most investments being private. In agri-food supply chains, processing waste is usually recycled to improve efficiency. Policies supporting bio-based production are oriented towards their technological uses (e.g., bioplastics for food packaging). Specific legislation for bio-based fertilizers is lacking, but some available measures concerning labels facilitate communication to consumers (health footprints). Internet of Things (IoT) and Blockchain technologies allow the automated management of a well-integrated and traceable agri-food chain, where biomass for recycling is also managed. In this way, bio-based waste and fertilizers are valorised. However, mineral fertilizers dominate the market due to the presence of large companies and pressure from lobbies.

The lack of environmental awareness leads to negligent management of natural resources in agriculture. In peri-urban areas, the intensive use of pesticides and inorganic fertilizers creates problems with dangerous residues from chemical inputs. The production and use of bio-based fertilizers are quite widespread but limited due to competition with fossil-based inorganic fertilizers.

3.2. The consistency of the scenarios

The next step was the validation of the robustness of the scenarios through the CIB analysis. The CIB matrix (Table 2) developed for the BBFs is made up of seven descriptors and three variants each. The resulting matrix is sized at 21 rows by 21 columns, filled with scores assigned by the research group, evaluating the direction of each interdependence between the variants. The CIB method can use different scoring (e.g., ±3) to measure the strength of relationships. Usually, the score is an integer value between -1 and 1, which indicates whether the situation indicated in the row favours (1) or hinders (-1) the one indicated in the column. The zero value indicates substantial neutrality, while the null value indicates the absence of interdependence between the two situations.

The CIB algorithm computes the algebraic sum of the scores of all the matrix combinations and considers more coherent scenarios when positive values prevail over negative ones. These are the scenarios that do not present contradictions between the different hypothesized situations. The number of consistent scenarios varies according to the scores assigned and can be very high if the interdependence relationships generate many possible combinations or even null if they outline alternative and non-overlapping situations. This methodology was used to evaluate whether the four hypothesized

Table 2. CIB matrix for the BBFs scenarios.

Descriptors and variants		A			B			C			D			E			F			G		
		1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
A. Innovation uptake process	*1. Linear transfer*													-1	1	0						
	2. Cooperative participation													1	0	-1						
	3. Selfish approach													-1	0	1						
B. Sustainability Awareness	*1. Societal rooted*							1	1	-1	1	0	-1	1	0	-1	1	1	-1	1	1	-1
	2. Consumers driven							0	1	0	1	1	0	1	1	-1	0	1	0	0	1	0
	3. Elite fashion							-1	1	0	0	1	1	0	1	0	-1	0	-1	0	0	1
C. Bioeconomy development	*1. Circular based*				1	0	-1				1	1	-1	1	0	0				1	0	-1
	2. Transition in progress				0	1	0				0	1	0	0	1	0				0	1	1
	3. Business as usual				-1	0	1				-1	0	1	-1	0	1				-1	1	0
D. Fertilizers Market	*1. Bio-based competitiveness*							1	-1	0							1	0	-1	1	1	-1
	2. Niche productions							0	1	0							0	1	0	0	0	1
	3. Inorganic power							-1	0	1							-1	0	1	-1	0	1
E. Agri-enviromental System	*1. Agroecological approach*				1	0	0	1	1	-1							1	0	-1	1	0	-1
	2. Low impact standards				0	1	0	0	1	0							0	1	0	0	1	1
	3. Sustainable oasis				-1	0	1	0	0	1							-1	0	1	0	0	1
F. Political Framework	*1. Systemic regulations*	0	1	0	1	0	-1				1	0	-1	1	0	-1				1	1	-1
	2. Environmental compliance	1	0	1	0	1	0				0	1	0	0	1	1				0	1	0
	3. Chemical lobbies	0	-1	1	-1	0	1				-1	0	1	-1	0	0				-1	0	1
G. Technological Solutions	*1. Accessible and effective*	0	1	0	1	0	-1	1	0	-1	1	0	-1	1	0	1	1	1	-1			
	2. Effective but complex	1	0	-1	0	1	0	0	1	0	1	1	0	0	1	-1	0	1	0			
	3. Efficient but ineffective	0	0	1	-1	0	1	-1	0	1	-1	0	1	-1	1	0	-1	0	1			

Source: own elaboration.

BBFs scenarios fall within the set of possible coherent scenarios.

The software application of the CIB algorithm extracted nine consistent scenarios with positive scores from 2,187 variants combinations. These scenarios were compared with the BBFs ones to assess correspondences and differences. Table 3 indicates the variants that characterize the scenarios identified by the CIB. Those inside the green columns coincide with the situations described in the BBFs narratives. In summary, the CIB analysis confirmed that the BBFs scenarios are consistent as no contradictions emerge in the relationships between the drivers considered.

The CIB analysis also identified five more scenarios in addition to those derived from the SSP methodology. These are situations that differ in a few elements from BBFs narratives but are equally plausible.

Table 3. CIB consistent scenarios with SSP overlapping results (■) and scenarios (grey columns).

	Scenarios								
Descriptors and Variants	1	2	3	4	5	6	7	8	9
A. Innovation adoption process									
1 Linear transfer				■					
2 Cooperative participation	■		□						
3 Selfish approach		□			□	■	□	□	■
B. Sustainability awareness									
1 Societal rooted	■	□							
2 Consumers driven			□	■		■			
3 Elite fashion					□		□	□	■
C. Bioeconomy patterns									
1 Circular based	■	□							
2 Transition in progress			□	■		■	□		
3 Business as usual					□			□	■
D. Fertiliser's market									
1 Bio-based competitiveness	■	□	□						
2 Niche productions				■					
3 Inorganic power					□	■	□	□	■
E. Agri-environmental system									
1 Agroecological approach	■		□						
2 Low impact standards				■	□	■	□	□	
3 Sustainable oasis		□							■
F. Political framework									
1 Systemic regulations	■		□						
2 Environmental compliance		□		■	□				
3 Chemical lobbies						■	□	□	■
G. Technological solutions									
1 Accessible and effective	■	□							
2 Effective but complex			□	■					
3 Efficient but ineffective					□	■	□	□	■

Source: own elaboration.

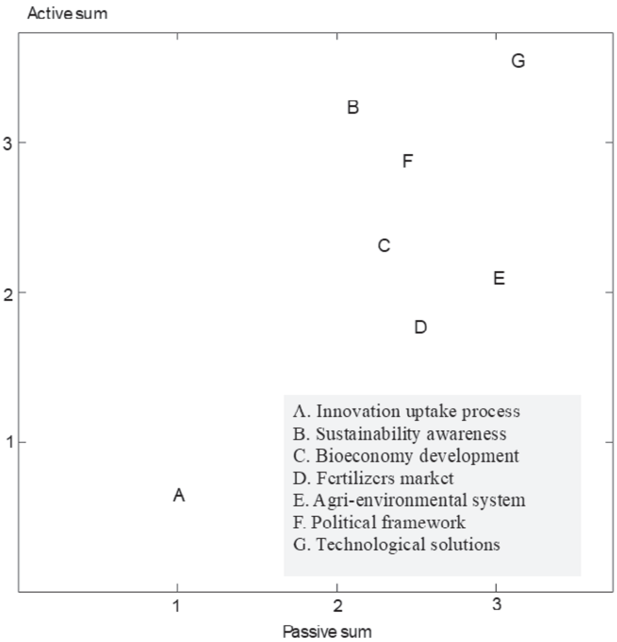

Figure 1. Influence profile of drivers. Source: own elaboration.

From the synoptic Table 2 of the CIB scenarios, it also emerges that some situations (variants) that are not particularly favourable to the development of BBF are more frequent. In the other scenarios identified by the CIB, the influence of chemical lobbies (F3) and the persistence in the market of mineral fertilizers (D3) are recurring variants, probably due to the setting of low environmental standards (E2). Technological processing is not efficient and is not equally capable of creating effective and valid BBFs (G3). The ecological transition process is unfinished (C2), and the production of BBF is still marginal and valued only within some social contexts (B3); the development of innovations is weak and individualistic (A3).

The CIB tool also provides a graphical representation of the influence force of descriptors. In the following graph (Figure 1), the descriptors in the upper right quadrant are the most influential, meaning they determine the status of the other factors the most.

Technological solutions are the most influential factor (high active score sum), while the innovation process is the least influential. This result is probably affected by the presence during participation processes of several people with technical skills who therefore emphasized the relevance of the technological drivers for the development of BBFs. Social awareness and the political context are very influential too, while economic megatrends are weaker as they depend more on other factors.

4. CONCLUSIONS

The exploratory scenarios describe future, plausible, and alternative situations, highlighting the technical and socio-economic conditions that could determine them. In this article, we have built four scenarios for BBFs to 2050, using context scenarios for the agri-food system identified in the literature and specific drivers for BBFs identified thanks to the active contribution of stakeholders. To validate the results, we first consulted external experts to verify the consistency of the scenarios. Subsequently, we used the CIB method in an original way to improve the robustness of the verification process.

The defined scenarios include a very advantageous situation for BBFs (BBFs on valorization path), where the technological and socio-economic conditions are favorable to the development of an efficient, well-organized, and politically supported supply chain. In a context of this type, where circularity permeates the economic system and represents a value for all citizens, a potential threat for BBFs lies in the competition in the use of the raw material, the residual biomass of the agri-food system. Conversely, in the less favorable scenario (BBFs on technocratic path), mineral fertilizers continue to dominate the market, supported by technology and public support, while a marginal BBF supply chain finds limited space in politics, hindered by powerful chemical lobbies. In the other two scenarios (BBFs on differentiation path and BBFs on polarization path), which are intermediate compared to the previous ones, the production and use of BBFs are reduced in both cases, but this situation is determined by different evolution of the drivers. In the first case, the difficulty of integrating companies and the lack of a widespread knowledge and innovation system contribute to the fragmentation of the production fabric and limit the diffusion of efficient technologies for BBFs. Their use is therefore uneven across the territory and between types of agricultural holdings. Finally, in the 'BBFs on polarization path' scenario, the production of BBFs is strongly localized in some areas where favorable conditions exist (for example, for the availability of biomass), while more generally it is hindered by various factors, such as limited environmental sensitivity and the lack of adequate technology and logistics.

The scenario analysis highlighted the particular importance of some drivers for the future development of BBFs, such as product quality, farmers' knowledge, adequate technology and logistics, and public intervention aimed not only at the regulation of the sector but also at the promotion of knowledge and use of BBFs, confirming what has also been found by others (Kurnawiati et al., 2023). The consultation of external experts has contributed to and strengthened the coherence of the defined scenarios. However, different driver evolutions may lead to the definition of other plausible scenarios. We therefore checked whether, among all the possible scenarios generated by the BBF drivers, the scenarios presented above were also included and what the relative degree of coherence was. For this purpose, we used the CIB algorithm. This approach aims to strengthen the verification of the results of the scenario analysis as the two paths are independent and start from different assumptions. The process of building storylines ensures that the factors considered are consistent with the object of the study (in our case the BBF supply chain), since they are based on specific information combined with expert assessments and stakeholder experiences. The CIB, meanwhile, focuses on interdependent relationships between the drivers that allow any inconsistencies to be highlighted. If the results of the two techniques overlap, the risk of producing inconsistent scenarios is lower. In our case, the results of the comparison demonstrate that the scenarios built for BBFs using the EUR-Agri-SSP and the stakeholder support are included among those indicated by the CIB as consistent but also indicate how other equally plausible narratives can be generated. This outcome is not surprising when we consider that one of the characteristics that guides the choice of drivers is uncertainty (in addition to relevance) and that, the greater the uncertainty, the more numerous the possible future realizations of the driver considered will be.

In addition to the methodological aspect, the analysis carried out on the BBFs case study produced a further result which contributes to confirming what has already been argued (Pernaa, 2017) regarding the ability of scenario analysis to create/increase knowledge through comparison between actors of different origins and experiences and the debate generated during the participatory process. This knowledge goes beyond the specific object of the investigation to include the ability to project oneself into the future, an ability which, however, only a structured and continuous path can ensure. The choice of stakeholders has an impact on the entire process of construction and evaluation of the scenarios and can represent a limit, where this choice is somehow lacking not only in terms of the breadth of knowledge on the object of the research but also by the lack of forecasting skills. On the other hand, the latter can be acquired along an interactive learning path between the research group and the actors involved in the scenario analysis.

Ultimately, the analysis provides stakeholders (researchers, policymakers, supply chain operators) with information to evaluate possible future trends in the BBF supply chain. The drivers identified and their evolutions traced in the scenarios constitute a decision support tool for any actions to be taken to favor (or hinder) the occurrence of desired (or unwanted) future situations. Monitoring the evolution of the identified drivers and constant and periodic discussion between stakeholders are the prerequisites for pursuing a desirable future development for BBFs.

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APPENDIX

A. List of drivers proposed by stakeholders grouped by categories.

Sustainability awareness

1. *Acceptance of BBF*
2. *Awareness of Producers (Farmers)*
3. *Awareness of Wastes as a Resource*
4. *Consolidation of Traditional Fertilisers*
5. *Demand of Healthy Products*
6. *Development of Sustainable Farming Method*
7. *Healthy Dietary Regimes*
8. *Higher Sustainability Awareness Thus Greater Demand*
9. *Improvement of the Landscape and of the Image of Our Agricultural Sector*
10. *Increase of Environmental Sensibility*
11. *Increased Awareness and Trust of Farmers*
12. *Increased Organic Production (Consumer - Export)*
13. *Increased Worldwide Demand for Organic Products*
14. *Increasing Awareness and Interest in Organic Production*
15. *Independence for Fertiliser*
16. *Public Awareness of Sustainability*
17. *Qualified Employment is Needed to Maintain a Sustainable Conscience*
18. *Raising Awareness*
19. *Sensibilization/Education/Promotion to Work with Alive Soils*
20. *Social Conscience about Use of Renewable Resources*
21. *Society Education about Environmental Problems Related to Agricultural Activity (Rc)*

Political Framework

1. *Administration for Farmer*
2. *Ban on Synthetic Fertilisers*
3. *Certain and Enhanced Regulation of Biomass / BBF*
4. *Certificates and Labels*
5. *Common Agricultural Policy/ Rural Development Programs*
6. *Compensation Measure for Soil C Sequestration*
7. *Design of a Common Regulation in Europe*
8. *Development of Regulation to Promote the Use of BBF*
9. *Economic Help to Develop BBF is Needed*
10. *Economic Sustainability Guaranteed*
11. *Environmental Responsive and Consistent Policies*
12. *Facilitation of Environmental Objectives Required by Legislation*
13. *Future Demands Imposed by Regulation (Water and Carbon Footprint Certifications) (Fa)*
14. *Influence of Lobby Groups*
15. *Intellectual Property Rights*
16. *Lack of Local Regulation*
17. *Lack of Political Will and Regulations to Support These Processes (Production, Distribution, Commercialization)*
18. *Legal Framework to be Develop*
19. *Legislation to Boast the Use of BBF If*

20. *Pressure on Transparency in the Chain*
21. *Protection of European Farmers Vs non-European Farmers*
22. *Raw Material Regulation*
23. *Recognition (Fps Public Health)*
24. *Regulation to Facilitate, Promote and Prioritize the Use of Organic Wastes to Produce BBF (Wp)*
25. *the Primary Sector is not Going to Lose Competitiveness*
26. *Variation in Specific Legislation for BBF*

Fertilizers Market
1. *Affordability of Rbff Production Process*
2. *Assessed Costs/Benefits of BBF*
3. *Competition with Other Fertilisers*
4. *Competitive Market Prices of BBF*
5. *Competitiveness of the Production Chain*
6. *Cost of Mineral Fertilizers*
7. *Cost of the Product (Including Full Production)*
8. *Costs of Production Will Determine Final Price of BBF*
9. *Decrease of the Biowaste Treatment Costs*
10. *Economic Imbalance of Costs of Wastes Management*
11. *Economic Studies Are Needed to Demonstrate Economic Profitability Growing with BBF and Alive Soils (Fa)*
12. *Economical Valorisation of the Food Final Products*
13. *Evolution of the Prices of Agricultural Products*
14. *High Prices of Chemical Fertilizers*
15. *Higher Prices of BBF in Comparison with Inorganic Fertilizers*
16. *Increase of Prices of Inorganic Fertilizers*
17. *Increase of the Price of Mineral Fertiliser*
18. *New Bio-Based Fertilizers Economically Viable Are Needed*
19. *Price of BBF: Competitive?*
20. *Production Costs (Competitors)*
21. *Qualitative Competitiveness*
22. *Reduction in Cost Price of BBF by Reducing Cost Price of Residual Flow*
23. *Remuneration of bio-based Resources*
24. *Valorisation Process must be Economically Sustainable*

Technological Solutions
1. *Accessibility of Technologies*
2. *Availability of Effective Technology*
3. *Availability, Homogeneity, and Stability in Time of Fbb*
4. *BBF Ease of Use*
5. *Continuity and Volumes of Inputs*
6. *Development at Big Scale of Technologies to Reduce Costs of Production of BBF*
7. *Ease of Technology Production*
8. *Efficiency of Technologies*
9. *Enhanced BBF Processing Technology*
10. *Ensuring Consistent Quality of End Product with Changing Input*
11. *Final BBF Consistent with Characteristics of Each Production Area*
12. *Lack of Innovation and Applicable Development of Last Valorisation Processes Developed (Rc)*
13. *Local Availability of Technological Solutions*
14. *Logistic*
15. *Management Methods Viable and Suitable for Private Companies*
16. *Need for Additional Investments*
17. *New Valorisation Processes must be in Agree to the Real Situation of the Agricultural Sector (Fm)*
18. *Nitrogen Level*
19. *Preferable BBF Traits*
20. *Production of Final Stables and Homogeneous BBF*
21. *Rationalization of BBF Production Processes*
22. *Reliability (Efficiency) and Easy to Use*
23. *Reorienting Production Sites Towards BBF*
24. *Risk of Contamination in the Process*
25. *Transportation Logistics*
26. *Used of Technologies not Proven*
27. *Weakly Developed Logistics for Production and Transport*

Innovation Uptake Process
1. *Creation of New Professional Activities*
2. *Farmers' and BBF Producers Mutual Learning and Influence*
3. *Generate the Union of the Different Actors of the Project*
4. *Importance of the Complete Supply Chain - All Components*
5. *Increasing Number of Producer Organizations That Promote the Use of Bio-Based Fertilizers*
6. *Lack of Knowledge about Waste Valorisation Technologies*
7. *Lack of Social Association Associative Willingness to Join These Initiatives*
8. *Low Technical Capacity of Actors Who have to Fuse Technique and Economy*
9. *Networking with Advisory Organizations*
10. *Occurrence of Fertilizers Producers*

Environmental System
1. *Additional Benefits (E.G. Nutrient Input in Soil)*
2. *Assessment of Product Life Cycle Environmental Impact*
3. *Characteristics of Soils at Local Level*
4. *Greenhouse Gases*
5. *Impact of Climate Change on Soil*
6. *Improvement on Food Consumption and Yield Obtained*
7. *Nutrient Balance in Soil and Surface Water.*
8. *Optimization of Residues Management*
9. *Reduction of Vegetal Effluents*

Bioeconomy Patterns
1. *Availability and Quality of Biomass*
2. *Boom of BBF Industry and Circular Economy*
3. *Competition in Residual Flows*
4. *Competition with Other Processing Options for Residual Flows*
5. *Increased Demand bio-based Resources*
6. *Lack of Recycling Culture*
7. *Lack of Research on Waste Characterization and Utilization*
8. *Low Availability of Sources (Different to Sugarcane) and Raw Materials*
9. *Measures Favouring Circular Economy (Green Deal)*
10. *Raw Materials (Residues) Are Readily Available*
11. *Role (Involvement) of Large Retail Chains as Waste Provider*
12. *Seasonality and Variation of Volume of Vegetable Residues Produced*
13. *Seasonality of Waste Production*
14. *Shift Towards a Circular Approach*
15. *Strength of Circular Economy*
16. *Sufficient Raw Material*

Source: own elaboration

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Is there an Animal Food Kuznets Curve, and does it matter?

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Abstract. Proteins from animal sources, including meat, and plant-based foods are essential for a healthy human diet. However, animal-based proteins have significantly higher environmental impacts (e.g., greenhouse gas emissions, deforestation, and water usage) and health risks (e.g., obesity, type 2 diabetes, kidney stones and cardiovascular diseases) compared to plant-based proteins. The consumption patterns of these proteins are strongly influenced by income levels. This study introduces the concept of an Animal Food Kuznets Curve by systematically analyzing the relationship between income and animal-based protein consumption. Utilizing a novel panel dataset spanning 28 years and covering 79 countries, we uncover an inverted U-shaped relationship between income and the consumption of animal-based and meat proteins. Our findings indicate that the turning points occur around 43,000-45,000 US$, corresponding to the 90th and 95th percentiles of the per capita income distribution in the sample. At these income levels, protein consumption is estimated at approximately 25 g/day for meat and 52 g/day for animal-based proteins, as compared to recommended total protein intake of 45-56 g/day. These insights highlight the critical need for targeted policy interventions, such as taxes, nudges, and informational campaigns to promote sustainable dietary choices across all income levels. Our study provides empirical evidence for the importance of integrating economic and environmental policies to enhance global food sustainability.

Keywords: protein consumption, consumption drivers, Environmental Kuznets Curve, mixed effects model, panel data.
JEL Codes: Q54, Q56, C23.

1. INTRODUCTION

Over the past 50 years, the global consumption of animal-based proteins, including meat, eggs, dairy, and seafood, has significantly increased in both absolute and per capita terms (Bonnet et al., 2020; Marques et al., 2018; Pais et al., 2021). This growth has been mainly driven by increased meat consumption (Bonnet et al., 2020; Sans and Combris, 2015). According to OECD and FAO (2023), global per capita meat consumption has nearly doubled, rising by 87 percent from about 23 kg per person per year in 1961 to 43 kg per person per year in 2021. Similarly, other animal-based foods have seen increases, with milk consumption by 16 percent and egg consumption by 129 percent. This tendency is in accordance with the nutrition transition featuring increasing demand for animal-based foods when income rises (Popkin, 1993). However, diets rich in animal-based protein have been linked to adverse health and environmental outcomes (Tilman and Clark, 2014), while diets with a higher composition of plant-based proteins are associated with less damaging impacts (Galli and Moretti, 2024). Several studies have called for urgency in shifting protein consumption from animal-based sources to plant-based sources (Willett et al., 2019), especially in upper-middle income countries with sustained economic growth rates (Duro et al., 2020). Indeed, the increase in global meat consumption (kg/year per capita) between 1961 and 2021 has been driven mainly by countries with rapid economic growth such as South Korea (1,935 percent), China (1,774 percent) and Indonesia (398 percent). Several studies have demonstrated that the first global protein transition, marked by a significant increase in demand for animal-based protein over the last century, was closely linked to changes in real income (Sans and Combris, 2015). The more recent second nutrition transition, characterized by a stabilization or decline in animal-based protein consumption, particularly meat (Godfray et al., 2018; Marques et al., 2018; Vranken et al., 2014), may also be attributed to similar factors. Economic growth has initially promoted animal-based consumption and then it has slowed it down. This brought some scholars to claim the existence of an Environmental Kuznets Curve (EKC) for animal-based food consumption, which could be named Animal Food Kuznets Curve (AFKC). According to the EKC original theory, the environmental impact of economic growth increases in the first phase and subsequently declines (Grossman, 1995; Grossman and Krueger, 1991). If such a trend proved true for animal-based food consumption, it would decrease the urgency of policies aiming at curbing its consumption since income growth would automatically lead to its decline. Nevertheless, the existence of an AFKC is to be empirically verified, and its actual effect on global consumption is to be assessed.

This paper aims at investigating interactions between protein consumption and income over the last 30 years. The research uniquely analyses protein intake from animal-based, meat and plant-based sources to understand the dynamics of change and the predominant factor of variation, i.e., income. While the existing literature has predominantly focused on meat consumption and its correlation with income (York and Gossard, 2004; Vranken et al., 2014), there is a noticeable gap concerning the consumption of protein from different sources. This paper aims to bridge this gap by comprehensively exploring differences in protein consumption across animal-based, meat and plant-based sources using a global panel dataset covering 28 years and 79 countries. The originality of this study is further highlighted by the application of the linear mixed effect model. This methodological advancement addresses cross-sectional dependence in errors within large panel datasets, thus enhancing the accuracy of parameter estimates compared to conventional fixed effects models.

2. NEGATIVE IMPACTS OF ANIMAL-BASED PROTEIN CONSUMPTION

Animal-based products are an essential source of nutrients – proteins, among others – to humans. However, among protein-rich foods, those of animal-based sources produce higher greenhouse gas (GHG) emissions (Dyer and Desjardins, 2022; Errickson et al., 2021), use more land (Van Zanten et al., 2018) and water (Mekonnen and Gerbens-Leenes, 2020), cause more acidification and eutrophication (Godfray et al., 2018; Poore and Nemecek, 2018). Among animal-based foods, meat has a higher environmental damage potential than those derived from eggs, milk and seafood (de Vries and de Boer, 2010). Among meats, beef proteins have the highest impact on the environment (de Vries and de Boer, 2010; Gaillac and Marbach, 2021).

There is an urgent need for transitioning to more sustainable protein sources, such as protein of vegetal sources – pulses, legumes and novel protein-rich foods (McClements and Grossmann, 2021) – which have a lower environmental impact (Mazac et al., 2022). Plant-based diets can reduce GHG emissions by 49%, land use by 76%, scarcity-weighted freshwater withdrawals by 19%, acidification by 50% and eutrophication by 49% (Poore and Nemecek, 2018).

Another reason to reduce consumption of animal-based products, particularly meat, is related with the potential adverse effects of its excessive consumption on human health. A higher availability of animal-based protein consumption would benefit food-insecure countries, where fewer alternatives are available to access nutrients and micronutrients. Here, a higher animal-based protein consumption would increase food and nutritional security. By contrast, the developed world, if anything, consumes an excessive amount of proteins (Aiking and de Boer, 2020). For instance, while the Lancet Commission on healthy diets suggests that an "adequate protein intake for adults is 0.8 g/kg bodyweight, which is 56 g/day for a 70-kg individual" (Willet et al., 2019) and the European Food Safety Authority (EFSA) sets an average requirement intake of 46 g protein per capita per day (Agostini et al., 2012), protein intake in the EU is around 82 g per day, of which 49 g from animal-based sources and 33 g from plant-based sources (Simon et al., 2024). This aspect highlights substantial inequalities of the food systems between developing and developed world, and also represents an increased risk for human health. Meat consumption contributes to global obesity (You and Henneberg, 2016), higher risks of type 2 diabetes (Malik et al., 2016), kidney stones (Asoudeh et al., 2022), cardiovascular disease mortality (Zheng et al., 2022), cancer mortality (Huang et al., 2021) in the specific, colorectal, breast and prostate cancer (Cellura et al., 2022; Gonzalez et al., 2020) and more generally all-cause mortality (Sun et al., 2021). Conversely, diets rich in plant-based proteins, such as legumes, nuts and seeds, while sufficient to achieve full protein adequacy in the developed world (Mariotti and Gardner, 2019), seem to confer protection against the incidence of cancers (Gonzalez et al., 2020) and to reduce global mortality (Springmann et al., 2016). Increasing the share of plant-based proteins will provide significant health and environmental co-benefits (Bonnet et al., 2020; Stylianou et al., 2021). This study aims to assess the relationships between income and different protein sources to highlight potential differences that can be useful to understand the impact of policies. The paper will discuss the relationship between food consumption and income using existing literature, which, however, rarely took into consideration protein sources other than meat, and explains the theory behind the model in Section 3. We will then outline the data and the econometric strategy we chose to apply to describe this relationship in Section 4. The results of the estimated models are presented in Section 5 and their implications are discussed in Section 6 and 7.

3. THE RELATIONSHIP BETWEEN ANIMAL-BASED PROTEIN CONSUMPTION AND INCOME

Rising real Gross Domestic Product (GDP at constant prices) over the last century has been identified as the root-cause of a global nutrition transition. The transition encompasses a shift towards animal-based sourced proteins in general (Gerbens-Leenes et al., 2010; Sans and Combris, 2015) and proteins from meat in particular (Milford et al., 2019; York and Gossard, 2004). As income increases, consumers tend to shift their dietary preferences toward more resource-demanding foods (Tilman and Clark, 2014). This transition is taking place at different stages and paces worldwide (Gerbens-Leenes et al., 2010). Consumption of animal-based foods is much higher in developed countries than in developing and least developed countries. However, the upward trend is more pronounced in developing countries (Henchion and Zimmermann, 2021), where the rise above the poverty line occurs at a faster pace than it did in developed countries (Sans and Combris, 2015; Drewnowski and Poulain, 2018). Meanwhile, in higher income countries a "second nutrition transition" seems to occur (Pais et al., 2021; Vranken et al., 2014). In these countries, the consumption of animal-based proteins, especially from meat, seems to stagnate or decline when reaching a high level of income. Vranken et al. (2014) and Cole and McCoskey (2017) have therefore found evidence of an inverted U-shape relationship between meat consumption and income, indicating that the consumption of unsustainable proteins could reach a maximum and then decline. Therefore, these studies suggested that meat protein consumption follows an EKC. Arguably, the reasons for an AFKC differ from those of the EKC. The latter is justified by the increasing environmental impact of the shift from an agricultural to an industrial economy, followed by a decreasing impact due to resources-saving technological progress and increasing environmental awareness. In the case of the AFKC, the same reasons do not apply, and the determinants have to be ascribed to the factors mentioned above.

The reasons behind this decline can be attributed to several factors: i) increasing awareness of the health risks associated with high meat consumption, ii) concerns about the environmental impact of meat production, including greenhouse gas emissions, deforestation, and water usage, iii) growing awareness of animal welfare, iv) the rising availability and popularity of plant-based meat alternatives, v) the spread of popular dietary trends, such as vegetarianism, veganism, and flexitarianism.

We therefore present a model of animal-based food consumption that incorporates the above reasons for an inverted U-shaped consumption-income pattern for animal-based food (AF) consumption. The theoretical model sheds light on past trends in AF consumption and the reasons that render possible an AFKC. Nevertheless, while the model may justify the existence of an AFKC, it does not predict it unequivocally.

The model (for a formal presentation see Appendix 1) assumes that utility from AF consumption has two components. The first one directly stems from its consumption per se, due to its taste and appetite value. Utility is therefore a positive function of animal-based food consumption, so that its marginal utility is positive, but decreasing, due to increasing satiation: additional AF consumption provides less and less additional utility. The second component is the nutritional and health one. According to the nutritional literature, consumption of animal-based proteins has initially a positive effect on nutrition and health (receding from famine, mortality declines, see e.g., Mathijs, 2015) but, at higher levels, it brings several adverse health effects (e.g., cardiovascular risks, obesity-related issues). Hence, if consumers are aware of and care about the negative impacts of high animal-based food consumption on health, this component of utility has an inverted U-shape. In addition, as mentioned above, concern for animal welfare and for the environment can be reasons for a lower utility associated with large animal-based food consumption (Frank, 2008). In this model, for simplicity we include these effects in the health one.

The model assumes that a consumer maximizes his/her utility subject to a budget constraint. The equilibrium condition states that the marginal utility from AF consumption per se, plus the marginal utility stemming from the variation in nutrition-health due to the effect on consumers' health of an additional AF consumption, equals the additional utility that could be drawn from other goods that could be purchased with the animal-based food price, i.e., the marginal opportunity cost of AF.

The marginal utility of AF consumption per se decreases when AF increases, and reaches a lower bound at zero for satiation, when further consumption provides no additional utility. The marginal utility from nutritional-health benefits also decreases with AF consumption and remains positive as long as the marginal health benefit is positive, then it becomes negative. When the marginal health benefits, at high consumption levels, become negative, they may determine a decrease in overall utility if disutility from health damages prevails over utility due to taste. In this case, an inverted U-shape of the income-consumption relationship results.

The model implies that a decrease in the AF price relative to all other prices (i.e., a decrease in real AF price) leads to higher AF consumption. This explains what actually happened in the past (FAO, 2009) when the relative price of AF declined with reference to other food prices.

The crucial question for the existence of an AFKC is nevertheless the shape of the relationship between income and AF consumption. Among necessities, animal-based food is more expensive than plant-based food. At low-income levels, a higher income allows a shift from cheap staple food to animal-based food, as empirically observed in all countries in the initial stages of development and as a general trend in the recent decades (Sans and Combris, 2015; Delgado et al., 2009; among others).

However, the model cannot unambiguously predict a priori whether a further income growth leads to an increase or decrease of AF consumption, because the resulting equilibrium will depend on how the marginal utilities of AF of other consumptions and of nutrition-health react to income, and on their interrelationships. The model allows for the existence of an AFKC, but does not imply its necessity. The form of the income-AF consumption relationship has therefore to be determined empirically.

Plant-based protein consumption also increases with income at the initial stages of development. However, its increase is presumably slower than the one of animal-based proteins, since income growth allows consumption of the more expensive animal-based proteins, so that in the diet the share of animal-based proteins grows. If consumption of animal-based proteins declines at high income levels, it is possible that plant-based protein consumption will increase as a substitute. The relationship between plant-based protein consumption and income must also be determined empirically.

4. MATERIALS AND METHODS

4.1. Variables and data

We employ a balanced panel dataset covering 79 countries from 1991 to 2018 (Table A.1 in Appendix 2). We draw on data from the Food and Agriculture Organization (FAO) New Balance Sheets (NBSs; FAO, 2021), where food supply quantities are used as proxies for consumption (Cole and McCoskey, 2017; You and Henneberg, 2016). These quantities are measured in grams per capita per day and reflect food reaching consumers, with the caveat that actual consumption may be lower due to waste and spoilage during preparation. The study classifies protein consumption into three types: "meat protein" from poultry, pork, goat, mutton and bovine; "animal-based protein" encompassing all animal products including dairy and eggs; and "plant-based protein" derived from cereals, vegetables, fruits, beans, nuts, seeds, roots and spices.

We explore potential determinants of protein consumption across three principal dimensions: economic, socio-cultural, and land use. In the economic dimension, the primary focus is income expressed by GDP per capita (p.c.) at chained Purchasing power parities (PPPs) measured in million constant 2017 US$. The data are collected from the Penn World Table (Feenstra et al., 2015), a set of national-accounts data to measure real GDP across countries and over time. In the presence of an inverted U-shape, i.e. Kuznets curve, we expect positive estimated coefficients for the linear terms and negative coefficient for the quadratic terms. In addition to income p.c., we recognize the substantial influence of food prices on protein consumption patterns. To capture this influence, we build national price indexes using data from FAOSTAT (FAO, 2022b). Specifically, we select the price of the most consumed item within each of the three protein sources (meat, animal-based and plant-based) for every country and year under study and build an index using the first year of the time series (1991) as base year. This approach aims to quantify how variations in food prices across different protein sources impact dietary choices and consumption behaviors globally. Indeed, our hypothesis is to observe a negative coefficient for the price index meaning that an increase in prices determines a reduction in protein consumption. In addition to own price for each protein source, we have also tested relative prices. In fact, as suggested by FAO (2009) over the last 50 years there has been a decline in the prices of livestock products relative to those of other products, making consumption of animal-based and plant-based foods more affordable than meat even without rising income. A third economic variable used in our empirical application is the trade openness, built as the ratio of imports and exports over national GDP. Our hypothesis is to observe a positive effect of trade on the three proteins consumption due to the likely larger availability of different products and thus protein sources.

Beyond economic factors, social and cultural influences could also shape protein consumption patterns. We integrate several key variables to explore these dimensions. First, the religious beliefs were incorporated by using the percentage of population adhering to Islam as a proxy to understand dietary restrictions that may affect consumption preferences, for example by reducing meat consumption and increasing plant-based protein intakes. Second, we integrate the percentage of women participating in the labour force as an indicator of evolving food preparation practices. Third, the percentage of adults with tertiary education levels is used to capture the influence of educational attainment on dietary preferences and awareness of nutritional choices, potentially affecting protein intake patterns. We hypothesize that more educated people tend to prefer diets with more plant-based food for both health and environmental concerns. However, we are aware that education is strongly correlated with income levels.

Finally, to further explore other contextual conditions likely influencing protein consumption, the study includes two proxies of land use: the harvested area per capita as a measure for the relevance of the agricultural sector for self-provision of proteins and the percentage of the population living in urban areas. These variables are used to examine the impact of urbanization on dietary habits and access to diverse food options, including protein sources.

Table 1 provides a comprehensive list of variables used in the study, and their descriptive statistics and sources. Unlike the typical practice in Environmental Kuznets Curve (EKC) literature, the study uses variables in their original levels instead of logarithmic transformations, aligning with findings by Hasanov et al. (2021).[1]

4.2. Econometric strategy

Since the mid-1950s, scholars testing the Kuznets Curve (KC) hypothesis on various environmental and non-environmental indicators have primarily used cross-sectional data and longitudinal data with fixed effects estimators (e.g., Vranken et al. (2014) for consumption of meat protein). However, traditional panel data estimators assume cross-sectional independence, basing the models on homogeneous coefficients and yielding inconsistent estimated parameters (Heck and Thomas, 2020).

Indeed, cross-sectional units may exhibit shared characteristics, such as spatial effects, omitted common factors, or socioeconomic networks interaction leading to cross-sectional dependence, calling for estimators that account for intercepts and slopes heterogeneity. The literature on heterogeneous panels has evolved along two main strands: i) the application of mean group (MG) estimators (Pesaran and Smith, 1995) and subsequent modifications (Augmented MG and Common Correlated Effects MG; Teal and Eberhardt, 2010), ii) the application of multilevel or mixed effect models to panel data (McCulloch et al., 2001).

The key distinction between panel models (such as MG estimators) and mixed effects models lies in the treatment of the independent variables. In mixed effects

[1] Hasanov (2021) argues that in non-linear logarithmic Environmental Kuznets Curves (EKC), the signs of estimated coefficients and the statistical significance of lower-order polynomial terms can vary arbitrarily based on the units of measurement chosen for the independent variables. Consequently, Hasanov suggests that researchers should first study the EKC in levels considering the potential issues with the logarithmic specification.

Table 1. List of variables with descriptive statistics.

Variable	Description	Mean	Std.	Min	Max	Source
Dependent variables						
MeatProt	Per capita Meat-based Protein consumption (g/day)	16.4	11.1	1.2	46.9	FAO (2021)
AnimalProt	Per capita Animal-based Protein consumption (g/day)	35.2	21.4	3.2	79.7	FAO (2021)
PlantProt	Per capita Plant-based Protein consumption (g/day)	44.0	10.1	22.9	82.7	FAO (2021)
Independent variables						
GDPPc	Per capita expenditure-side real GDP at chained PPPs (000 US$)	16.6	16.3	0.4	90.3	Penn world table (Feenstra et al., 2015)
GDPPc^2	Squared GDPPc	541.7	880.9	0.2	8154.2	Penn world table (Feenstra et al., 2015)
Price Index	Animal-based products	0.99	0.16	-0.88	2.65	
	Meat products	0.98	0.17	-0.45	2.50	
	Plant-based products	1.11	0.52	-2.73	4.67	FAO (2022b)
Trade	(Imports+exports) / GDP (%)	68.7	34	13.8	227.4	World Bank (2022a)
Education	Share of post-secondary education (%)	10.2	8.9	0.15	48.3	World Bank (2022b)
PerMus	Share of Muslims over population (%)	23.4	35.7	0	99.8	ARDA (2022)
PerFemWork	Share of female employment (%)	40.2	9.3	10.7	56	World Bank (2022c)
Urbanization	Share of people living in urban areas (%)	58.6	22.2	5.5	95.3	World Bank (2022d)
HarvArea	Harvested area/population (per capita ha)	0.172	0.2	0	1.4	FAO (2022a)
N. obs.	*2212*					
N. groups	*79*					

Sources: FAO, Penn World Table, World Bank, ARDA and own calculation.

models, independent variables are treated as non-random variables, whereas in panel data models, they are always assumed to be random. Another significant difference is in estimating the average effects (invariant between individuals) and individual (or random) effects. In the case of MG estimators, individual-specific ordinary least-squares (OLS) regressions are estimated then the individual-specific parameters are averaged across the panel to determine an overall effect. In the case of mixed effect models, the estimated parameters are the common effect with the random effects representing individual deviations from this average, inferred from estimated variances and covariances (Dinda, 2004).

A meta-analysis conducted by Saqib and Benhmad (2021) on more than five hundred studies concluded that the econometric strategy does not significantly impact the test of the EKC hypothesis. However, they highlighted the greater reliability of longitudinal data and the robustness of methods that deal with heterogeneous panels such as MG estimators and mixed effect models.

In this paper, we employ a mixed effect model because of our focus on the variation in regression coefficients rather than a global behaviour as an average of country-specific dynamics. Country-specific estimates, limited by the income ranges, cannot properly identify the curvature of a general function. To account for intercept and slopes heterogeneity in parameters the unknown parameters are decomposed in a fixed term γ (constant across countries) and a random term δ (specific for each country). Thus, the relationship between protein consumption per capita (animal-, plant-based and meat) and GDP per capita is modelled as:

$$(Proteins/P)_{it} = (\gamma_{s0} + \delta_{si0}) + (\gamma_{s1} + \delta_{si1})\ (GDP/P)_{sit} + (\gamma_{s2} + \delta_{si2})\ (GDP/P)^2_{sit} + \Sigma^{J}_{j=3}\ \beta_{sij}X_{sitj} + \varepsilon_{it} \quad (1)$$

where $s= a,m,p$ identifies the protein source (animal-, plant-based and meat), $i=1,\dots,N$ indicates the countries, $t=1,\dots,T$ the time periods, GDP is defined as above and P is population, X_j the j-covariates. Note that $\frac{GDP^2}{P}$ represents the potential non-linear effect of GDP per capita on proteins consumption and it is used in the Kuznets framework to check the inverted U-shaped curvature of the relation.

This model has been estimated using maximum likelihood estimators for the three sources of protein (Rabe-Hesketh and Skrondal, 2008) and likelihood-ratio tests have been employed to compare different models and to validate the use of random coefficients. Moreover, the models are first estimated with an unstructured random-effects covariance matrix, which allows for distinct variances and covariances between all random-effects covariates. However, inconsistent estimations for the plant-based protein model necessitated an identity covariance structure, assuming equal variances.

According to the literature on testing the nature of the time-series to select the appropriate panel estimator (Perman and Stern, 2003; Eberhardt, 2012), the model of equation [1] was tested relative to: i) cross-sectional dependence; ii) presence of unit roots (i.e., stationarity); iii) long-run relationship (i.e., cointegration).

To select the appropriate test for investigating unit roots, we initially checked the cross-sectional dependence of the series using the Pesaran test (Pesaran, 2021) under the null hypothesis of cross-sectional independence. Most variables exhibited cross-sectional dependence (except for trade) (see Table A.2 in Appendix 3). Subsequently, we tested the stationarity of the series by implementing the modified pCADF test (Costantini and Lupi, 2013) which consider cross-sectional dependence under the null hypothesis of non-stationarity. The results suggested that the null hypothesis of non-stationarity can be rejected only after transforming the series in their first differences except for the urbanization rate and the education (Table A.3 in Appendix 3). Then, we checked the cointegration assumption to prevent the regression from providing biased statistical evidence of the relationship among variables. Cointegration was investigated through various tests, including the Phillips-Perron, the Modified Phillips-Perron, the Augmented Dickey-Fuller tests (Pedroni, 1999; Pedroni, 2004) and the so-called Westerlund test (Westerlund, 2005) by assuming the presence of cross-sectional dependences (Table A.4 in Appendix 3). The rejection of the null hypothesis of all these tests indicates that our models are cointegrated. The findings support the selection of the mixed effect model as appropriate to estimate heterogenous coefficients for intercepts and slopes.

5. RESULTS

Table 2 presents the estimated coefficients of the model of meat animal-based and plant-based protein consumption which exhibit overall significance. Likelihood-ratio tests have been applied to compare different models and different covariates. Education and urbanization rate turned out to be non-stationary even when transformed in their first differences and were therefore not used to avoid spurious estimated coefficients (see Table A.3 in the Appendix 3). Prices for the three protein sources are not statistically significant and hence are not included in our preferred specification in Table 2 (see Table A.5 for the estimated coefficients of model including prices).[2] Table 2 also reports the estimated standard deviations for the intercept, the GDP per capita and the GDP^2 per capita coefficients. All of these standard deviations are statistically significant, indicating the intercept and slopes heterogeneity and thus supporting the use of the mixed effects model.

The most important determinant of meat protein consumption is per capita income, with both its estimates of the linear and the quadratic term highly significant. The estimates indicate that a thousand dollar increase in per capita income induces a 0.725 g/day increase in meat protein consumption. Notably, the negative sign of the squared term suggests that meat protein consumption does increase with income, but at a decreasing pace.

Among the variables aside from income, the Trade and the percentage of Muslims are significant. Specifically, every additional percentage point in the ratio of imports plus exports over GDP implies a 0.008 g/day increase in the average meat protein consumption. A percentage point increase in the share of Muslims over the population translates into a 0.11 g/day decrease in the average meat protein consumption, ceteris paribus. These results are consistent with Andreoli et al. (2021) and Milford et al. (2019). Female participation, however, does not show statistical significance, as in Milford et al. (2014).

The positive sign of the GDP parameter and the negative sign of the GDP^2 parameter, both significant, suggest the existence of an inverted U-shaped relationship, thus supporting the existence of an AFKC where meat protein consumption increases with per capita income up to a maximum before decreasing. A crucial point for assessing the policy implications of the AFKC is nevertheless determining the level of the turning point. This can be calculated as $-\hat{\gamma}_1/(2 \bullet \hat{\gamma}_2)$ where $\hat{\gamma}_1$ is the estimated parameter of per capita income and $\hat{\gamma}_2$ the estimated parameter of its square.[3] This simple calculation results in a turning point of 42,923 US$,[4] located between the 90th and the 95th percentiles of the per capita income distribution in the whole sample, and above the 80th percentile of the income distribution in the last year of the panel (2018). It could be argued that the turning point should also be estimated consid-

[2] We used version 18 of STATA for Windows to carry out the analysis of the data in this paper. The mixed command has been used to estimate the mixed models presented in Table 2.

[3] The formula for the maximum income in the estimated second-degree equation is obtained by setting the derivative of the equation to zero and solving for the income variable.

[4] To present a more concise table of results, the coefficients have been rounded to three decimal places. Consequently, the turning point value derived from rounded coefficients differs from the one presented in the text, which uses estimated coefficients to six decimal places.

Table 2. Results of the models of protein consumption.

Indep. variables	Dependent variables					
	Meat Protein		Animal-based Protein		Plant-based Protein	
	Coef.	Std.Err.	Coef.	Std.Err.	Coef.	Std.Err.
GDPPc	0.725***	0.135	1.255***	0.206	1.506***	0.419
$GDPPc^2$	-0.008***	0.003	-0.015***	0.004	-0.003	0.002
Trade	0.008***	0.003	0.019***	0.005	0.032***	0.005
HarvArea	1.097	1.317	1.930	1.863	-15.479***	1.739
PerMus	-0.105***	0.0281	-0.177***	0.484	0.212***	0.421
PerFemWork	-0.008	0.033	0.058	0.048	0.113**	0.046
Constant	11.092***	2.191	25.517***	3.689	30.675***	2.613
sd(GDPPc)	1.086	0.124	1.686	0.161	3.644	0.361
sd($GDPPc^2$)	0.021	0.006	0.030	0.004	0.005	0.002
sd(Constant)	13.364	1.414	25.170	2.378	12.892	1.120
sd(Residual)	1.541	0.028	2.167	0.035	2.093	0.034
N. obs.	2212		2212		2212	
N. groups	79		79		79	
Wald Chisq(6)	78.33***		108.10***		194.50***	
Log likelihood	-4533.46		-5302.99		-5300.83	

*, **, *** indicate that statistics are significant at the 10%, 5% and 1% level of significance respectively.

ering the variation of the estimated parameters. Unfortunately, the turning point results from the ratio of two normal random variables, which results in a Cauchy distribution, whose expected value and variance are undefined. However, its mode and median are defined, and the distribution is symmetrical. We therefore perform a Monte Carlo simulation of the median turning point. We randomly draw couples of $\hat{\gamma}_1$ and $\hat{\gamma}_2$ parameters from a bivariate normal distribution, calculate the turning point, repeated for 1000 draws, and individuate the median turning point of these simulations. By repeating the procedure 10,000 times we obtain an empirical distribution of the medians, from which we calculate their mean and standard deviation. The result of 42,891 US$ is sensibly similar to the simple calculation from the estimated parameters. The standard deviation is relatively modest, 318 US$, and the range went from a minimum of 41,867 to a maximum of 44,159 US$. The minimum value is around the 90th percentile.

Comparisons with previous studies reveal similar turning point estimates, i.e. 46,000-66,000 constant 2017 International US$ p.c. (Andreoli et al., 2021); 36,375-49,848 constant 2005 US$ p.c. (Cole et al., 2013); 35,000-53,000 constant 2005 international US$ p.c. (Vranken et al., 2014), indicating consistency across analyses. However, employing mixed effects models alongside Monte Carlo simulation produces more efficient estimates with reduced variability.

Table 3. Predicted protein consumption at the turning points.

	Meat Protein	Animal-based Protein
Mean	24.61	51.62
Min	16.16	35.02
Max	29.57	61.96
Mean-SD	20.45	43.79
Mean+SD	28.76	59.45

Furthermore, the results allow us to predict the meat protein consumption corresponding to the turning point, by using the estimated parameters and the per capita income of the turning point and setting the other variables at their mean. To appreciate the variation of the prediction, we also calculate the predicted consumption when the other variables are taken at the minimum and maximum of their observed values,[5] and when they are taken at their mean plus/minus their standard deviation. Table 3 presents the results.

The calculated meat protein consumption at the income turning point and the mean of the other variables is 24.61 g/day, slightly below the 75th percentile. The maximum value (29.57 g/day) is between the 85th

[5] When calculating the maximum and minimum consumption, variables with a negative parameter were taken as positive, so to identify the maximum possible range.

and the 90th percentile, while the minimum (16.16 g/day) is between the 55th and the 60th percentile.

The results of the model of animal-based protein consumption (Table 2) are similar to the ones of meat protein consumption, as meat constitutes about 30 percent of total animal-based protein intake. The Trade variable has a significant and positive impact on consumption, higher than for meat (every additional percentage point in the ratio of imports plus exports over GDP implies a 0.019 g/day increase in the average meat protein consumption). Similarly, the share of Muslims over the population is significant and negative, suggesting that a 1 percent increase in the share generates 0.17 g/day decrease in animal-based protein consumption. Both per capita income and its square estimated parameters are significant, with larger absolute values than the respective parameters of meat consumption, thus suggesting a more rapid increase but also a faster slowing down of the growth. The turning point is located at 41,928 US$, slightly lower than the turning point of meat consumption, but still within the 90th and the 95th percentile of income distribution. Strictly considered, the results indicate that the consumption of animal-based products other than meat start declining at a lower income level than meat consumption. However, the small difference in the turning point, along with the likely variation in the estimates, suggest that in practice there is no appreciable difference in the behaviour of meat relative to the other animal-based proteins.

Animal-based protein consumption at the turning point, calculated as above (Table 3), is 51.62 g/day, falling between the 70th and 75th percentile, for the whole panel and 2018. The maximum (61.95 g/day) and the minimum (35.02 g/day) values are located over the 80th percentile and between the median and the 60th percentile, respectively, for both the panel and the 2018 distribution. Also, it should be considered that the adequate total protein intake for average adults suggested by the Lancet Commission on healthy diets is 56 g/day (Willet et al., 2019) and the average requirement intake set by the EFSA is 46 g total protein per capita per day (Agostoni et al., 2012).

In contrast, the results of the model for plant-based proteins (Table 2) differ from the previous ones mainly in the fact that the quadratic term of GDP turns out not to be statistically different from zero, meaning that the AFKC hypothesis is not confirmed in this case and that plant-based protein consumption increases linearly with income. Among the other estimated coefficients, the openness to international trade positively influences plant-based protein consumption, possibly due to the exposure to consumption models or via their increased availability. Every additional percentage point in the ratio of imports plus exports over GDP implies a 0.03 g/day increase in the average plant-based protein consumption. The per capita harvested area negatively impacts plant-based protein consumption, as one per capita hectare more induces a decrease of consumption of 15.5 g/day.

Nevertheless, one per capita hectare is more than 5-fold the average (0.17), so the size of the estimated parameter should be related to the one of the marginal effects in the covariate. A possible -admittedly questionable- explanation of this counterintuitive finding is that when more land is available it is mainly devoted to cereal crops rather than pulses. Consistently with the negative effect on animal-based protein consumption, the share of Muslims over the population has a positive and significant effect, as a one percent increase of their share induces a 0.21 g/day increase in the average plant-based protein consumption. Since the squared per capita income parameter, although exhibiting a negative sign, is non-significant, no turning point can be consistently predicted, with plant-based protein consumption increasing linearly with income, at a rate of 1.50 g/day increase for every additional thousand dollars.

6. DISCUSSION

The empirical results suggest the existence of an inverted U-shaped relationship between animal-based and meat protein consumption and per capita income and a linear relationship between per capita income and plant-based protein consumption. Both models of animal-based and meat protein consumption capture an initial increase in the amount of protein from these sources as income grows. Taste, appetite and the need to increase protein consumption for optimal nutrition can also be considered responsible for this initial increase. As consumers have a rising purchasing power from a growing income, they diversify their bundle of goods and increase their consumption of foods rich in proteins, as also observed by the theory of nutrition transition (Popkin, 1993). In particular, within the diet composition, the animal-based food proportion increases and the plant-based one decreases, as shown by all historical records. However, the historical experience of developed countries shows that consumption keeps increasing until it reaches an amount that may cause negative externalities, consistently with the theoretical model presented.

Nevertheless, we found that the inversion of the trends is predicted at very high-income levels. This is consistent with both the assumption of the positive effect of income on the taste-appetite driver of consumption and with the negative health effects at high income levels.

Our investigation also found a linear increase of plant-based protein consumption with income. The increase of plant-based protein consumption is lower than that of animal-based and meat but it is continuous. It is possible in fact that when animal-based and meat protein consumption decline plant-based proteins act as substitutes. In fact, the popularity of novel protein consumption with plant-based origins has been recently observed (McClements and Grossmann, 2021).

A somewhat counterintuitive result is that meat protein consumption actually starts declining at a slightly higher income level than animal-based protein consumption. A tentative explanation can relate these trends to a composition effect of rising incomes. At low-income levels, a rising income allows consumption of “non-meat” animal-based proteins (eggs, dairy, fish, etc., generally cheaper than meat) in addition to plant-based ones, as also suggested by the higher income parameter of animal-based than meat protein consumption. As income further rises, meat consumption becomes affordable, and substitutes for “non-meat” animal-based protein consumption, up to the point that the latter starts to decline. This has been empirically observed before (e.g., see Akpalu and Okyere, 2022) and is consistent with the theory of nutrition transition (Dagevos and Voordouw, 2017).

The high level of the turning points, especially the one of meat protein consumption, have important sustainability implications related to the environment and health, with significant consequences for policy makers. Even though the consumption of unsustainable protein reaches a peak and decreases, the peak is at a very high level of income. The majority of the world population is positioned well below the income turning point and still has a long way to go before it reaches the level that, according to our results, decreases the consumption of unsustainable proteins. Thus, the global level of meat and animal-based protein consumption is expected to grow for at least the near future and with that, the impacts on health and the environment. Hence, income growth does not warrant a decrease in animal-based protein consumption sufficient to curb its environmental impact.

7. CONCLUSIONS AND POLICY IMPLICATIONS

This study analysed how animal-based protein consumption is determined by per capita income. We modelled this relationship empirically through a panel of 79 countries over 28 years, distinguishing between meat and more generally animal-based proteins. In addition, we also modelled the relationship between plant-based proteins and per capita income.

Our main goal was determining whether an Animal Food Kuznets Curve (AFKC) exists, according to which animal-based protein consumption increases with income and then declines. Our results suggested that an AFKC exists, since the estimates show an initial increasing and then decreasing significant trend of animal-base food (AF) consumption relative to real income. It was also possible to calculate the per capita income level at which AF protein consumption starts to decline, corresponding to 42-43,000 US$, i.e., over the 90th percentile of the per capita income distribution. By contrast, plant-based protein consumption monotonically increases with income.

Some limitations of this study are acknowledged. We tried to build indexes for prices using the price of the most consumed item in every type of protein source, but they turned out to be non-significant, so we were forced to proxy them with variables whose relationship with prices could be weak. Other explanatory factors, in particular income, have had a much more pronounced effect on animal-based foods consumption than prices, resulting in the limited influence of prices on protein consumption found in this study and previous literature (inter alia Mildford et al., 2019). We adopted Mildford et al.’ (2019) argument that in addition to income, natural conditions can be an important determinant of protein consumption. We therefore included per capita harvested area as a control, like Cole and McCoskey (2017). The socio-cultural determinants of diets are arguably important and, even if we tested several, most were correlated with income and others were not significant. This may be due to the inadequacy of those variables to represent the actual socio-cultural determinants.

Despite these limitations, this study is consistent with previous literature and has important policy implications. The policy interest in detecting an AFKC is because such a trend, in principle, would decrease the concern for the environmental and health impacts of animal-based food (AF) consumption. If a rising income would curb AF consumption, policies aiming at reducing it would be less urgent. Unfortunately, the income levels at which we found that AF starts to decline are so high that it is unlikely that this trend can cope with the environmental and health impacts that the growing consumption is creating. More so, because most of the predictable growth of animal-based protein consumption will take place in developing countries. For these countries, the path for reaching income levels determining an inversion of the trend is still long. The inescapable policy implications that the negative environmental impacts of animal-based food consumption must be tackled directly. Interventions can be envisaged on the production side from a technical point of view, since for instance some techniques allow lower GHG emissions from bovines (Thomson and Rowntree, 2020). Changing the production mix could also help since the environmental impact of poultry and pigs is lower than that of bovines. However, supply is driven by demand, and this calls for interventions on consumers both regarding the type of animal-based products and the quantity of consumption. The regulation of meat and animal-based consumption is one of the major challenges that countries must face in the coming decades (Willett et al., 2019) with the goal of a protein transition reducing the share of animal-based proteins in human diets (Simon et al., 2024). Bonnet et al. (2020) discuss the justification for meat regulation and the different tools that can be used. Their discussion includes economic tools such as taxes (see also Funke et al., 2022), nudging, and informational instruments. There is also an extensive literature on the effects of labelling and information on health and environmental impacts of food, and especially meat (e.g., Canavari and Coderoni, 2020; Edenbrandt and Lagerkvist, 2021; Bazoche et al., 2023). The results are mixed but generally suggest an albeit limited effectiveness of these policies. Regardless, our results suggest that an explicit policy in this regard is needed, since it cannot be expected that income growth will curb excessive consumption of animal-based food.

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APPENDIX 1

In formal terms, the model of AF consumption assumes the consumer maximizes his/her utility subject to a budget constraint:

$$\text{Max } U[a, H(a), C] \quad [A1]$$
$$\text{s.t.: } C + p_a = I$$

where a is animal-based protein consumption, H indicates health-nutrition components of utility as a function of animal food consumption, C is expenditure for all other consumption goods, I is income, p_a is the price of a and the price of C is taken as numeraire. The usual general assumptions hold: $U'_a > 0$, $U''_a < 0$; $U'_C > 0$, $U''_C < 0$; $U'_H > 0$, $U''_H < 0$. To represent the U-shape of nutritional-health benefits, it is assumed that $H'_a \geq 0$ for $a \leq \overline{a}$, $H'_a < 0$ for $a > \overline{a}$ where $\overline{a}$ is the animal-based protein consumption yielding the maximum nutrition-health benefit; H''_a is assumed < 0.

The first order conditions (FOCs) is:

$$U'_a + U'_H H'_a = p_a U'_C \quad [A2]$$

Equation [A2] simply states that, at equilibrium, the marginal utility from consumption of AF (the first left-side term), plus the marginal utility from the nutritional-health benefits from its consumption (the second left-side term) is equal to the additional utility that could be drawn from other goods that could be purchased with the animal food price, i.e., the marginal opportunity cost of AF (the right-side term).

The effect of income on AF consumption can be computed as the derivative of a with respect to I in eqn. [A2]. The result is nevertheless a complex function of the second direct and cross derivatives of a, H, C, and its sign cannot be unambiguously determined, it can be positive or negative.

APPENDIX 2

Table A.1. List of countries analysed.

Country	ISO CODE
Algeria	DZA
Argentina	ARG
Australia	AUS
Austria	AUT
Bangladesh	BGD
Bolivia	BOL
Brazil	BRA
Belize	BLZ
Cameroon	CMR
Canada	CAN
Cabo Verde	CPV
Sri Lanka	LKA
Chile	CHL
China	CHN
Colombia	COL
Congo	COG
Cyprus	CYP
Denmark	DNK
Dominican Republic	DOM
Ecuador	ECU
Egypt	EGY
El Salvador	SLV
Finland	FIN
France	FRA
Gambia	GMB
Germany	DEU
Ghana	GHA
Greece	GRC
Guinea	GIN
Honduras	HND
Hungary	HUN
India	IND
Indonesia	IDN
Iran (Islamic Republic of)	IRN
Ireland	IRL
Israel	ISR
Italy	ITA
Côte d’Ivoire	CIV
Japan	JPN
Jordan	JOR
Kenya	KEN
Cambodia	KHM
Republic of Korea	KOR
Lao People’s Democratic Republic	LAO
Lebanon	LBN
Madagascar	MDG
Malaysia	MYS
Mali	MLI
Mauritius	MUS
Mexico	MEX
Morocco	MAR
Mozambique	MOZ
Namibia	NAM
Nepal	NPL
Netherlands	NLD
New Zealand	NZL
Nicaragua	NIC
Niger	NER
Nigeria	NGA

Country	ISO CODE
Norway	NOR
Pakistan	PAK
Panama	PAN
Paraguay	PRY
Peru	PER
Philippines	PHL
Poland	POL
Portugal	PRT
Rwanda	RWA
Saudi Arabia	SAU
South Africa	ZAF
Spain	ESP
Sweden	SWE
Switzerland	CHE
Togo	TGO
Turkey	TUR
United Kingdom	GBR
United States of America	USA
Burkina Faso	BFA
Uruguay	URY

APPENDIX 3

Table A.2. Test of cross-sectional dependence of variables.

Variable#	Pesaran test
AnimalProt	2.678***
MeatProt	2.398**
PlantProt	2.798***
GDPPc	9.247***
$GDPPc^2$	16.342***
Trade	0.158
HarvArea	5.03***
PerFemWork	3.804***
Urbanization	1.948*
Education	85.837***
Animal-based Price Index	12.883***
Meat Price Index	6.536***
Plant-based Price Index	24.181***

#The percentage of Muslim (PerMus) has not been tested because time invariant.
*, **, *** stand for the significance level of 10%, 5% and 1% respectively. The null hypothesis is the absence of cross-sectional dependence.

Table A.3. Unit root test on variables and their first difference.

Variable	pCADF test	Variable	pCADF test
AnimalProt	2.965	ΔAnimalProt	-8.341***
MeatProt	1.408	ΔMeatProt	-10.136***
PlantProt	3.616	ΔPlantProt	-19.977***
GDPPc	5.426	ΔGDPPc	-3.426***
$GDPPc^2$	6.295	$\Delta GDPPc^2$	-1.592*
Trade	4.052	ΔTrade	-7.158**
HarvArea	2.232	ΔHarvArea	-7.700***
PerFemWork	1.631	ΔPerFemWork	-2.565***
Urbanization	4.302	ΔUrbanization	6.272
Education	11.310	ΔEducation	3.016
Animal-based Price Index	-12.225***	ΔAnimal-based Price Index	-20.497***
Meat Price Index	-12.825***	ΔMeat Price Index	-5.473***
Plant-based Price Index	-16.698***	ΔPlant-based Price Index	-9.583***

*, **, *** stand for the significance level of 10%, 5% and 1% respectively. The null hypothesis is non-stationarity.

Table A.4. Cointegration test assuming cross-sectional dependence.

Test name	AnimalProt	MeatProt	PlantProt
Pedroni			
Modified Phillips–Perron t	4.590***	3.697***	1.88**
Phillips–Perron t	-7.509***	-8.279***	-9.710***
Augmented Dickey–Fuller t	-8.99***	-10.195***	-10.324***
Westerlund			
Variance ratio	-2.579 ***	-2.751***	-1.6434*

*, **, *** indicate that statistics are significant at the 10%, 5% and 1% level of significance respectively. The null hypothesis is no-cointegration.

Table A.5. Results of the full models of protein consumption.

Indep. variables	Dependent variables					
	Animal-based Protein		Meat Protein		Plant-based Protein	
	Coef.	Std.Err.	Coef.	Std.Err.	Coef.	Std.Err.
GDPPc	1.256***	0.206	0.725***	0.135	1.505***	0.419
$GDPPc^2$	-0.015***	0.004	-0.008**	0.003	-0.002	0.001
Trade	0.018***	0.005	0.008**	0.003	0.032***	0.004
HarvArea	1.190	1.862	1.087	1.317	-15.486***	1.738
PerMus	-0.177***	0.048	-0.105***	0.028	0.211***	0.421
PerFemWork	0.057	0.047	-0.008	0.033	0.111**	0.046
Price Index (animal-based)	0.304	0.289				
Price Index (meat)			0.065	0.200		
Price Index (plant-based)					-0.184	0.148
Constant	25.245***	3.697	11.033***	2.199	30.910***	2.619***
sd(GDPPc)	1.686	0.161	1.087	0.125	3.644	0.361
sd($GDPPc^2$)	0.029	0.003	0.021	0.006	0.005	0.002
sd(Constant)	25.17	2.378	13.369	1.415	12.894	1.119
sd(Residual)	2.167	0.035	1.541	0.028	2.092	0.033
N. obs.	2212		2212		2212	
N. groups	79		79		79	
Wald Chisq(6)	109.25***		78.31***		196.14***	
Log likelihood	-5302.43		-4533.41		-5300.07	

*, **, *** indicate that statistics are significant at the 10%, 5% and 1% level of significance respectively.

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Do agroholdings cope better with the agency problem? Empirical evidence from corporate farms in Russia

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Abstract. The agricultural industry in Russia demonstrated a notable growth since 2010. Russian policymakers strive to further increase agricultural production and set new targets for the industry for the years ahead. While agroholdings are regarded as one of the main driving forces behind the recent success in the agricultural sector, they are also believed to be the main locomotive that will move agriculture towards the set goals. In spite of their growing importance, the literature on agroholdings is still relatively immature and fails to provide clear evidence of their financial efficiency as opposed to non-agroholding farms. The current study utilizes a manually sourced longitudinal dataset of 203 corporate farms in Russia and provides a new empirical evidence on the financial performance of agroholding farms through the prism of an agency problem. Our findings reveal a significant positive relationship between agroholding membership and financial performance, as indicated by two accounting indicators – return on assets (ROA) and return on sales (ROS). We further observe that agroholdings face lower agency costs, which to a certain extent, explain their higher financial performance compared to stand-alone farms. The study offers empirical recommendations for policymakers and corporate executives in the Russian agricultural sector.

Keywords: agroholding, corporate farm, agency cost, farm performance, Russia.
JEL Codes: M14, Q12, Q13.

1. INTRODUCTION

The agri-food industry in Russia has illustrated profound growth over the past few years. Its gross agricultural output jumped more than threefold, from RUB 2.46 trillion in 2010 to RUB 8.56 trillion in 2022 (RosStat, 2022). During the same period, the export of agricultural products skyrocketed by more than five times, from USD 8.1 billion in 2010 to USD 41.6 billion in 2022 (AgroExport, 2023). In the agricultural year of 2021-2022, Russia produced a record amount of almost 150 million tonnes of grain, of which 45

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million was exported, maintaining its position as the world's largest grain exporter since 2017 (AgroInvestor, 2023). Substantial progress can also be seen in the production of poultry and pork. Between 2008 and 2017, poultry production increased by over 150%, while pork output nearly doubled (Wegren et al., 2019). Since the dissolution of the Soviet Union, Russia has become one of the world's largest importers of agri-food products. However, over the last decade, the import of agri-food products in Russia has dropped significantly, by around 67%, from USD 43 billion in 2013 (an all-time high since 1990) to nearly USD 30 billion in 2022, thereby narrowing the negative trade balance in agri-food products (WTO, 2023). The substantial fall in the level of agri-food imports was largely caused by the introduction of an import embargo on a list of agri-food products by Russia in August 2014 (Bobojonov et al., 2018). Nowadays, Russia is the largest exporter of wheat and beet pulp and ranks among the top-3 exporters of sunflower oil, peas, oil cake, oil meal, flaxseed, and barley in the world (USDA, 2018a; Uzun et al., 2019). Yet, the Russian government aims to further increase both the volume and variety of exported agri-food products. In 2018, the president of Russia decreed an increase in the export of agri-food products to USD 45 billion and to position Russia among the top exporters of agri-food products globally (Petukhov, 2018). To achieve these ambitious goals, the Russian government introduced a national program for the development of agriculture for 2013-2020, with a total budget of RUB 2.28 trillion (USD 76 billion) (USDA, 2012).

It is commonly believed that agroholdings play a major role in the substantial growth of agri-food production in Russia (Ryzhova & Ivanov, 2023). Agroholdings are also considered the driving force for the realization of the ambitious production and export targets set by the government (Liefert & Liefert, 2015; Wegren & Elvestad, 2018). Russian agroholdings represent a significant concentration of agricultural land, resources, and production (Wegren et al., 2023). In 2016, the top-5 agroholdings operated around 3.2 million hectares of agricultural land, the top-20 companies produced nearly half of the total animal feed, and the top-15 companies accounted for 75% of all grain exports (Wegren, 2018). A similar pattern can be observed in the meat industry, with nearly half of the country's meat being produced by the top-25 companies (Agroinvestor, 2018b), and approximately 60% of all pork and poultry production accounted for by the top-20 and top-10 companies, respectively (Agroinvestor, 2018a; USDA, 2018b). Furthermore, agroholdings wield significant economic power, with less than a quarter of farms accounting for 93% of all profits (Wegren, 2018).

As policymakers primarily rely on agroholdings for the realization of the set targets, they have been the main recipients of financial support from the government (Wegren & Elvestad, 2018). For instance, in 2015, only 248 large agri-food farms (1.2% out of the total number), including agroholdings, received over 40% of all subsidies (Uzun et al., 2019). In addition to substantial state support, agroholdings attract significant financial investments from both local and international investors. From 2012 to 2016 alone, the Russian agri-food industry received over USD 3 billion of overseas and approximately RUB 1 trillion of local investments, with most of these investments going to agroholdings (Wegren, 2018).

Despite the significant growth and increasing role of Russian agroholdings in domestic agri-food production, the existing literature on agroholdings is still in its infancy and has certain gaps to be filled (Matyukha et al., 2015; Visser et al., 2014). First, most of the existing research on agroholdings focuses on their production efficiency (e.g., Hahlbrock & Hockmann, 2011), with studies concentrating on the financial performance of agroholdings being virtually non-existent. It is worth mentioning that corporate farms in Russia are highly vulnerable to financial insolvency, with around 25% of all bankruptcy cases in the country resulting from corporate farms (Yastrebova, 2015). Understanding the financial efficiency of agroholdings is therefore crucial, especially in light of their significant, often "too big to fail," roles in the agri-food sector of Russia. Second, while prior research attempts to identify the production efficiency of agroholdings, it is still not clear which specific attributes and capabilities make agroholdings more efficient compared to other forms of agri-food production. To the best of the authors' knowledge, this study is a pioneering attempt to understand the financial efficiency of agroholdings through the lens of the agency problem. An agency problem is a conflict of interest between the principals (shareholders) and agents (managers) of an enterprise. A situation of agency conflict may arise due to diverging goals between the shareholder and the manager, or because it is difficult and costly for the shareholder to control and monitor the manager's actions (Berle & Means, 1932; Eisenhardt, 1989; Jensen & Meckling, 1976). Consequently, this may result in ineffective and inadequate management of companies, which could then negatively impact the company's financial performance. The remainder of the paper is organized as follows: Section 2 provides a theoretical framework and an overview of the literature on agroholdings and their efficiency. Section 3 describes the methodology and data employed in the study. This is followed by Section 4, where the results of our empirical analysis are presented and discussed. Finally, we present our concluding remarks in Section 5.

2. THEORETICAL FRAMEWORK AND REVIEW OF LITERATURE

Agroholdings are specific types of business groups in agriculture that are unique to post-communist countries like Kazakhstan, Russia, and Ukraine (KRU). They began to emerge in the KRU countries in the 2000s and have been growing considerably since then (Rada et al., 2017; Ryzhova & Ivanov, 2023; Visser et al., 2014). Although there is no formal definition of agroholdings, there is a consensus in the existing literature that an agroholding is a conglomerate of legally autonomous enterprises, which may include agricultural producers, processors, service providers, and other entities involved in agriculture. The holding company maintains control of the group through ownership of a controlling block of shares (Matyukha et al., 2015; Spoor et al., 2012; Uzun et al., 2021). In this study, we attempt to investigate agroholdings through the lens of an agency problem. An agency problem is a conflict of interest between the shareholders (principals) and managers (agents) of a company, which is regarded as one of the main drawbacks of corporate farms, compared to traditional family farms (Hermans et al., 2017). In a family farm setting, there is no separation of ownership and control, and the farms are operated and managed by their owners. This alignment incentivizes managers to work more efficiently, as they are also the owners and thus the residual claimants of the generated revenue. Conversely, corporate farms are managed by hired managers, who are not the residual claimants of the profits and therefore have less incentive to maximize farm income (Hermans et al., 2017). Such a misalignment of interests between owners and managers can lead to agency conflicts (Chaddad & Valentinov, 2017; Valentinov et al., 2015).

Agency conflicts are common in all corporate farms. However, the extent of the agency problem and related costs might differ from one corporate farm to another. One of the main factors that can enhance a corporate farm's ability to cope with and minimize potential agency conflicts is the use of advanced and complex management and monitoring technologies. These technologies include performance evaluation systems, incentive compensation programs, formal control mechanisms, and digitized accounting and budgeting systems, among others (Chaddad & Valentinov, 2017). In comparison to stand-alone corporate farms, agroholdings have better access to resources, both external and internal within the group, which allows them to afford expensive, modern management and monitoring techniques and to implement the best international practices for enhancing their corporate governance mechanisms. Indeed, Hermans et al. (2017) and Petrick (2017) argue that agroholdings employ stimulating performance evaluation systems and offer incentive-based compensation programs. Agroholdings also utilize contemporary management practices and advanced technology for monitoring and supervising their workforce and production processes (Balmann et al., 2015; Liefert et al., 2013). Furthermore, Gagalyuk & Kovalova (2024) note an increasing adoption of digital technologies by agroholdings, which enhances their production and organizational performance.

Additionally, companies with concentrated ownership structures are believed to have lower agency costs, due to the ability and willingness of large blockholders to more effectively monitor and control the companies' management (Shleifer & Vishny, 1997; Wang & Shailer, 2015). The data used in this study shows considerably higher levels of ownership concentration in agroholding affiliates, with the ownership stake of the largest shareholders averaging 74% as opposed to only 56% in unaffiliated farms.

Therefore, agroholding affiliates may be better at minimizing their agency costs compared to stand-alone farms. If agroholding members do indeed face lower agency-related costs, then it is reasonable to expect them to demonstrate better financial performance.

Nonetheless, prior empirical research indicates both positive and negative impacts of agroholding membership on performance (Lefebvre, 2023; Matyukha et al., 2015; Tleubayev et al., 2022; Visser et al., 2014).

One group of researchers has found that agroholding members have performance advantages over nonmember farms. Examples of these advantages for agroholding members in Russia include higher land and labor productivity (Rylko et al., 2008) and greater scale efficiency (Hahlbrock & Hockmann, 2011), compared to other forms of agri-food production. Furthermore, Hahlbrock and Hockmann (2011) note that agroholding affiliates also demonstrate higher total factor productivity due to better implementation of contemporary technology. Epshtein et al. (2013) report similar findings, revealing that agroholding members achieve better efficiency thanks to their higher use of the latest production technology and strong corporate control mechanisms. Another advantage of agroholdings is the existence of internal trade markets that decrease dependence on external suppliers, lower price uncertainties, and significantly reduce transaction costs (Hockmann et al., 2011). Moreover, the vertical and/or horizontal integration of agroholdings allows their affiliates to benefit from economies of scope and to gain a significant economic advantage over non-affiliated farms (Davydova & Franks, 2015). Lastly, Tleubayev et al. (2022) observe that agroholding members show higher technical efficiency. They argue that the agroholding model of agri-food production provides better access to essential resources, such as within-group machinery, equipment, and capital markets, making holding farms more technically efficient.

Another group of scholars finds a negative relationship between agroholding membership and performance or does not find any significant relationship. For example, Hockmann et al. (2005) analyzed 100 large-scale farms in the Belgorod region of Russia and observed lower levels of efficiency among agroholdings despite their higher use of up-to-date production technology. Similar findings were reported by Hockmann et al. (2009) in the case of the Oryol and Belgorod regions of Russia. Lower levels of production efficiency were also observed among grain-producing holdings in Russia. Although agroholdings had more investments and technology and used substantially higher levels of fertilizers, the holding farms did not show significantly higher levels of grain yield (Uzun et al., 2012). A subsequent investigation by Matyukha et al. (2015) also failed to find evidence of economic advantages for agroholding members compared to independent farms. Lastly, studies by Gataulina et al. (2014) and Guriev & Rachinsky (2004) also did not find any significant difference in average productivity levels between agroholding affiliates and non-affiliated farms.

3. METHODOLOGY AND DATA

3.1. Models and variables

Baseline regression model:

$$y_{it} = \alpha_{it} + \beta_1 x_{1it} + \beta_2 x_{2it} + \beta_3 x_{3it} + \beta_4 x_{4it} + \beta_5 x_{5it} + \beta_6 x_{6it} + \beta_7 x_{7it} + \varepsilon_{it} \quad (1)$$

In this model, $\boldsymbol{y}$ represents the financial performance of farms, measured by return on assets (ROA) and return on sales (ROS). Existing research suggests two broader categories of indicators for measuring enterprise performance: indicators based on market value (e.g., Tobin's Q) and accounting-based indicators (e.g., return on assets). Since the market value-based measures for the farms used in this study are not publicly available, we focus on two widely used accounting-based indicators to measure farm performance: return on assets (ROA) and return on sales (ROS) (Adams & Ferreira, 2009; Ehrhardt et al., 2003; Liu et al., 2014).

$\boldsymbol{x_1}$ is the independent variable representing agroholding membership. Unfortunately, there is still no formally specified definition for agroholdings. However, there is a consensus among researchers that agroholdings are certain types of business groups in the agri-food sector, consisting of several legally autonomous farms, with controlling stakes in the ownership shares of these farms owned by a holding company (Hermans et al., 2017; Visser et al., 2012). In this study, we adhere to the above consensus and consider a farm a member of an agroholding if over 50% of the ownership shares of that farm are owned by a holding enterprise.

In addition to agroholding membership, which is the main explanatory variable in our model, we also control for a number of board ($\boldsymbol{x_2}$...$\boldsymbol{x_4}$) and farm specific variables ($\boldsymbol{x_5}$...$\boldsymbol{x_7}$).

As per board characteristics, we control for the number of directors on the board ($\boldsymbol{x_2}$) (e.g. Yermack, 1996), the share of independent directors on the board ($\boldsymbol{x_3}$) (e.g. Black & Kim, 2012) and gender diversity on the board ($\boldsymbol{x_4}$) (e.g. Terjesen et al., 2016).

As per farm specific characteristics, we control for farm age ($\boldsymbol{x_5}$) (e.g. Reddy et al., 2008), farm size ($\boldsymbol{x_6}$) (e.g. Debrah & Adanu, 2022), and leverage, the ratio of total debts to total assets ($\boldsymbol{x_7}$) (e.g. García-Meca & Sánchez-Ballesta, 2011).

Extended regression model:

$$y_{it} = \alpha_{it} + \beta_1 x_{1it} + \beta_2 x_{2it} + \beta_3 x_{3it} + \beta_4 x_{4it} + \beta_5 x_{5it} + \beta_6 x_{6it} + \beta_7 x_{7it} + \beta_8 x_{8it} + \beta_9 x_{9it} + \varepsilon_{it} \quad (2)$$

In the extended model, we consider the possibility that agroholding members might face lower agency costs, which may potentially result to their higher financial performance, compared to non-agroholding farms. In this model, $\boldsymbol{x_8}$ is an agency cost variable and $\boldsymbol{x_9}$ is an interaction term between agroholding affiliation and agency cost. We measure the agency cost, using two widely used proxies for enterprise level agency costs: operating expense ratio *(OER)* and asset turnover ratio *(ATO)* (e.g. Rashid, 2015; Singh & Davidson III, 2003). The other variables are the same as those specified in Model (1).

Table 1 illustrates the farm performance, agroholding affiliation and other control variables employed in this research.

3.2. Robustness tests

We conduct standard tests to come up with the model that is most suitable for the longitudinal data

Table 1. Variables and descriptions.

Variables	Description
Panel A: Dependent variables	
ROA	Net Income / Total Assets
ROS	Net Income / Sales
Panel B: Explanatory variables	
AGRH_MEM	Dummy variable, which is equal to 1 if more than 50% of the farm is owned by a holding company and 0 otherwise
Panel C: Control variables	
Board characteristics	
BSIZE	The total number of directors in the boardroom
BOD_IND	Percentage of independent directors in the boardroom
BOD_DIV	Percentage of female directors in the boardroom
Farm characteristics	
FAGE	The number of years since the farm was first registered by the state
FSIZE	Natural logarithm of the farm's total assets
LEVERAGE	Total debt / total assets
Agency cost	
OER	Operating expenses / Sales
ATO	Sales / Assets

Source: compiled by authors.

under study. While the F-test, the Breusch-Pagan Lagrangian multiplier test (Appendices 2 and 3 respectively) illustrate the significance of fixed and random effects, the results of the Hausman test suggest the significance of random effects over the fixed effects (Appendix 4). Hausman test fails to reject the null hypothesis that the random effects model is consistent and more efficient than the fixed effects model. Hence, in this study we employ a random effects model to conduct the regression analyses.

Conducting a regression analysis with longitudinal data where the number of cross-sectional observations (N) are higher that the number of time-periods (T) may lead to a potential issue of cross-sectional dependence in the error terms (De Hoyos & Sarafidis, 2006). To control for such a potential issue, we also run our baseline model using the Driscoll-Kray (DK) robust standard errors, as suggested by (Hoechle, 2007). In addition to cross-sectional dependence in the error terms, the Driscoll-Kray (DK) robust standard errors also control for potential heteroscedasticity and autocorrelation in the model (Hoechle, 2007).

Endogeneity is another problem that may potentially distort the results of the analysis. Based on prior research (Campbell & Mínguez-Vera, 2008; Doan et al., 2023; Marinova et al., 2016), we control for potential endogeneity in the model by employing the 2SLS (two-stage least squares) method. In a 2SLS model, we use the first lag of the explanatory variable as an instrumental variable, as suggested by Caramanis & Lennox (2008) and García-Meca & Sánchez-Ballesta (2011).

3.3. Data

Current research utilizes a manually sourced longitudinal dataset of 203 corporate farms from 27 administrative regions in Russia for the years from 2012 to 2017. The sample was chosen through the convenience sampling method, where availability and accessibility are the criteria for the selection of the research sample (Etikan, 2016; Henry, 1990). Because longitudinal data for the majority of Russia's corporate farms are not publicly accessible, our sample consists of 203 corporate farms for which panel data for the variables of interest was publicly available.

The data on the variables of interest was sourced from the quarterly and annual reports, as well as the financial statements of those farms. The document sources are publicly accessible through the portal of the "Interfax - Corporate Information Disclosure Center (CIDC)[1]", which is the agency authorized to release public information on the Russian securities market.

Descriptive statistics of the main variables utilized in this research are described in Table 2. The average

[1] https://www.e-disclosure.ru/

Table 2. Descriptive statistics of key variables.

Variables	Obs	Mean	Std	Min	Max
ROA	1218	4.7%	0.1	-0.85	0.84
ROS	1218	5.75%	0.27	-2.26	2.93
AGRH_MEM	1218	27.7%	0.45	0	1
BSIZE	1218	6	1.68	3	15
BOD_IND	1218	50.8%	0.38	0	1.8
BOD_DIV	1218	29.27%	0.22	0	1
FAGE	1218	16	6.16	0	25
FSIZE	1218	12.92	1.57	7.25	18.87
LEVERAGE	1218	47.4%	0.31	0.006	1.83

Source: compiled by authors.

agroholding affiliation among the sampled farms is 28%. Board of directors, on average, consists of six members. Furthermore, around half of the boardrooms are composed of independent directors and female directors represent less than a third of the boards. Average farm in this sample is 16 years old and has a size in terms of total assets of around RUB 2.3 billion. The average ratio of total debt to total assets is about 47%. Lastly, performance indicators such as return on assets *(ROA)* and return on sales are *(ROS)* 4.7% and 5.75%, respectively.

4. RESULTS AND DISCUSSIONS

We begin our analysis with the comparison of the average performance variables of agroholding members versus stand-alone farms. Table 3 presents the results of the standard z-test. In terms of both performance measures (*ROA* and *ROS*), agroholding affiliates demostrate better performance, compared to non-member farms. The *ROA* and *ROS* of agroholding members are higher by 1.3% and 4.9% respectively, than those for non-agroholding farms. The differences in both measures are statistically significant at 5% significance level.

We continue our analysis by running the random effects (RE) regression model with *ROA* and *ROS* as dependent variables and a dummy for agroholding affiliation *(AGRH_MEM)* as the main explanatory variable. The first and the second columns of table 4 present the results of the RE model. The results suggest a significant positive effect of agroholding affiliation *(AGRH_MEM)* on farm performance (both *ROA* and *ROS*). Similar with the results of the z-test, agroholding affiliation has a stronger effect on *ROS*, compared to *ROA*. Agroholding affiliates illustrate *ROA* and *ROS* that are by 2.6% and 4% higher compared to stand-alone enterprises, respectively. These results are also robust to potential cross-sectional dependence (Table 4: columns 3 and 4) and potential endogeneity (Table 4: columns 5 and 6).

While the results of z-test and random effects model reveal better financial performance of agroholding affiliated farms, it is also important to explore what exact characteristics of agroholding affiliates make them financially better off. As mentioned earlier in the paper, we expect that the level of agency cost might to a certain degree, explain the performance differences between agroholding and non-agroholding farms. To test this hypothesis, we proceed to the next step of our analysis and compare the average levels of agency costs between agroholding affiliates and independent companies. As suggested by prior studies (Rashid, 2015; Singh & Davidson III, 2003), we employ two most widely used proxies for measuring company level agency costs: operating expense ratio *(OER)* and asset turnover ratio *(ATO)*. Table 5 illustrates the results of this comparison.

The results exhibit a significantly higher agency cost, measured in terms of operating expense ratio *(OER)*, by independent farms (19.23%), as opposed to agroholding members (18.18%). Differences in agency costs, measured in terms of asset turnover *(ATO)*, are found to be statistically insignificant, hence in our further analyses we proceed with only operating expense ratio *(OER)* as a measure for agency cost variable *(AG_COST)*.

Having revealed that agroholding members have lower agency costs, we test for the robustness of this result and extend our baseline regression model by including the interaction term *(AGHR_MEMxAG_COST)* between the agroholding affiliation variable *(AGRH_MEM)* and the agency cost variable *(AG_COST)*. Table 6 presents the results of this extended model (2).

Agency cost *(AG_COST)* appears to have a significant negative impact on both *ROA* and *ROS*. At the same time, the estimates of the interaction term variable *(AGHR_MEMxAG_COST)* are found to be significantly positive, both for *ROA* (0.44) and for *ROS* (0.87). This suggests that the negative effects of the agency cost on farm performance are significantly lower for agroholding members, compared to stand-alone farms. While a point increase in the agency costs of independent farms leads to a decrease in their *ROA* and *ROS* by 0.93 and 2.24 points respectively, a similar increase in the agency costs of agroholding members leads to only 0.49 and 1.37 points decrease in the levels of their *ROA* and *ROS*, respectively. This implies that agroholding members perform better in dealing with the agency conflict, compared to unaffiliated farms. Hence, the agency problem can be regarded as one of the main matters that can to a certain degree, explain the better financial performance

Table 3. Averages of performance variables, agroholding affiliates VS independent farms.

Performance variables	Whole sample	Agroholding affiliates	Independent farms	Difference	Z-score
Return on assets (ROA)	4.7%	5.6%	4.3%	1.3%	2.25**
Return on sales (ROS)	5.7%	9.3%	4.4%	4.9%	3.33***

*** p<0.01, ** p<0.05, * p<0.1.
Z-scores are calculated using the methodology suggested by Paternoster et al. (1998).
Source: compiled by authors.

Table 4. The impact of agroholding affiliation on farm performance (standard errors in parentheses).

Variables	Random Effects (RE)		DK robust standard errors		2SLS	
	(1) ROA	(2) ROS	(3) ROA	(4) ROS	(5) ROA	(6) ROS
AGHR_MEM	0.026*** (0.008)	0.040* (0.023)	0.026* (0.012)	0.040** (0.013)	0.034** (0.016)	0.084** (0.042)
FAGE	-0.001 (0.001)	-0.003** (0.002)	-0.001 (0.001)	-0.003** (0.001)	-0.001 (0.001)	-0.003** (0.002)
FSIZE	0.008*** (0.003)	0.035*** (0.007)	0.008 (0.005)	0.035*** (0.008)	0.008** (0.003)	0.03*** (0.008)
LEVERAGE	-0.143*** (0.013)	-0.234*** (0.033)	-0.143*** (0.011)	-0.234*** (0.029)	-0.143*** (0.013)	-0.232*** (0.033)
BSIZE	-0.002 (0.002)	0.004(0.006)	-0.002 (0.002)	0.004 (0.006)	-0.002 (0.002)	0.005 (0.006)
BOD_IND	0.025** (0.009)	0.073*** (0.026)	0.025 (0.014)	0.073** (0.027)	0.026** (0.009)	0.075*** (0.026)
BOD_DIV	0.053*** (0.016)	0.099** (0.041)	0.053*** (0.012)	0.099*** (0.019)	0.053*** (0.016)	0.104** (0.041)
_cons	-0.000 (0.038)	-0.326*** (0.098)	-0.000 (0.085)	-0.326* (0.128)	0.006 (0.039)	-0.29*** (0.103)
R-squared	0.189	0.125	0.189	0.125	0.186	0.120

*** p<0.01, ** p<0.05, * p<0.1.
Source: compiled by authors.

Table 5. Averages of agency cost variables, agroholding affiliates VS independent farms.

Agency cost variables	Whole sample	Agroholding members	Independent farms	Difference	Z-score
Operating expense ratio (OER)	18.94%	18.18%	19.23%	1.05%	3.46***
Asset turnover (ATO)	113%	116%	112%	4%	0.61

*** p<0.01, ** p<0.05, * p<0.1.
Operating expense ratio (OER) = Operating expenses / Sales.
Asset turnover ratio (ATO) = Sales / Assets.
Source: compiled by authors.

of agroholding affiliates. Several factors might provide potential explanations for this.

To begin with, agroholdings tend to use stimulating performance evaluation systems and offer attractive compensation contracts to their employees, including the top executive management (Hermans et al., 2017; Petrick, 2017) . Knowing that their efforts actually count and that their income depends on the farm performance, managers would be more likely to work hard for the good of the farm. Moreover, when managers receive attractive compensation, they tend to better value their position and try not to risk their top posts in the company. It is therefore less likely that such managers would engage in the expropriation of farm assets for their own benefit, putting personal interests above the interests of the company and its shareholders (Florackis, 2008; Sajid et al., 2012).

In addition, the increasing use of digital technologies by agroholdings enhance their production and organizational performance (Gagalyuk & Kovalova, 2024).

They also tend to implement modern management practices and advanced technology to monitor and supervise their workforce, including the top executive management (Hermans et al., 2017; Liefert et al., 2013). These practices of agroholdings decrease the agency costs related with the supervision of the hired labor and manage-

Table 6. The impact of agroholding affiliationand agency cost on farm performance (standard errors in parentheses).

Variables	Random Effects (RE)	
	(3) ROA	(4) ROS
AG_COST	-0.9314*** (0.1595)	-2.2374*** (0.4099)
AGHR_MEM	0.1036*** (0.0311)	0.1912** (0.0808)
AGHR_MEMxAG_COST	0.4431*** (0.1659)	0.8664** (0.4298)
FAGE	-0.0016*** (0.0006)	-0.0051*** (0.0015)
FSIZE	0.0044* (0.0026)	0.0239*** (0.0063)
LEVERAGE	-0.1248*** (0.0122)	-0.1823*** (0.03)
BSIZE	-0.0018 (0.0022)	0.0044 (0.0053)
BOD_IND	0.026*** (0.0095)	0.075*** (0.0236)
BOD_DIV	0.0531*** (0.0151)	0.1017*** (0.038)
_cons	0.1424*** (0.0393)	0.0704 (0.0961)
R-squared	0.2570	0.2206

*** p<0.01, ** p<0.05, * p<0.1.
Source: compiled by authors.

ment. Finally, yet importantly, agroholdings tend to be the largest shareholders in the ownership structure of their affiliates, holding on average 74% of all shares of their member companies. Such huge ownership shares of agroholdings, give them both power and willingness to control that the managers of their affiliated farms act at the best interest of the company and its shareholders (Shleifer & Vishny, 1997; Wang & Shailer, 2015), thereby minimizing the expropriation risk by managers. All of the above factors decrease the potential conflicts between the principals (shareholders) and agents (managers) of the companies belonging to agroholdings and therefore minimize their agency costs, which in turn leads to a higher financial performance by holding farms.

5. CONCLUSION

Russian agri-food industry exhibited noticeable growth during the last decade. While agroholdings accounted for a major part of this growth, they are also expected to be the driving force for reaching the ambitious future goals set for the industry by the government. Nonetheless, existing literature on agroholdings is still relatively immature and fails to provide clear evidence on financial efficiency of agroholdings as opposed to non-agroholding farms. The current study utilizes unique farm-level data on the Russian corporate agri-food enterprises and provides new empirical evidence on the financial efficiency of agroholding affiliated farms.

Besides its empirical contribution, this research is also one of the first attempts to offer a theoretical explanation for the emergence and growth of agroholdings through the framework of an agency problem. While agency conflicts are common to all corporate farms, this study proposes that agroholdings perform better at minimizing the agency costs, compared to stand-alone farms. This is because agroholdings have better access to both external and internal resources, which allows them to afford modern and advanced management and monitoring techniques, implement best international corporate governance practices, such as performance evaluation systems, incentive compensation programs and other formal control mechanisms. We therefore hypothesize that the lower agency costs faced by agroholdings make them financially better off, as opposed to non-agroholding farms. Indeed, the results of the study indicate that agroholdings have substantially lower agency costs, compared to non-agroholding farms, which translates into to better financial performance (both *ROA* and *ROS*) of the former.

The results of this research could appeal to policy makers, executives and shareholders involved in the agricultural sector in Russia. For policy makers, this study suggests additional evidence that agroholdings may be more suitable for adapting to current institutional and market conditions compared to other types of agricultural producers, and that they could be the main catalyst for pushing the agricultural sector towards its objectives. However, this does not mean that government support should only be focused on agroholdings. Instead, against the backdrop of evidence on agroholdings' financial advantages, policy makers should encourage better access to resources for other forms of agricultural producers. This may include stimulating better access to capital, labor and contemporary management and monitoring techniques, including digital technologies, among others.

For the shareholders and executives of corporate farms, the findings of this research underscore the importance of managerial efficiency and encouragement for farm's financial performance. It is crucial for corporate farms to adopt up-to-date management and monitoring techniques and to introduce stimulating compensation practices that help in aligning management's interests with those of the shareholders, thus minimizing potential agency conflicts.

While this study makes a few contributions to the existing literature, it does have some limitations that should be examined in future research. Firstly, the sample selection in this study was driven by data, including only sample farms with publicly available data. This resulted in the sample consisting of mostly larger-sized corporate farms that the average size of corporate farms in the population. Therefore, it is important to interpret the findings of this research carefully, as they may not apply to a wider population. Future research should focus on a more diverse sample that encompasses the entire population, including relatively smaller corporate farms. Secondly, in this study, we focus only on farm level features for explaining the differences in farm financial performance. Upcoming research may advance by incorporating macro-level factors beyond the influence of individual farms. These may include variables that control for regional differences in weather and climate conditions, as well as differences in agricultural and market infrastructure, among others.

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Farm characteristics and exogenous factors influencing the choice to buy land in Italy

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Abstract. Access to land is one of the key factors of farm growth. However, related research is characterised by important gaps, in particular, facing the change over time in the nature and role of drivers of the land market. The objective of this paper is to identify the endogenous and exogenous factors that affect the decision to purchase land in Italy between 2013 and 2020. Five probit regression models were implemented to understand the role of a set of different determinants in land investment decision. The results show that factors related to capital in machinery and plant, energy production and the presence of a successor or young farmer are endogenous factors that positively influence the purchase decision. The ratio of rented land to utilised agricultural area and of family work units to total work units are endogenous factors that negatively affect the purchase decision. Exogenous factors related to the cost of capital and inflation rate affect the purchase of land in an opposite way, negatively and positively respectively. The role of Utilised Agricultural Area and Value Added per hectare varies depending on the specialisation considered. The research can support policymakers in designing policies to promote the survival and growth of farms, as well as to facilitate land investment by reducing barriers to land acquisition.

Keywords: agricultural land market, land purchase, probit regression model, investment decision, purchase decision.
JEL Codes: Q15, Q12.

1. INTRODUCTION

Land represents a durable, fixed, heterogeneous, and non-reproducible resource and is one of the key productive factors of a farm. The purchase of land is one of the ways through which a farmer can access this fixed productive factor and represents a form of investment in a capital good. Compared to other forms of farm size growth, on the one hand, the purchase of land may require a major financial commitment and thus limits the investment in other productive assets (Jeong et al., 2022; Swinnen et al., 2016).

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On the other hand, the full transfer of rights allows the new owner to use the land as a collateral asset in order to have greater access to credit (Binswanger et al., 1995; Bradfield et al., 2023; Swinnen et al., 2016). In comparison to investments in other types of on-farm assets, the purchase of land rarely takes place at the same time as it is planned because it is not certain that the farmer will find the supply on the local market meeting his/her needs/capacity (Elhorst, 1993). For the farmer, the availability of land can be one of the main obstacles to the development and growth of the farm (Yanore et al., 2024). The land market is characterised by rigid supply and the purchase of land far from the farm centre would lead to increased costs and downtime (Cotteleer et al., 2008; Schimmenti et al., 2013). For all these reasons, the land market is generally defined as thin and local.

The lack of data availability and the absence of well-structured databases on land transactions, especially in Europe, has influenced and limited the research on the land market (De Noni et al., 2019). Over the years, research mainly focused on identifying the determinants of land value in specific local agricultural land markets or on how agricultural policy payments could influence land value (Baldoni et al., 2023; Czyzewski et al., 2017; Latruffe and Le Mouël, 2009; Michalek et al., 2014; Varacca et al., 2022). However, when analysing the literature relating to the investment decision, there appears to be little ex-post empirical research that takes into consideration the investment in land.

The objective of this paper is to identify determinants that have influenced the farmer's decision to purchase land in Italy between 2013 and 2020. The work is carried out using FADN data and factors are selected based on a literature review and data availability. The main novelty of the paper is that we use an original analytical framework and a conceptual model developed on the basis of the literature analysis using multiple streams of research, namely structural change in agriculture and the growth of farm size, the investment decision and the land market literature.

The paper continues in Section 2 with the design of the framework. In Section 3 we proceed with the descriptive analysis of the available data and the presentation of the methodology. In Section 4, the results of the analysis are presented and will be discussed in Section 5. Section 6 is dedicated to the conclusions drawn from this study.

In order to contextualize this research, a premise is needed. To the best of our knowledge, there are no studies that have identified the factors that may influence the decision of Italian farmers to invest in land. Consequently, this study and its results should be considered a preliminary exploratory attempt to identify and understand the effects of certain factors selected based on the original analytical framework.

2. THEORETICAL FRAMEWORK

Land is a factor of production that is strongly connected to and not divisible from three other farm inputs such as machinery, (family) labour and buildings (Plogmann et al., 2022).

Over the years, mechanisation and technological innovation have played an important role in improving farmers' labour management and replacing the labour force leaving rural areas for better paid non-agricultural work. The adoption of machinery and technological innovation, especially when it is expensive and complex, have stimulated farmers to allocate their managerial skills, capital, and farm assets for the production of a few types of output and, thus, farm specialisation. These three factors have contributed to the development of both economies of scale and size. Although technological innovation is accessible to small and large farms, the latter seem to have more financial and managerial capacities, both internal and external, to invest in this factor. Thus, the growth in farm size induced by technological innovation seems to be stronger in large farms than in small ones. According to the theoretical literature, these dynamics generate pressures on small farms that might decide to exit the agricultural sector (Plogmann et al., 2022). In this regard, researchers have identified "off-farm income" as a factor that could play a dual role in the survival of small farms. On the one hand, the income generated by off-farm activities could represent the first step of the farm's exit from the sector. On the other hand, this source of income could allow the farmer to remain within the agricultural sector because it could contribute to the stabilisation of the farmer's income and facilitate access to credit, investment in farm assets, and stimulate the growth of farms managed by young farmers (Goddard et al., 1993; Hallam, 1991; Harrington and Reinsel, 1995; Key, 2020; Neuenfeldt et al., 2019; Weiss, 1999; Zimmermann et al., 2009).

Human capital is one of the main factors that can influence a farmer's investment decision. When talking about human capital, reference is made to demographic characteristics of the farmer and their family. In particular, the age of the farmer and the presence of a potential successor, and the level of education are among the main characteristics that can affect farm size and investment in land. As the age of the farmer increases, the farm enters the so-called *maturity* and/or *decline* phase and the farmer may be more reluctant to increase the farm size (Bremmer and Oude Lansink, 2002). The presence of a potential successor could prevent the farm from entering the decline phase and thus positively affect the investment in a fixed input (Huber et al., 2015). Furthermore, the purchase of land could entail a major financial commitment and the application for a bank loan. In this regard, the presence of a young farmer or a successor could positively influence the time horizon of the investment and favour the purchase decision (Elhorst, 1993; Huber et al., 2015; Oskam et al., 2009; Oude Lansink et al., 2001). In addition to these factors, human capital also includes managerial skills that if not possessed by the farmer can be found in the external environment e.g. by turning to advisory and consultancy services (Boehlje, 1992). According to the literature, larger farms may have greater economic and financial capacities to access such services.

The decision to invest in land is not only influenced by structural and socio-demographic characteristics of the farm, but also by exogenous factors such as the macroeconomic environment, land market regulations, and agricultural policies.

The purchase of land represents an investment in a capital good that may require a major financial commitment. In this sense, the cost of capital and the financial position of the farmer could influence the decision and the level of investment. As the interest rate increases, the probability that the farmer is willing to invest and the level of investment decreases.

Land is not only an important production asset of a farm but also a "safe- heaven" asset (Schimmenti et al., 2013), attracting the interest of non-farmers who decide to invest in it to protect the capital value from inflation. An increase in the inflation rate leads to an increase in the price of land and vice versa (Elhorst, 1993; Lawley, 2021; Szymańska et al., 2021; Thijssen, 1996). Policymakers can use land regulation as an instrument to defend the farmers' position and mitigate potential speculative force in farmland market. Each European Member State has full decision-making power over its own land regulation. In general, Western European countries have a more liberal land regulation than Eastern European countries. Among the Western countries, Italy is one of the European countries with the most liberal land regulation (Swinnen et al., 2016). With the aim of facilitating access to land for medium-sized farms with financial means, many European countries have provided for the right of pre-emption to be exercised either by local governments, as in France, Germany and the Netherlands, or by farmers, as in Italy (Galletto, 2018). In particular, the Italian government introduced this instrument to reduce the fragmentation of Italian farms, to improve the consolidation of the Italian agricultural sector and to facilitate the development of family farms. In Italy, Art. 8 Law n. 590/1965 and art. 7 Law n. 817/1971 establish that the Italian farmer may exercise the right of pre-emption of land if at least one of three cases occurs: a) he/she is the co-owner of the farm, b) he/she is a professional farmer who directly borders land for sale, c) if he/she has been renting the land for at least two years (Legge 590/1965; Legge 817/1971).The right of pre-emption has also been extended to agricultural partnerships (as a rule, simple partnerships, and general partnerships) if at least half of the partners are "*owner-operator farmer*". Subsequently, between 2009 and 2016, the Italian State implemented tax concessions to improve the farmer's position. The law states that: a) the Italian farmer with a family farm does not have to pay income tax or land use tax; b) the Italian farmer is exempt from paying income tax on the use of the land; c) in case of land purchase, when the buyer is a "*owner-operator farmer*" or professional agricultural entrepreneur, she/he will pay only 1% of the purchase price as tax, while any other buyer will pay 15%. In 2017, the European Parliament called on all Member States to review their land regulation in order to ensure fair access to land and to prevent it from being concentrated within a few large farms (European Parliament, 2017).

In addition to preserving the farmer's position, land regulation influences the capitalization of subsidies provided by agricultural policies within the value of land and rental rates. Stringent land regulation on the land market and land rental market would reduce the capitalisation of subsidies within the land price and rent. The literature presents both theoretical and empirical studies on whether and how much of the subsidies provided through policies are capitalised within the land price value. From a theoretical study, in a perfect market, decoupled direct payments, coupled direct payments, rural development programmes and environmental payments could be capitalised within the land price. However, empirical studies suggest that capitalisation in a real land market is lower than theorised and depends on many factors such as subsidy type, land supply elasticity and farm credit constraints. In addition to influencing land value, subsidies can also influence a farmer's investment decision and level of investment. Subsidies were introduced with the main objective of supporting the farmer's income and represent a form of income not affected by production risks. Consequently, subsidies could positively influence the investment decision and level especially in the presence of an imperfect market.

The identified factors are not independent but interact and influence each other (Zimmermann et al., 2009).

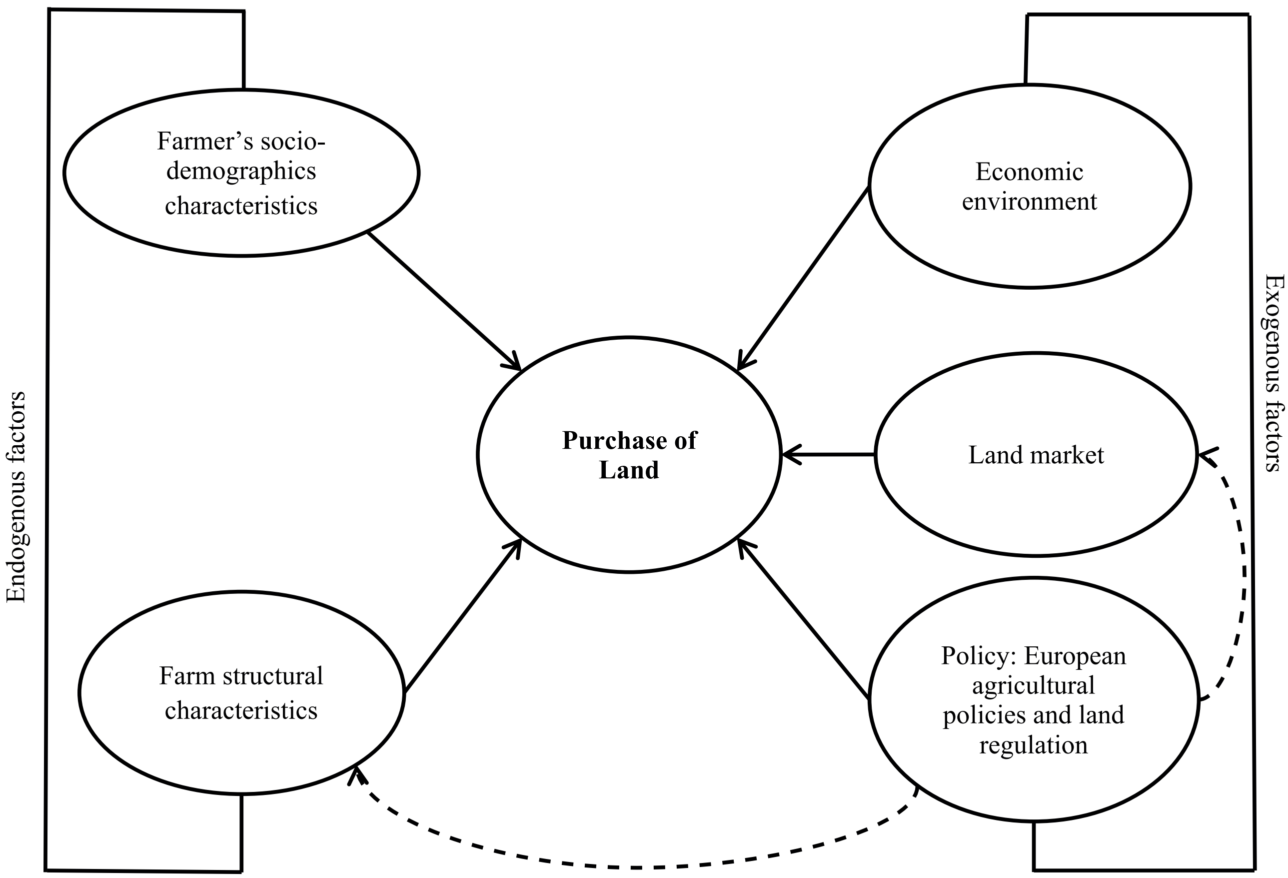

Figure 1. Conceptual model developed based on the literature review.

In the literature, four empirical studies concerning the farm size growth were identified that adopted a regression model with the farm size as the dependent variable (Akimowicz et al., 2013; Bremmer and Oude Lansink, 2002; Brenes-Muñoz et al., 2016; Weiss, 1999). In the literature related to investment decision, two empirical researches were identified that also considered land as a form of investment (Elhorst, 1993; Oskam et al., 2009). In addition, Jeong et al. (2022) identified farm economic characteristics that could affect the decision to buy or lease land in Korea by adopting the machine learning algorithm "random forest". Finally, Ziemer and White (1981) attempted to better estimate farmland demand in Georgia between 1970 and 1978 by accounting for the process underlying the decision to purchase.

Based on the literature review, factors endogenous and exogenous to the farm that may have an influence have been identified and summarised in a conceptual model shown in Figure 1. Similar to the studies on farm size growth (Zimmermann et al., 2009), we do not assume that the identified exogenous and endogenous factors are independent of each other, but that they interact and condition each other.

3. MATERIALS AND METHODOLOGY

3.1. Data and descriptive analysis

The analysis was conducted on Italian FADN data of Italian farms observed between 2013 and 2020. The data represent an unbalanced panel data consisting of 84610 observations representing 24212 farms. On average, the same farm remains in the sample for about 3 to 4 years.

For each farm, there is information on the structural characteristics of the farm, data on the farm's balance sheet, and data on the socio-demographic characteristics of the farms.

Of the 24212 farms in the sample, 919 made at least one investment in land during the period in question, of these 176 farms made more than one investment (Table 1).

Around 90% of the sample is characterised by specialised farms in cereals, arable crops, horticulture, fruit

Table 1 Descriptive analysis: Dimension of the unbalanced panel data.

	Full Sample	Buyer	%
Number of observations	84610	1095	1.3
Number of farms	24212	919	3.8

crops, olive growing, viticulture, dairy cattle, herbivores and granivores. The remaining 9.45% by non-specialised farms, of which 9.4% are mixed crop and livestock farms. Thirty-two percent of the sample is specialised in annual crops, 29.9% are permanent crops and 27.8% livestock farms (Table 2). Thirty-nine percent of the land purchases were conducted by farms specialising in permanent crops, followed by farms specialising in annual crops and livestock. In particular, 18% of the recorded transactions were conducted by farms specialising in fruit crops, 16.5% by vineyards, and 12% by farms specialising in arable crops (Table 2).

In terms of average UAA, specialised livestock farms are the largest, followed by annual crops and permanent crops. Among all specialisations, farms specialised in viticulture have the smallest average farm size followed by those specialised in fruit crops and horticulture. There is an important difference in farm size between horticultural farms and those specialised in other annual crops. Farms specialised in permanent crops have lower "RENT/UAA" ratios than farms specialised in annual crops and livestock (Appendix 1).

3.2. Empirical Model

Since the investment decision represents a discrete problem (Elhorst, 1993), to estimate the probability of participation decision we adopted a probit regression model.

The empirical model implemented to conduct the quantitative analysis was developed based on the conceptual model in figure 1 and peculiarities of FADN data. In particular, the characteristics of our database did not allow us to conduct a dynamic analysis, which would be appropriate since investments in capital stock are not annual investments (Lefebvre et al., 2015) and generally do not occur at the same time as they are planned (Elhorst, 1993).

The empirical probit model used is described by the following equation:

Where:

$$y^*i = \beta_0 + \sum_{k=1}^{K} \beta_{ki} x_{ki} + \varepsilon_i$$

y^*_i is the binary dependent variable that assumes a value equal to 1 in the year in which the purchase occurs, 0 otherwise.
ε_i is the composite error term.
i represents the single observation,
x_{ki} is the observed value of explanatory variables that described factors linked to farm characteristics, farmer

Table 2. Descriptive statistics of the sample based on farm specialization.

Specialization	Sample N. Observations	% Total observation	Buyers N. Observations	% Total observation
No specialisation:	7997	9.45	91	8.3
Unclassifiable farms	11	0.013	0	0
Mixed crops and livestock farming	7986	9.4	91	8.3
Annual Crops	27796	32.9	312	28.5
Cereals	8812	10.4	102	9.3
Arable Crops	10292	12.2	133	12.15
Horticulture	8692	10.3	77	7.03
Permanent Crops	25305	29.9	432	39.45
Fruit Crops	10721	12.7	202	18.45
Olive growing	4034	4.8	47	4.3
Viticulture	10550	12.5	183	16.7
Livestock farms	23512	27.8	260	23.75
Dairy cattle	7339	8.7	102	9.3
Herbivores	12108	14.3	102	9.3
Granivores	4065	4.8	56	5.1
TOT	84610	100	1095	100

socio-demographic characteristics and exogenous variables.

The effect of x_i on is represented by . and are respectively the intercept and the errors for *i*.

The equation is estimated using the 'glm' function in Rstudio of the 'stats' package.

The explanatory variables (Table 3) introduced in the probit model are listed and defined below.

3.2.1. Description of the explanatory variables and expected relation

Utilized agricultural area

It is unclear what effect the initial size of the farm may have on the growth of farm size and on the investment decision. Given the nature and characteristic of the data of this variable, it was decided to introduce as an explanatory variable the "UAA SQ" which represents the squared value of the total initial UAA of the farm regardless of whether it is owned, leased, or free use. The use of the square variable is able to catch the non-linear effect of it. Assuming that farm size can also be a measure of the farm's ability to generate income (Oude Lansink et al. 2001), we expect this variable to have a positive effect on the investment decision.

Value added per hectares

This variable was introduced as an explanatory variable representing the productivity of land. Through this variable, the aim is to understand whether the productivity per hectare derived from the farm's activity affects the growth of the farm size through purchase. According to the literature, the farmer is encouraged to buy land when productivity is high (Ciaian et al., 2010). Therefore, it is assumed that, as productivity per hectare increases, the likelihood of the farmer investing in land increases.

Value added per total work unit

This explanatory variable represents the productivity of farm labour. It is defined as the ratio of value added to total work units. It is assumed that as productivity per labour unit increases, the probability of the farmer purchasing land also increases.

Production Specialisation

When not focusing on a single specialization (e.g., the dairy sector), the researchers introduced a categorical variable related to farm specialisation (e.g Akimowicz et al., 2013) in order to understand whether the type of farm could influence the farm growth or investment decision. This is probably related to the fact that the type of assets needed by a farm varies according to their specialisation (Lefebvre et al., 2015). The data at our disposal include specialised and non-specialised farms. Specialisation is defined according to the technical-economic orientation of the FADN database (FADN, 2018). In contrast to this original classification, in this model farms classified as "mixed crop and livestock" are included in the "non-specialised farms". Specialised farms fall into 9 categories: Cereal crops, arable crops, horticulture, fruit crops, olive crops, viticulture, dairy cattle, herbivores and granivores. Therefore, the explanatory variable was introduced into the model to account for the nine specialisation categories. "*No specialisation*" is used as the reference category since specialisation is one of the main drivers of the search for economies of scale and farm growth. Introducing this variable allows us to understand not only whether specialised farms invest more than non-specialised ones, but also whether the probability of buying land in Italy changes as specialisation changes.

*Utilised agricultural area *Specialisation*

The necessary assets of a farm and the "optimal size" vary depending on the type of farming (Lefebvre et al., 2015; Plogmann et al., 2022). In order to test whether the effect of farm size can vary according to the type of farming, it was decided to combine the two previous variables "UAAsq" and "Specialisation"., (Bremmer and Oude Lansink, 2002).

Rent/Utilised agricultural area

On the one hand, renting allows the farm more flexibility and the possibility to invest its liquidity in other productive assets (Swinnen et al., 2016). On the other hand, land managed as property allows the farmer to use it as collateral capital and thus to have greater access to credit (Swinnen et al., 2016). It was decided to introduce the ratio of the land managed under rent to the total utilised agricultural area of the farm as an inverse measure of the amount of collateral available (Benjamin and Phimister, 2002; Lefebvre et al., 2015). However, expectations on the direction of the effects of this variable are ambiguous.

Machinery Plant Value

Machinery and plant represent another form of collateral capital for a farm. It is assumed that high values of this variable correspond to a farm's recent investment in such productive assets that vary proportionally to the farm area (Plogmann et al., 2022). Furthermore, there is a correlation between the intention to purchase land and investment in other farm assets (Lefebvre et al., 2015).

Therefore, it is hypothesised that the farm is inclined to purchase with the aim of maximising the productive capacity of the asset in which it has previously invested.

Common Agricultural Policy

The Common Agricultural Policy has been identified as an exogenous factor that can influence the land price, but also the decision and level of investment. Subsidies received and capital financing are not the same for every farm and for this reason it can be considered as an endogenous variable linked to structural characteristics of the farm. It was decided to introduce two continuous variables. the first, the ratio of income subsidies per hectare related to the first pillar of the Common Agricultural Policy and COM. The second, the value of the investment subsidies received by the farm between 2013 and 2020 and connected to the measures of the second pillar of the Common Agricultural Policy.

Pre-purchase

Investment in land is a planned, long-term investment (Elhorst, 1993; Oskam et al., 2009; Oude Lansink et al., 2001). The land market is thin and local, and it could be difficult for a farmer to find the amount of land he wants at one time. (Cotteleer et al., 2008; Elhorst, 1993). Therefore, it may happen that the farmer must make more than one purchase to reach the desired level of investment. The dummy variable "Pre_Purchase" assumes a value equal to one when the purchasing farm has already made a purchase previously between 2011 and 2020.

Diversification activities

In the literature reviewed, researchers have not considered the role that farm-related activities can have on farm growth and the investment decision. The related activities that can be stimulated by RDP measures allow for a diversification of the farm activity and represent a different form of income for the agricultural firm. Three dummy variables were introduced for three agricultural related activities: agrotourism, energy production and contracting. It is expected that conducting agricultural related activities increases the probability that the purchase will occur.

Family work units

Family labour can be considered as a fixed input of production within the farm (Elhorst, 1993) and Elhorst's research showed that as family labour input increases, investment increases. Weiss (1999) and Oude Lansink et al. (2001) showed that the number of family members affects farm growth and the investment decision. The variable FWU/TWU was introduced into the model as a measure of how much the business depends on family labour. It is hypothesised that family farms have a greater interest in investing in the farm and farm growth and thus, as this ratio increases, the probability that the farm invests in land increases.

Age of farmer and successor

The age of the farmer and the presence of the successor can affect the growth of the farm and the investment decision. Since there may be several farmers and potential successors with different ages on the same farm, it was decided to create four dummy variables related to the holder and his/her age, and one related to the presence of the successor. In particular, four age ranges were identified to which dummy variables corresponded. Each dummy variable relating to the holder takes the value of one if there are no successors for that observation and if the holder or all the holders fall within the range defined by the dummy variable. If the observation corresponds to more than one holder falling in different age groups, all variables related to the holders will have value zero. The variable relating to the presence of a successor will take a value of 1 if there is at least one potential successor between the ages of 1 year and 40 years. A successor was the one who was classified within the dataset as the 'son' or 'grandson' of the farmer.

Off-farm income

In the literature, it is unclear whether the earning of an off-farm income can be a prelude to leaving the sector or represents a form of income that allows the farm to survive better and not leave the sector (Lefebvre et al., 2015; Plogmann et al., 2022). Based on the available data, a dummy variable was created which takes the value of 1 if the farmer or a member of his or her family who is employed part-time or full-time on the farm earns an off-farm income >2000 euros.

3.2.2. Exogenous factors

As mentioned before, land is considered an asset that can be used as collateral and a safe investment option. The model introduces two external factors: inflation rate and interest rate. It is assumed that when inflation rates rise, the likelihood of purchasing land also increases. However, buying land may require a significant investment that the farm may need to finance through a bank loan. As interest rates go up, the probability of making such an investment decrease. The inflation rate values, *Consumer Price Index-CPI*, are obtained from the ISTAT website every December of the reference year, while the

Table 3 Definition of the explanatory variables and expected effects on the decision to buy land.

Variables	Specification	Type of variable	Expected effect
Farm structural characteristics			
UAAsq	Utilised Agricultural Area square	Continuous	+
Production specialisation	Agricultural specialisations considered are: cereals, arable crops, horticulture, fruit crops, olive growing, viticulture, dairy cattle, herbivores, granivores.	Categorical; Non-specialised farms as reference	+
VA/ha	Ratio between Value added (excluding Income subsidies and COM subsidies) and UAA	Continuous	+
VA/ TWU	Ratio between Value Added and total work units	Continuous	+
UAASQ *Production Specialisation		Continuous*categorical; non-specialised farms as reference	+
VA/ha*Specialisation		Continuous*categorical; Non-Specialised farms as reference	+
VA/TWU*Specialisation		Continuous*categorical; Non-Specialised farms as reference	+
RENT/UAA	The ratio of the rented UAA to the UAA	Continuous	+/-
Machinery_ Plant value	Value of Machinery+ equipment + plant; It represents a proxy variable for level of innovation on farms	Continuous	+
Income subsidies/ha	Aid per hectare provided by First Pillar and COM	Continuous	+
Investment subsidy	Investment aid (Second Pillar)	Continuous	+
Energy Production	Farm produces renewable energy	Dummy	+
Subcontracting activities	Farm carries subcontracting activities	Dummy	+
Agrotourism	Farm carries out agrotourism activities	Dummy	+
Pre_purchase	Purchases made between 2010-2020	Dummy	+
FWU/TWU	Ratio of family work units to total work units	Continuous	+
Farmer sociodemographic characteristics			
FARMER_18_39	The farm manager is between 18 and 39 years old	Dummy	+
FARMER_40_49	The farm manager is between 40 and 49 years old	Dummy	+
FARMER_50_59	The farm manager is between 50 and 59 years old	Dummy	-
FARMER_OVER60	The farm manager is aged 60 old or older	Dummy	-
SUCC_1_39	There is a potential successor aged between 1 and 39 on the farm	Dummy	+
OFFFARM_INCOME	Farmer with non-agricultural income >2,000 euro; Children/ grandchildren, father-in-law, parent, wife employed part-time or regularly with non-agricultural income >2000 euro	Dummy	+
Exogenous variables			
INTEREST RATE	Interest rate recorded for each year on the Ministry of the Treasury website	Continuous	+
INFLATION_ RATE	Inflation rate taken for each year from the ISTAT website	Continuous	-

interest rate is determined by the average annual yield of Italian BTPs (*Multi-year Treasury Bonds*), which can be found on the website of the Italian Treasury Ministry.

3.2.3. Descriptive analysis of explanatory variables

Table 4 shows the descriptive analysis of the variables included in the model, in particular each variable has two values: one for all farms and one for "buyers" (farms investing in land during the reference period). The average initial area of the sample is 33.7 ha, which increases by about 5 ha if only buyers are taken into account. The value related to value added per hectare (VA/ha) exhibits significant variations among the farms. Nevertheless, these differences decrease considerably when only the buyers are considered. Furthermore, the average value of the variable "VA/ha" is lower for the buyers, whereas the median value for buyers is higher than the value within the entire sample. The average value of machinery and plant of the farms that invested in land is more than twice as high as the sample average.

Table 4. Description of the variables and expected effects.

Variable	Min	Mean	Median	Standard Deviation	Max
Farm structural characteristics					
UAA	0.01	33.72	15.1	57.7	1754
UAA_BUYER	0.23	37.73	19.54	62.17	909.75
UAAsq	0	4467.1	227.9	32704.46	3076516.0
UAAsq_BUYER	0.1	5286	381.8	35908.68	827645
VA/ha	-209342	7121	2108	32496.66	3792972
VA/ha_BUYER	-2711	6345	3027	10541.81	117597
VA/TWU	-838045	35197	25057	38215.14	1069950
VA/TWU_BUYER	-18615	43418	32776	43381.17	468484
Machinery and Plant Value	-1628809	34683	6310	114923.9	5450764
Machineryand Plant Value_BUYER	0	79280	30239	210057.8	4900435
Rent/UAA	0	0.38	0.19	0.41	1
Rent/UAA_BUYER	0	0.3446	0.1954	0.3785	1
Income Subsidies/ha	0	260.1	373.8	1071.23	121033.9
Income Subsidies/ha_Buyer	0	386.4	273.6	510.5	6408
Investment subsidy	0	583.9	0	6.866.118	639170
Capital Account_Buyer	0	2008	0	15679	435000
Energy production	0	0.3679	0	0.18816	1
Energy production_ Buyer	0	0.075	0	0.264	1
Subcontracting activities	0	0.03543	0	0.1848	1
Subcontracting activities_buyer	0	0.064	0	0.246	1
Agroturism	0	0.04306	0	0.20298	1
Agroturism_ buyer	0	0.05	0	0.218	1
Pre_Purchase	0	0.0026	0	0.051	1
Pre_Purchase_Buyer	0	0.2	0	0.4	1
FWU/TWU	0	0.837	1	0.25	1
FWU/TWU_Buyer	0.017	0.75	0.92	0.29	1
Farmer sociodemographic characteristics					
18≤FARMER≤39	0	0.14	0	0.35	1
18≤FARMER≤39_ Buyer	0	0.17	0	0.38	1
40≤FARMER≤49	0	0.21	0	0.41	1
40≤FARMER≤49_ Buyer	0	0.25	0	0.43	1
50≤FARMER≤59	0	0.23	0	0.42	1
50≤FARMER≤59_ Buyer	0	0.22	0	0.41	1
FARMER>60	0	0.28	0	0.45	1
FARMER>60_Buyer	0	0.16	0	0.37	1
1≤SUCCESSOR≤39	0	0.09	0	0.29	1
1≤SUCCESSOR≤39_ Buyer	0	0.13	0	0.34	1
OFF_FARM INCOME	0	0.16	0	0.36	1
OFF_FARM INCOME_Buyer	0	0.24	0	0.43	1
Exogenous factors					
Inflation rate	-0.20	0.45	0.5	0.42	1.1
Interest rate	1.14	1.86	1.81	0.77	3.6

There are also important differences in both the median value and the standard deviation. For the ratio of rented area to total farm area and of family labour units to total farm hours, there are no important differences between the farms that purchase and the entire sample. It should be noted that the purchasing farms have on average lower FWU/TWU than the sample farms. The sample farms received, on average, a higher subsidy/hectare and capital financing than the buying farms. Analysing the value of the median and standard deviation of the variable for subsidies/ha related to the first pillar, the farms received a higher subsidy and a greater dispersion of values around the mean. For the period taken into account, there are no important differences in the variables related to the exogenous context.

3.4.2. Empirical models

To the best of our knowledge, there is no research of this type in the literature. Therefore, it was decided to run five probit regression models to better understand how different factors might influence the land investment decision:

- Model 1: the model considers all the variables described above and summarised in Table 5 except for the variables "VA/ha" and "VA/TWU". Thus, the model only considers the "UAAsq" as the farm size variable.
- Model 2: Same as previous model, but the variable "UAAsq" also interacts with specialisation ("UAAsq* Specialisation").
- Model 3: to model 1, the two variables farm productivity per ha (VA/ha) and farm productivity per total work unit (VA/TWU) were included.
- Model4: same as model 3 adding an interaction between the variable "Specialization" and the two variables "UAAsq" and "VA/ha" ("UUAsq* Specialisation", and "VA/ha*Specialisation").
- Model 5: same as model 3 but the "UAAsq", "VA/ha" and VA/TWU variables interact with the specialisation variable.

4. RESULTS

4.1. Correlation analysis and VIF analysis

To verify that there is no relationship among the independent variables, a Pearson correlation analysis and Variance Inflation factors (VIF) were conducted. The results (Appendix 2) show that the indices between the independent variables are far from the threshold values. Thus, it can be ruled out that there is multicollinearity between the variables considered in the empirical model developed.

4.2. Probit regression models

The five implemented models (Tables 5, 6, 7, 8, 9) explain between 19 and 20% of the land investment decision of the observed farms between 2013 and 2020. Even adding the two variables "VA/ha" and "VA/TWU" and the interaction of the variable "Specialisation" with "UAAsq", "VA/ ha", and "VA/TWU" did not improve the model. As the intercept value also shows, there are other factors that were not considered that influenced the purchase decision. In addition to the value of Pseudo R2 not varying, the sign of the independent variables also never changes in the different models implemented. This indicates a good level of robustness of the model.

From the analysis and comparison of the five implemented probit regression models, it is evident that the variables that influenced the land investment decision are: the ratio of the rented utilised agricultural area to the utilised agricultural area (RENT/UAA), the ratio of family work units to total work (FWU/TWU), value of machinery and plant (Mechanization_ plant value), production of renewable energy (Energy production) and "Subcontracting activities", the age of the farmer, the presence of a successor, "Off farm income", and the two exogenous variables respectively inflation rate and interest rate. These variables are statistically significant in all implemented models despite introducing a new variable and the interaction between variables that differentiate model 1 from the other four models.

The results of the five models show that, contrary to what was hypothesized, firm size and land productivity negatively influence the probability of purchasing land, while confirming the positive effect of the variable related to labour productivity. Among these three variables, the variable UAAsq, although it appears to be less statistically significant, it is the one whose effect remains consistent and stable within the five models despite the introduction of the interaction with the specialisation variable (model 2, model 4 and model 5). In this regard, model 2, model 4 and model 5 show that when the farm specialises in permanent crops such as fruit crops and viticulture, and in the production of horticulture, and herbivore livestock, the initial farm size positively influences the land purchase decision. Unlike farm size, the effects of land productivity (VA/ha) and labour productivity (VA/TWU) are lost when these two variables interact with the categorical variable relating to the type of farming (model 3, 4 and 5). Specifically, model 4 and 5 show that productivity per hectare increases the probability of buying land when the farm specialises in fruit crops ($p<0.05$). In contrast to land productivity, labour productivity not only loses its significance when interacting with the specialisation variable but also does not seem to influence the investment decision in any of the specialisation considered.

Regarding the specialization variable, the results are inconclusive. The impact of the few specialization categories that appear to influence the probability of purchase is neither stable nor consistent across the five

Table 5. Probit regression results based on the Model 1 specification.

Variable	Estimate	Std.error	Statistic	p. value	
(Intercept)	-2.02925	0.104478	-19.4227	4.96E-84	***
Farm structural characteristics					
UAASq	-1.2E-06	7.1E-07	-1.72448	0.084622	.
No specialisation					
Cereals	0.050576	0.061861	0.817562	0.413607	
Arable Crops	0.055266	0.05832	0.947622	0.343322	
Horticulture	-0.13114	0.065892	-1.99019	0.04657	*
Fruit Crops	0.127162	0.055627	2.285978	0.022256	*
Olive growing	-0.01181	0.074624	-0.15824	0.87427	
Viticulture	0.124953	0.055829	2.238162	0.025211	*
Dairy cattle	0.039657	0.062406	0.635463	0.525127	
Herbivores	-0.04975	0.05958	-0.835	0.403718	
Granivores	0.014759	0.074215	0.198868	0.842366	
RENT/UAA	-0.1214	0.033698	-3.60269	0.000315	***
FWU/TWU	-0.33055	0.049356	-6.69724	2.12E-11	***
Machinary_ Plant Value	3.19E-07	7.02E-08	4.539024	5.65E-06	***
Subsidies UE/SAU`	1.9E-06	1.06E-05	0.179035	0.85791	
Capital Account	1.74E-06	1.09E-06	1.585145	0.112933	
Energy production	0.145373	0.05958	2.439938	0.01469	*
Subcontracting activities	0.211659	0.058079	3.644351	0.000268	***
Agrotourism	-0.03798	0.061303	-0.61953	0.53557	
Pre_PURCHASE	7.473506	24.51225	0.304889	0.760451	
Farm socio-demographic characteristics					
FARMER_18_39	0.223549	0.080916	2.762715	0.005732	**
FARMER_40_49	0.176139	0.078891	2.23268	0.02557	*
FARMER_50_59	0.102417	0.079003	1.296358	0.194852	
FARMER_OVER60	-0.04849	0.079899	-0.60692	0.543907	
SUCC_1_39	0.210418	0.082712	2.543965	0.01096	*
OFF_FARM INCOME	0.116554	0.032475	3.58899	0.000332	***
Exogenous factors					
Inflation rate	0.102711	0.031766	3.233331	0.001224	**
Interest rate	-0.12116	0.020088	-6.03132	1.63E-09	***
N. observations				84610	
N. farms				24212	
Pseudo R^2				0.1969	
AIC				9449.1	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

models. Specialization affects, not always positively, the dependent variable when considering farms specialized in fruit crops, viticulture, and horticulture. For the latter category, specialization has a negative impact on land acquisition. Models 1 and 3 show that farms specializing in permanent crops are more likely to purchase land. The effect of these specialisations changes when the variables land productivity (VA/ha) and labour productivity (VA/TWU) and the interaction between these two variables and specialisation are introduced into the model.

The farm is not inclined to purchase as the ratio of rented area to UAA (RENT/UAA) and the ratio of FWU to TWU (FWU/TWU) increases. In all models analysed, these variables are statistically significant ($p<0.001$) and negatively influence the probability of buying land. Consistent with the hypothesis, the variable relating to the value of machinery and plant positively affects the probability of purchase. Of the three agricultural-related activities considered, subcontracting activity ($p<0.000$) and energy production ($p<0.5$) are statistically signifi-

Table 6. Probit regression results based on the Model 2 specification.

Variable	Estimate	Std.error	Statistic	p. value	
(Intercept)	-1.97278	0.106974	-18.4418	6.07E-76	***
Farm structural characteristics					
UAASq	-1.8E-05	1.01E-05	-1.76454	0.077641	.
No specialisation			*ref.		
Cereals	0.014812	0.065264	0.226955	0.820458	
Arable Crops	0.035546	0.061341	0.579489	0.562259	
Horticulture	-0.17526	0.068388	-2.56278	0.010384	*
Fruit Crops	0.080197	0.058392	1.373422	0.169621	
Olive growing	-0.01889	0.079616	-0.2372	0.812499	
Viticulture	0.081881	0.058412	1.401778	0.160982	
Dairy cattle	0.016336	0.066267	0.246521	0.805279	
Herbivores	-0.09526	0.062141	-1.53296	0.125286	
Granivores	0.009716	0.078393	0.123935	0.901367	
*UAAsq*No specialisation*			*ref.		
UAAsq*Cereals	1.63E-05	1.02E-05	1.591816	0.111426	
UAA sq*Arable Crops	1.2E-05	1.05E-05	1.144364	0.252473	
UAA sq*Horticulture	1.8E-05	1.02E-05	1.76043	0.078335	.
UAA sq*Fruit Crops	2.21E-05	1.06E-05	2.090571	0.036567	*
UAA sq*Olive growing	-2.8E-05	4.34E-05	-0.64604	0.518253	
UAA sq*Viticulture	2.01E-05	1.05E-05	1.913096	0.055736	.
UAA sq*Dairy cattle	1.36E-05	1.05E-05	1.304731	0.191985	
UAA sq*Herbivores	1.72E-05	1.01E-05	1.705913	0.088024	.
UAA sq*Granivores	-1.1E-06	1.61E-05	-0.06829	0.945555	
RENT/UAA	-0.11873	0.033778	-3.51498	0.00044	***
FWU/TWU	-0.34668	0.050258	-6.8979	5.28E-12	***
Machinary_ Plant Value	3.59E-07	7.3E-08	4.916479	8.81E-07	***
Subsidies EU/SAU`	1.19E-06	1.1E-05	0.107778	0.914172	
Capital Account	1.66E-06	1.1E-06	1.50566	0.132155	
Energy production	0.154468	0.059736	2.58584	0.009714	**
Subcontracting activities	0.217539	0.058278	3.732783	0.000189	***
Agrotourism	-0.04088	0.061488	-0.66492	0.506102	
Pre_PURCHASE	12.8663	40.68004	0.316281	0.75179	
Farm socio-demographic characteristics					
FARMER_18_39	0.21479	0.081078	2.64919	0.008068	**
FARMER_40_49	0.17053	0.079045	2.157388	0.030975	*
FARMER_50_59	0.09462	0.079167	1.195197	0.23201	
FARMER_OVER60	-0.05634	0.080087	-0.70349	0.481748	
SUCC_1_39	0.20331	0.082879	2.453102	0.014163	*
OFF_FARM INCOME	0.116426	0.032544	3.577474	0.000347	***
Exogenous factors					
Inflation rate	0.103918	0.031817	3.266172	0.00109	**
Interest rate	-0.12202	0.020131	-6.06119	1.35E-09	***
N. observations				84610	
N. farms				24212	
Pseudo R^2				9446.3	
AIC				0.1986	

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1.

Table 7. Probit regression results based on the Model 3 specification.

Variable	Estimate	Std.error	Statistic	p. value	
(Intercept)	-2.045	0.105	-19.397	8.18E-84	***
Farm structural characteristics					
UAASq	-1.5E-06	7.7E-07	-2.00308	0.0451687	*
AV/ha	-1.6E-06	9.46E-07	-1.7294	0.08373801	.
AV/TWU	8.63E-07	3.3E-07	2.616924	0.0088726	**
No specialisation			*ref.		
Cereals	0.037215	0.062066	0.599605	0.54876961	
Arable Crops	0.050264	0.058365	0.861204	0.38912569	
Horticulture	-0.10695	0.067537	-1.5835	0.11330853	
Fruit Crops	0.128527	0.055697	2.307599	0.02102146	*
Olive growing	-0.01248	0.074735	-0.16703	0.86734686	
Viticulture	0.122659	0.056015	2.189751	0.02854231	*
Dairy cattle	0.025609	0.062677	0.408584	0.68284533	
Herbivores	-0.05549	0.05965	-0.93024	0.35224614	
Granivores	0.001192	0.076438	0.015592	0.9875601	
RENT/UAA	-0.12716	0.033848	-3.75693	0.00017201	***
FWU/TWU	-0.33126	0.049916	-6.63638	3.2148E-11	***
Machinary_ Plant Value	2.8E-07	7.26E-08	3.856252	0.00011514	***
Subsidies UE/SAU`	2.34E-06	1.18E-05	0.197617	0.84334507	
Capital Account	1.77E-06	1.09E-06	1.620226	0.10518384	
Energy production	0.135872	0.059832	2.270884	0.023154	*
Subcontracting activities	0.207201	0.058176	3.561636	0.00036855	***
Agrotourism	-0.03057	0.061388	-0.49806	0.6184439	
Pre_PURCHASE	7.463387	24.52	0.30438	0.76083871	
Farm socio-demographic characteristics					
FARMER_18_39	0.223439	0.080945	2.760367	0.00577364	*
FARMER_40_49	0.173963	0.078917	2.204384	0.02749733	*
FARMER_50_59	0.100882	0.079033	1.27645	0.20179632	
FARMER_OVER60	-0.04797	0.079945	-0.60002	0.54849104	
SUCC_1_39	0.212866	0.082742	2.572654	0.01009221	*
OFF_FARM INCOME	0.120334	0.03258	3.693551	0.00022114	***
Exogenous factors					
Inflation rate	0.101524	0.031788	3.193758	0.00140434	**
Interest rate	-0.11983	0.02009	-5.96484	2.4488E-09	***
N. observations					
N. farms					
Pseudo R^2		0.197			
AIC		9444.2			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

cant in all models and positively influence the probability of the farmer investing in the farmland. All five models show that carrying out agro-tourism activities does not influence the farmer's decision to invest in land. Subcontracting activity and value in machinery and plant are the two variables related to farm characteristics that are most statistically significant (p<0.001) and positively influence the decision to purchase land.

From the analyses carried out, the two variables related to agricultural policy subsidies do not seem to influence the decision to invest in land. In all other models the two variables have no effect on the dependent variable.

Regarding the sociodemographic variables, the presence of the successor aged between 1 and 39 years positively influences the purchase decision in all the models implemented. The age of the farmer/holder also seems to

Table 8. Probit regression results based on the Model 4 specification.

Variable	Estimate	Std.error	Statistic	p. value	
(Intercept)	-1.99374	0.108933	-18.3024	7.92E-75	***
Farm structural characteristics					
UAASq	-1.9E-05	1.04E-05	-1.85328	0.063842	.
AV/ha	-7.1E-07	2.63E-06	-0.2676	0.789008	
AV/TWU	1E-06	3.51E-07	2.855578	0.004296	**
No specialisation			*ref.		
Cereals	0.072043	0.083218	0.865717	0.386645	
Arable Crops	0.055166	0.066467	0.829975	0.406553	
Horticulture	-0.10531	0.077387	-1.36083	0.173566	
Fruit Crops	0.007115	0.065407	0.108785	0.913373	
Olive growing	0.068962	0.10743	0.641925	0.520922	
Viticulture	0.056009	0.063879	0.876809	0.380591	
Dairy cattle	0.000847	0.077215	0.010964	0.991252	
Herbivores	-0.08485	0.065411	-1.29714	0.194583	
Granivores	0.007139	0.086704	0.082343	0.934374	
*UAAsq*No specialisation*			*ref.		
UAAsq*Cereals	1.75E-05	1.06E-05	1.649353	0.099075	.
UAA sq*Arable Crops	1.24E-05	1.1E-05	1.134469	0.256598	
UAA sq*Horticulture	1.9E-05	1.07E-05	1.76849	0.076979	.
UAA sq*Fruit Crops	2.42E-05	1.09E-05	2.223406	0.026188	*
UAA sq*Olive growing	-3.5E-05	4.61E-05	-0.75006	0.453221	
UAA sq*Viticulture	2.14E-05	1.09E-05	1.967757	0.049096	*
UAA sq*Dairy cattle	1.5E-05	1.08E-05	1.39341	0.163496	
UAA sq*Herbivores	1.86E-05	1.04E-05	1.781584	0.074817	.
UAA sq*Granivores	-5.2E-06	1.74E-05	-0.29753	0.76606	
*VA/ha*No specialisation*			*ref.		
VA/ha*Cereals	-7.3E-05	5.29E-05	-1.38756	0.165271	
VA/ha*Arable Crops	-1E-05	8.97E-06	-1.12181	0.261942	
VA/ha*Horticulture	-3.7E-06	3.45E-06	-1.08411	0.278315	
VA/ha*Fruit Crops	8.52E-06	4.23E-06	2.01371	0.04404	*
VA/ha*Olive growing	-3.4E-05	2.67E-05	-1.26886	0.204491	
VA/ha*Viticulture	2.22E-06	3.93E-06	0.564954	0.572105	
VA/ha*Dairy cattle	-1.6E-06	8.2E-06	-0.19265	0.847235	
VA/ha*Herbivores	-1.1E-05	9.75E-06	-1.13936	0.254554	
VA/ha*Granivores	-1.2E-06	3.17E-06	-0.36899	0.712137	
RENT/UAA	-0.12428	0.034028	-3.65222	0.00026	***
FWU/TWU	-0.3474	0.051617	-6.73025	1.69E-11	***
Machinary_ Plant Value	3.04E-07	7.6E-08	4.001466	6.3E-05	***
Subsidies UE/SAU`	1.85E-05	1.72E-05	1.07629	0.281797	
Capital Account	1.66E-06	1.11E-06	1.500508	0.133483	
Energy production	0.147989	0.06	2.46649	0.013644	*
Subcontracting activities	0.214248	0.058618	3.654989	0.000257	***
Agrotourism	-0.04545	0.062279	-0.72979	0.465517	
Pre_PURCHASE	13.97034	39.52004	0.3535	0.723714	
Farm socio-demographic characteristics					
FARMER_18_39	0.211627	0.081357	2.601209	0.00929	**
FARMER_40_49	0.166384	0.079334	2.097254	0.035971	*
FARMER_50_59	0.090013	0.079462	1.132779	0.257307	

(Continued)

Table 8. (Continued).

Variable	Estimate	Std.error	Statistic	p. value	
FARMER_OVER60	-0.05757	0.08041	-0.71592	0.474042	
SUCC_1_39	0.197505	0.083187	2.374226	0.017586	*
OFF_FARM INCOME	0.116606	0.03276	3.559429	0.000372	***
Exogenous factors					
Inflation rate	0.102362	0.031866	3.212269	0.001317	**
Interest rate	-0.12011	0.020178	-5.95262	2.64E-09	***
N. observations				84610	
N. farms				24121	
Pseudo R^2				0.2	
AIC				9440	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

affect the investment decision. The results from the five models suggest that, in general, being between 18 and 50 years old has a positive effect on the decision to buy land. This probability is even higher if the farmer is aged 18-40. As was hypothesised, the variable on the perception of off-farm income has a positive influence on the purchase decision and is one of the most statistically significant variables (p<0.001).

Consistent with the hypothesis, the variables relating to the external macroeconomic environment, i.e., the inflation and interest rates, influence the investment decision in opposite direction. As the inflation rate increases, the probability of investment decision increases. As the interest rate increases, the probability that the farmer will invest in land decreases.

5. DISCUSSION

In comparison to the few empirical studies on the growth of farm size and investment decision including land, this research is conducted on the entire FADN dataset collected at the national level. The analyses are not based on a sample of farms specialising in one type of farming and/or located in a specific and limited geographical area. Our data are characterised by 90% observations of farms specialising in 9 different productions and differing in farm and socio-demographic characteristics. This heterogeneity of the analysed sample is due to intrinsic characteristics of the Italian agricultural sector. The average surface area of the farms in the sample is about 30 ha above the average UAA recorded in the last ISTAT 2010-2020 census (ISTAT, 2022). This is because the FADN sample is stratified and selects companies with a Standard Output above 8,000 Euro. In any case, the FADN data maintain a certain degree of representativeness of the agricultural sector and represent a useful resource in terms of the amount of data collected in Europe (Centre for European Policy Studies, 2008; Ciaian et al., 2010).

Out of the total observations, only 1095 (1.29%) invested in land between 2013 and 2020. The high number of zero-observations can be attributed to the specific characteristics of the land factor and of the land market, as it is unlikely that farms invest in capital goods every year (Elhorst, 1993; Nilsen and Schiantarelli, 2003; Oskam et al., 2009). The high number of zero-observations and the complexity of ignoring the heterogeneity effect are some of the reasons why quantitative research using micro-data in the investment decision-making process is challenging (Elhorst, 1993).

In the empirical studies on the farm size growth and the investment decision, the role of utilised agricultural area is unclear. The five models do not allow to clarify, but to better understand the role of this variable. The initial farm size influences the investment decision negatively but has a different effect depending on farm specialisation. This had already partly emerged in the study conducted by Bremmer and Oude Lansink (2002), which found that UAA had a positive influence on the size growth of arable crops farms and a negative influence on the growth of farms specialized in protected horticulture. In this research, the positive effect of the variable "UAA SQ" in the case of farms specialising in fruit crops, viticulture and horticulture can be linked to two different considerations. The first one is linked to characteristics of the FADN data. The mean and median value for permanent crops and horticulture farms is lower than for other crops. This could confirm the hypothesis that when a farm is very large it does not tend to invest in the land input (Lefebvre et al., 2015). The second one is related to the intrinsic characteristics of the type of farming.

Table 9. Probit regression results based on the Model 5 specification.

Variable	Estimate	Std.error	Statistic	p. value	
(Intercept)	-1.99498	0.115489	-17.2742	7.36E-67	***
Farm structural characteristics					
UAASq	-2E-05	1.11E-05	-1.81586	0.069391	.
VA/ha	-7.9E-07	2.86E-06	-0.27699	0.781788	
VA/TWU	1.32E-06	1.65E-06	0.799903	0.423767	
No specialisation					
Cereals	0.07122	0.092882	0.766783	0.443211	
Arable Crops	0.09771	0.082926	1.178278	0.238686	
Horticulture	-0.13821	0.097122	-1.42309	0.15471	
Fruit Crops	0.023628	0.081487	0.28996	0.771847	
Olive growing	0.051554	0.121524	0.424233	0.671396	
Viticulture	0.057211	0.077299	0.740133	0.459219	
Dairy cattle	0.082709	0.093701	0.88269	0.377404	
Herbivores	-0.07159	0.080316	-0.89129	0.372772	
Granivores	-0.03472	0.103522	-0.33543	0.737302	
*UAAsq*No specialisation*					
UAAsq*Cereals	1.78E-05	1.13E-05	1.576344	0.114946	
UAA sq*Arable Crops	1.49E-05	1.16E-05	1.281408	0.200051	
UAA sq*Horticulture	1.92E-05	1.16E-05	1.644969	0.099976	.
UAA sq*Fruit Crops	2.51E-05	1.15E-05	2.170636	0.029959	*
UAA sq*Olive growing	-4.5E-05	5.18E-05	-0.86149	0.388966	
UAA sq*Viticulture	2.2E-05	1.15E-05	1.912193	0.055851	.
UAA sq*Dairy cattle	1.7E-05	1.14E-05	1.488127	0.136717	
UAA sq*Herbivores	1.94E-05	1.11E-05	1.747083	0.080623	.
UAA sq*Granivores	-1.1E-05	1.95E-05	-0.56654	0.571024	
*VA/ha*No specialisation*					
VA/ha*Cereals	-8.6E-05	5.8E-05	-1.48766	0.136839	
VA/ha*Arable Crops	-8E-06	8.82E-06	-0.9121	0.361714	
VA/ha*Horticulture	-3.7E-06	3.63E-06	-1.02881	0.303568	
VA/ha*Fruit Crops	9.08E-06	4.61E-06	1.968187	0.049047	*
VA/ha*Olive growing	-4.3E-05	3.07E-05	-1.41899	0.155902	
VA/ha*Viticulture	1.76E-06	4.38E-06	0.401473	0.688072	
VA/ha*Dairy cattle	6.37E-06	8.45E-06	0.753606	0.451086	
VA/ha*Herbivores	-1.1E-05	1.02E-05	-1.0554	0.291243	
VA/ha*Granivores	-1.8E-06	3.54E-06	-0.50791	0.611519	
*AV/TWU*No specialisation*					
AV/TWU*Cereals	2.36E-07	2.02E-06	0.116892	0.906946	
AV/TWU*Arable Crops	-1.7E-06	2.09E-06	-0.81922	0.412663	
AV/TWU*Horticulture	7.66E-07	2.04E-06	0.375434	0.707337	
AV/TWU*Fruit Crops	-7.4E-07	2.09E-06	-0.35518	0.722453	
AV/TWU*Olive growing	2.06E-06	3.96E-06	0.519424	0.603465	
AV/TWU*Viticulture	-5.5E-08	1.86E-06	-0.02988	0.976165	
AV/TWU*Dairy cattle	-2.7E-06	2.1E-06	-1.29293	0.196035	
AV/TWU*Herbivores	-5.1E-07	1.9E-06	-0.27174	0.785824	
AV/TWU*Granivores	5.28E-07	1.79E-06	0.295245	0.767807	
RENT/UAA	-0.12308	0.034091	-3.6102	0.000306	***
FWU/TWU	-0.35157	0.051736	-6.79551	1.08E-11	***
Machinary_ Plant Value	3.23E-07	7.85E-08	4.112943	3.91E-05	***

(Continued)

Table 9. (Continued).

Variable	Estimate	Std.error	Statistic	p. value	
Subsidies UE/SAU`	1.88E-05	1.72E-05	1.093637	0.274114	
Capital Account	1.7E-06	1.11E-06	1.532366	0.125432	
Energy production	0.147376	0.060086	2.452755	0.014177	*
Subcontracting activities	0.213639	0.058772	3.635061	0.000278	***
Agrotourism	-0.04862	0.062315	-0.78028	0.435227	
Pre_PURCHASE	15.53225	38.49138	0.403525	0.686562	
Farm socio-demographic characteristics					
FARMER_18_39	0.209433	0.081497	2.569824	0.010175	*
FARMER_40_49	0.163576	0.079486	2.057915	0.039598	**
FARMER_50_59	0.088748	0.079589	1.115078	0.264817	
FARMER_OVER60	-0.05863	0.080534	-0.72797	0.46663	
SUCC_1_39	0.194356	0.083337	2.332157	0.019692	*
OFF_FARM INCOME	0.113544	0.032812	3.460433	0.000539	***
Exogenous factors					
Inflation rate	0.102934	0.031912	3.225551	0.001257	**
Interest rate	-0.12062	0.020214	-5.96728	2.41E-09	***
N. observations				84610	
N. farms				24612	
Pseudo R^2				0.2	
AIC				9450	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Unlike annual crops, farms producing permanent crops may prefer to establish new orchards on their own land. Obviously, permanent crops require a higher investment cost and return on investment time than annual crops. This could explain why farmers specializing in perennial crops might have an incentive to buy land because it grants them a property right that cannot be guaranteed by the rental contract. This aspect could be particularly relevant in a country like Italy where the law allows leases of less than 15 years. This consideration could explain the positive effect exerted by land productivity in the case of companies specialized in fruit crops.

With regard to the effect of specialisation, the results showed that specialisation per se does not affect the probability of land purchase of the farms in the sample, contrary to what was assumed on the basis on the theoretical literature. The introduction of interactions of this categorical variable with the variables UAA, VA/ha, and VA/TWU has allowed for a better understanding of the behaviour of these factors. The results of the interactions suggest that the effect of firm size, initiation, and farm productivity may vary according to the specialization. Consequently, specialisation plays an important and crucial role in understanding and differentiating the effect of other factors on the probability of land investment. This would confirm what has emerged from the theoretical literature, namely that the factors that can determine farm growth are not independent but interact with each other. The effect of specialisation on farm growth and size had already emerged in the research conducted by Akimowicz et al. (2013) according to which specialisation influenced farm size, changes in farm size and growth intensity in the Midi-Pyrenees region between 2000 and 2007.

Although theoretically it would be desirable for a farm to have a balance between owned and rented land, as the ratio of rented to total area (RENT/UAA) increases, the likelihood of farms increasing their share of owned land decreases. This result could be a confirmation of the findings of the last census of the Italian agricultural sector according to which the amount of land managed under lease has increased and this form of management is also becoming established in Italy (ISTAT, 2022). The descriptive analysis of the data in Annex 1 shows that the farms in the sample specialised in permanent crops have far lower "RENT/UAA" ratios than those specialised in annual crops and livestock farming. Understanding whether isolating this variable would have a different effect depending on the specialisations would be interesting.

The results for the value of capital of machinery and plant confirm what the Bremmer et al. (2002), Lefebvre et al.(2015), and Jeong et al. (2022) research had already found. The former had shown how the degree of mechanisation influenced farm growth for arable crops and horticulture in the Netherlands. Lefebvre et al. (2015)'s study of farmers' investment intentions in six European countries had shown that farmers are most likely to invest in one asset class after they have already invested in another. The correlation between the intention to invest in two types of assets was also shown between land and the purchase of machinery and machinery replacement. Furthermore, research by Jeong et al. (2022) had shown that the value of inventory and fixed assets were positively related to land acquisition.

To the best of our knowledge, no research in the literature has included variables related to agricultural policies and activities in models to explain farm growth or land investment. The results on subsidies and funding related to European Agricultural Policies do not confirm the hypothesis that agricultural policies can directly influence the decision to invest in land. Rather, subsidies could be seen as a useful tool for the farmer to manage periods of market fluctuations rather than as a form of income to make a long-term investment. The RDP measures do not directly finance land purchases, but they encompass financing for investments in tangible farm assets, innovation, and farm diversification. The correlation analysis allows us to exclude the presence of a relationship between "Capital account" and the value of machinery, and of these two variables with the dummy variable relating to subcontracting and energy production. The results for the latter two variables and the forms of income derived from off-farm income lead to the conclusion that the investment in a capital good is supported by forms of income derived from a diversification of the activities carried out by the farmer.

The results confirm the conclusions of previous research on the positive effect of the presence of a successor and a young farmer. Indeed, in line with the hypothesis, the presence of a young farmer or a farmer under 50 years of age positively influences the probability of purchase. This is probably due to the fact that the age of the holder has an impact on the time horizon of the investment.

The results for the introduced exogenous variables confirm the hypothesis. The macroeconomic context influences the investment decision. The inflation rate was not included in the empirical literature analysed on farm size growth and investment decision, while the results regarding the cost of capital confirm what has already found by Elhorst (1993) and Oskam et al. (2009). It is worth noting that there were no significant changes in interest rates and inflation rates during the considered period. It would be necessary and useful to observe farms over a longer period to fully understand the impact of exogenous factors related to the macroeconomic context, such as those that have occurred in the last two years.

The models explain 19% of the land investment decision, suggesting that there are other factors not considered that influence the decision to purchase land. The relative Pseudo R^2 value is lower than that of other studies on structural change but more in line with studies on investment decision. As in other research (i.e. (Akimowicz et al., 2013), the available data and their quality have influenced the choice of explanatory variables and the type of analysis. It was not possible to conduct the analysis on balanced panel data and include explanatory variables related to the financial position of the farm, its local area, and national and municipal land regulation. Investments in capital goods could represent a significant investment that may even require a bank loan. These are rational decisions that the farmer makes after analysis of the internal and external business contest. Therefore, in order to study and understand this type of investment it would be appropriate to carry out the analysis on farms observed over a long period of time. When testing and implementing the model, we attempted to include the regional variable as a categorical variable. However, this variable reduced the statistical significance of other explanatory variables related to farm structure. The regional variable already contains information related to other variables such as specialisation, UAA, and RENT/UAA. This is because the Italian territory is highly heterogeneous regarding territorial structure, production, and farm management. For this reason, it was preferred not to include it. Furthermore, the land market is thin and local, and the absence of precise geolocation data for farms prevented the consideration of other external factors. Farmers tend to buy land near their activity to reduce and avoid downtime (Cotteleer et al., 2008). In this regard, the introduction of variables related to the right of pre-emption could be useful in understanding the Italian land market, given that such right is provided for within Italian legislation.

Finally, in addition to data availability, the lack of literature has influenced the design of the theoretical framework for developing the conceptual model and the interpretation and discussion of the results.

6. CONCLUSIONS

This research represents a first attempt at an ex-post study using microdata to identify the factors that have influenced the land investment decision in Italy by introducing variables related to structural and socio-demographic characteristics, economic performances, agriculture policies and the macroeconomic environment. The results showed that more than subsidies provided by agricultural policies, income-generating activities from other on-farm and off-farm activities positively influence land investment. In addition, specialisation appears to be an important factor not so much in the purchase decision, but in understanding and differentiating the effect of other farm structural factors on the likelihood of land investment. The variables RENT/UAA and Family Work units/Total Work Units are the main farm characteristics that negatively influence the probability of purchasing land in Italy. As expected, the presence and age of the successor have been confirmed as important sociodemographic characteristics for growth through acquisition. The research shows that the interest rate and inflation rate influence the probability of buying land. The five implemented models explain approximately 20% of the land investment decisions of the analysed farms. Therefore, other factors and the interaction between factors can influence farmers' decisions.

The lack of a well-structured database conditioned and limited this research as well as the empirical research analysed in the literature on farm size growth and land investment decisions. In particular, probit analysis on a balanced panel of farms observed over a long period of time was not possible with the available database. Investment in land is much less frequent than other types of investment. It is made following a farmer's consideration of available farm assets, his/her own financial resources, the supply of land on the local land market, and macro-economic factors (i.e. interest rate and inflation rate). For this reason, the analysis of a balanced panel of farms observed for a long time could allow a more accurate analysis of the effect of determinants on the decision to purchase land. In addition, the database influenced the identification and selection of variables that could best capture the determinants that may influence the farmer's decision and prevented the introduction of variables related to e.g. the financial situation of the farm and land regulation.

In the future, the problem of the structured database could be solved by linking the databases available to different Italian institutions. The availability of a well-structured database could be useful to capture and continuously monitor the dynamics and changes within the land market and in farm management. The growth and spread of rented land and the entry into the agricultural sector of young farmers willing to purchase land could require the updating and adaptation of current land policies and regulations that directly and indirectly influence farm management choices and could provide tools, including financial ones, to effectively support generational turnover within the sector by facilitating access to land and avoiding the loss of agricultural land.

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APPENDIX

Appendix 1. Descriptive analysis of sample farm size based on farm specialization

Specialisation	Min			VA/UL	Mean			VA/TWU	Median			VA/TWU	sd			VA/TWU	Max			VA/TWU
	UAA	RENT/UAA	VA/ha		UAA	RENT/UAA	VA/ha		UAA	RENT/UAA	VA/ha		UAA	RENT/UAA	VA/ha		UAA	RENT/UAA	VA/ha	
No Specialised	0.01	0	-9964.8	-232589	32.33	0.38	4014.3	26437	15.77	0.21	1340.7	19547	51.39	0.41	29376.48	26155.84	920.1	1	1486980	574922
Annual crops	0.06	0	-71723	-153306	36.17	0.41	9380	34724	18	0.28	1370	24767	60.23	0.42	35042.68	36542.29	1754	1	1395764	1069950
Cereals	0.06	0	-13250	-153306	51.51	0.4	1039.6	38694	30	0.26	867.9	26348	67.6	0.41	1542	39848	1279	1	103921.6	509952
Arable crops	0.29	0	-20331	-111453	39.3	0.44	2719.2	32453	21.35	0.41	1083.4	23383	64.7	0.42	5877.1	38000	1754	1	120828.1	1069950
Horticulture	0.07	0	-71723	-107227	16.9	0.38	25721	33388	4.5	0.15	9282	25162	37.29	0.42	59108	30447	1101.75	1	1395764	617558
Permanent crops	0.2	0	-35024	-96116	14.73	0.27	6033	29864	7.81	0	3928	23011	25.13	0.39	7820.81	27845	526.87	1	248960	728767
Fruit crops	0.2	0	-5497	-29242	14.03	0.26	6514	29666	7.53	0	4472	23411	24.5	0.38	7182.5	24810	413	1	7182.5	416912
Olive crops	0.85	0	-3148	-23401	18.86	0.26	2903	23265	10.55	0	2199	19409	28.43	0.39	2953.2	18167	394	1	67758	205770
Viticulture	0.3	0	-35024	-96116	13.85	0.28	6741	32589	7.14	0	4185	24348	24.25	0.39	9299	32924	526.87	1	248960	728767
Livestock sector	0.05	0	-209342	-838045	51.74	0.46	6680	44475	28	0.44	1727	31113	73.45	0.41	44480	49666	1687.54	1	3792972	863036
Dairy cattle	0.2	0	-9222	-164891	49.13	0.48	4292	48736	27	0.49	2917	37914	65.66	0.4	5119	42163	770	1	90039	796655
Herbivores	0.1	0	-52896	-234751	61.15	0.47	2347.2	33066	36.26	0.44	853.1	24237	83.43	0.41	12450	36867	1687	1	403098	587929
Granivores	0.05	0	-209342	-838045	28.43	0.44	23898	70768	13.19	0.37	7439	52388	43.27	0.42	102830	76804	514.55	1	3792972	863036

Appendix 2 Analysis of relationships among independent variables

Table A1. Results of Pearson correlation analysis (Part 1).

Variable	UAASq	VA/ha	VA/TWU	Specialization	RENT/UAA	FWU/TWU	Machinery_ Plant Value	Subsidies UE/ SAU`	Capital Account	Energy production	Subcontracting activities	Agrotourism	Pre_ PURCHASE
Farm structural characteristics													
UAASq	1	-0.023	0.167	0.023	0.048	-0.140	0.206	0.000	0.020	0.043	0.027	0.027	0.007
VA/ha	-0.023	1	0.123	0.028	-0.016	-0.120	0.015	0.068	0.008	0.019	-0.010	0.014	-0.001
VA/TWU	0.167	0.123	1	0.119	0.108	-0.152	0.272	0.105	0.038	0.151	0.045	0.004	0.023
Specialization	0.023	0.028	0.119	1	0.029	-0.028	0.037	-0.004	0.027	0.055	-0.069	0.003	-0.003
RENT/UAA	0.048	-0.016	0.108	0.029	1	0.023	0.045	0.017	0.025	0.047	0.065	-0.007	-0.005
FWU/TWU	-0.140	-0.120	-0.152	-0.028	0.023	1	-0.184	-0.055	-0.064	-0.076	-0.001	-0.060	-0.024
Machinary_ Plant Value	0.206	0.015	0.272	0.037	0.045	-0.184	1	0.044	0.121	0.281	0.083	0.037	0.041
Subsidies UE/SAU`	0.000	0.068	0.105	-0.004	0.017	-0.055	0.044	1	0.029	0.015	-0.004	-0.015	0.000
Capital Account	0.020	0.008	0.038	0.027	0.025	-0.064	0.121	0.029	1	0.058	0.008	0.017	0.030
Energy production	0.043	0.019	0.151	0.055	0.047	-0.076	0.281	0.015	0.058	1	0.060	0.071	0.018
Subcontracting activities	0.027	-0.010	0.045	-0.069	0.065	-0.001	0.083	-0.004	0.008	0.060	1	0.00	0.01
Agrotourism	0.027	0.014	0.004	0.003	-0.007	-0.060	0.037	-0.015	0.017	0.071	-0.004	1	0.003
Pre_PURCHASE	0.007	-0.001	0.023	-0.003	-0.005	-0.024	0.041	0.000	0.030	0.018	0.010	0.003	1
Farm socio-demographic characteristics													
FARMER_18_39	2E-05	-0.010	0.004	0.042	0.168	0.000	0.033	-0.001	0.038	0.001	0.008	0.021	0.005
FARMER_4049	4E-03	0.014	0.046	0.040	0.099	-0.042	0.020	-0.003	0.013	0.011	0.019	0.013	0.009
FARMER_5059	-6E-03	0.004	0.015	-0.006	-0.008	-0.017	-0.014	-0.004	-0.017	0.002	0.007	-0.013	-0.002
FARMER_OVER60	-2E-02	-0.019	-0.083	-0.113	-0.183	0.026	-0.085	-0.008	-0.037	-0.049	-0.053	-0.049	-0.020
SUCC_1_39	2E-02	0.012	0.023	0.070	-0.025	0.033	0.064	0.002	0.017	0.046	0.023	0.047	0.012
OFF_FARM INCOME	-3E-03	-0.018	-0.064	-0.015	-0.073	-0.016	0.005	-0.018	-0.003	0.001	0.002	0.037	0.019
Exogenous factors													
Inflation rate	5E-03	0.001151	0.008	0.001	-0.003	0.006	-0.001	-0.027	-0.008	-0.001	-0.001	-0.003	-0.003
Interest rate	6E-03	0.008741	-0.015	0.001	-0.032	-0.004	-0.001	-0.011	0.017	-0.020	-0.013	-0.016	-0.016

Table A1. Results of Pearson correlation analysis (Part 2).

Variable	FARMER_ 18_39	FARMER_ 4049	FARMER_ 5059	FARMER_ OVER60	SUCC_1_39	OFF_FARM INCOME	Inflation rate	Interest rate
Farm structural characteristics								
UAASq	0.000	0.004	-0.006	-0.015	0.022	-0.003	0.005	0.006
VA/ha	-0.010	0.014	0.004	-0.019	0.012	-0.018	0.001	0.009
VA/TWU	0.004	0.046	0.015	-0.083	0.023	-0.064	0.008	-0.015
Specialization	0.042	0.040	-0.006	-0.113	0.070	-0.015	0.001	0.001
RENT/UAA	0.168	0.099	-0.008	-0.183	-0.025	-0.073	-0.003	-0.032
FWU/TWU	0.000	-0.042	-0.017	0.026	0.033	-0.016	0.006	-0.004
Machinery_ Plant Value	0.033	0.020	-0.014	-0.085	0.064	0.005	-0.001	-0.001
Subsidies UE/SAU`	-0.001	-0.003	-0.004	-0.008	0.002	-0.018	-0.027	-0.011
Capital Account	0.038	0.013	-0.017	-0.037	0.017	-0.003	-0.008	0.017
Energy production	0.001	0.011	0.002	-0.049	0.046	0.001	-0.001	-0.020
Subcontracting activities	0.01	0.02	0.01	-0.05	0.02	0.00	0.00	-0.01
Agrotourism	0.021	0.013	-0.013	-0.049	0.047	0.037	-0.003	-0.016
Pre_PURCHASE	0.005	0.009	-0.002	-0.020	0.012	0.019	-0.003	-0.016
Farm socio-demographic characteristics								
FARMER_18_39	1	-0.211	-0.222	-0.256	-0.134	-0.003	-0.010	0.005
FARMER_4049	-0.211	1	-0.283	-0.325	-0.170	0.021	0.002	0.014
FARMER_5059	-0.222	-0.283	1	-0.342	-0.179	0.019	0.002	-0.014
FARMER_OVER60	-0.256	-0.325	-0.342	1	-0.206	-0.119	0.001	-0.004
SUCC_1_39	-0.134	-0.170	-0.179	-0.206	1	0.103	0.006	-0.006
OFF_FARM INCOME	-0.003	0.021	0.019	-0.119	0.103	1	-0.005	-0.014
Exogenous factors								
Inflation rate	-0.010	0.002	0.002	0.001	0.006	-0.005	1	0.326
Interest rate	0.005	0.014	-0.014	-0.004	-0.006	-0.014	0.326	1

Table A2. Results of Variance Inflation factors (VIF).

Variable	GVIF	Df	GVIF^(1/(2*Df))
UAASq	1.307725	1	1.143558
VA/ha	1.225749	1	1.107136
VA/TWU	1.327513	1	1.152178
Specialization	1.593554	9	1.026225
RENT/UAA	1.120124	1	1.058359
FWU/TWU	1.224457	1	1.106552
Machinary_ Plant Value	1.420266	1	1.191749
Subsidies EU/SAU`	1.053369	1	1.026337
Capital Account	1.027879	1	1.013844
Energy production	1.172852	1	1.082983
Subcontracting activities	1.038119	1	1.018881
Agrotourism	1.02539	1	1.012615
Pre_PURCHASE	1	1	1
FARMER_18_39	5.514689	1	2.348338
FARMER_4049	6.76246	1	2.600473
FARMER_5059	6.554576	1	2.560191
FARMER_OVER60	6.17286	1	2.484524
SUCC_1_39	4.445275	1	2.108382
OFF_FARM INCOME	1.056985	1	1.028098
Inflation rate	1.11444	1	1.05567
Interest rate	1.117942	1	1.057328

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Soils and ecosystem services: policy narratives and instruments for soil health in the EU

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Abstract. European soils and their status is a matter of concern that has entered the policy arena and the objective to restore soil health is part of the Soil strategy to 2030. Aim of this study is to explore the integration of the concept of soil health and the provision of soil ecosystem service by conducting i) a content analysis of EU policies and ii) a scoping review of literature over policy instruments for soil governance. Results show a focus on soil fertility, mainly soil organic matter, while services such as conservation of biodiversity or cultural heritage still appear underrepresented. Findings are reinforced by the gap in literature, providing little evidence of policy instruments contributing to soil health. A more coordinated effort among policy sectors is required to prioritize soil health in the EU; invesitgating the role of market-based instruments could complement what public policies are lacking.

Keywords: soil health, ecosystem services, policy instruments, incentives, soil monitoring law.
JEL Codes: Q10, Q15, Q57.

1. INTRODUCTION

Soil is a non-renewable and multi-functional resource which contributes significantly to global food security, hosting one of the greatest concentrations of biodiversity on the planet and providing further Ecosystem Services (ES) that include air and water purification, climate regulation and conservation of cultural heritage (FAO and ITPS, 2015). However, soils are under great pressure derived from both bio-physical processes and human-driven processes, such as erosion, floods and landslides, loss of soil organic matter, salinisation, contamination, compaction, sealing, and loss of soil biodiversity (Turpin et al., 2017; IPBES, 2018). When those processes impact soils' status, their ability to provide ES is reduced or lost, with an estimated cost of around 50 billion euros yearly in the EU (COM 2021/699). Therefore, maintaining and enhancing the capacity of soils to provide ES can bring economic benefits and is critical to sustain ES and ensure human well-being (MEA, 2005).

Acknowledging the interconnectedness between soil, plant, animal (humans included) and ecosystem health as framed by the One Health concept (van Bruggen et al., 2019), soil health can be understood as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems"[1]Primarily drawing from soil quality, the adoption of soil health in scientific literature started in the 1990s and developed by recognizing the role of biological processes in soil formation and functioning, identifying soils as ecosystems, mapping soils' biodiversity and assigning to it an international scale (Lehmann et al., 2020). Soil health can be a useful metaphor that relates ecosystem functioning to human well-being, but its understanding and interpretation highly depends on the actors, issues, and values at stake in a given context (Janzen et al., 2021).

Recently, the soil health concept has entered the EU policy arena (Panagos et al., 2022) as testified by the Soil Strategy for 2030, included in the European Green Deal proposal to reach carbon neutrality by 2050. The strategy defines healthy soils as in good chemical, biological and physical condition, and thus able to continuously provide as much ES as possible; it also aims at restoring 60 to 70% of European soils, currently considered unhealthy (COM 2021/699). There is increasing evidence of the connection between decreasing soil health and loss of ES (Lehmann et al., 2020; IPBES, 2018); for instance, freshwater availability is affected by a reduction of soil organic matter in agricultural and forest soils (Keesstra et al., 2021); soil sealing in urban areas impacts human physical and mental well-being by hindering access to green areas (McElwee, 2021). However, investigating ES when applied to soil requires a deep understanding of chemical, physical and biological soil properties, additionally recognising benefits derived from soil components at different spatial scales (i.e., plot, field, landscape, regional area, countries, global). Comprehensive studies on valuation of soil ES are rare to be found often addressing methodological limitations derived from need of suitable and comparable indicators (Vysna et al., 2022; Baveye et al., 2016; Dominati et al., 2014).

If the current EU Soil Strategy (COM 2021/699) adopts a definition of soil health that heavily relates to ES, it can prove useful to understand to what extent this definition is integrated into actual soil governance. By soil governance we mean the mix of different policies and set of instruments available for regulating, incentivizing, and informing about the management of soils (Heuser, 2022; Rogge and Reichardt, 2016; Juerges and Hansjürgens, 2018). Recent reviews have investigated available policy instruments to soil governance worldwide (Juerges and Hansjürgens, 2018) and in EU Member States (Ronchi et al., 2019), however without addressing the connection to soil ES.

This study aims to explore how far the concept of soil health and the provision of soil ES is integrated into current policy instruments in the EU by conducting a content analysis of policy documents. To the best of our knowledge, no such works exist at EU level. Moreover, we aim at individuating proof of effective implementation of policy instruments for delivery of ES by fostering soil health.

The topic of soil health holds growing interest both in the scientific and policy community, considering the upcoming EU Soil Monitoring Law. If the law is implemented it will constitute the first binding instrument for soil regulation at EU level and will require MS to achieve responsive agri-environmental interventions within national public policy. Addressing governance gaps and policy needs could contribute in ensuring purposeful action towards soil health. In the next section, the policy narrative of soil health is framed in order to gain an overview of definitions that characterize soil health as well as policy instruments referring to sustainability transition. Following the methodology will be presented. Results and discussions are structured in two sections, to address both research aims.

2. FRAMING THE SOIL HEALTH NARRATIVE

Understanding the concept of soil health requires some clarification: while the previously used attributes of soil fertility and soil quality refer to the local/regional level and focus on productivity, nutrients, and water cycles (Bünemann et al., 2018), soil health is told to encompass a larger range of ES. Lehman et al. (2022) include in the description of soil health "public" ES such as climate mitigation and control, access to recreational and spiritual places to improve human wellbeing and provision of habitat for above and below ground biodiversity. Janzen et al. (2021) refer to soil health as a metaphor for an organism in good conditions and suggest considering soil as a (complex) organism, defining its healthy conditions as "[...] the vitality of a soil in sustaining the socio-ecological functions of its enfolding land" (Janzen et al., 2021, p. 2).

Therefore, according to the authors, soil health allows to relate the issue to a broader public of stakeholders – not only farmers and landowners, but also local and national authorities – underlying how far sustainable soil

[1] As defined by the Intergovernmental technical panel on soils, available at: Towards a definition of soil health (fao.org), accessed July 3rd 2024.

governance goes beyond the field level thus constitutes a policy concern (Juerges and Hansjürgens, 2018).

The body of literature describes how emerging concepts and needs enter the policy agenda and then into policy cycle. Shanahan et al. (2011) claim that policy narratives are central to the policy cycle: being created by a broad set of actors, narratives are the device through which policy programs and the connected values and beliefs are communicated. The process of creating narratives finds its counterpart in the agenda setting, that is the operationalization of (certain) issues into a decisional level, the two phases happen ongoingly and alternately (Gonzalez Lago et al,. 2019).

From a political point of view, as described by Montanarella and Alva (2015), even though soils are essential to sustainable development, they have never been the specific focus of a multilateral environmental agreement. Given the diversity of services that soils can provide, it is no surprise to find a set of policy domains competing for land use, including agriculture, forestry, protected areas, urbanization, and energy production (Löbmann et al., 2022).

Focusing on the EU, after the proposal, discussion, and withdrawal of a Thematic strategy for soil protection in 2014, MS have found themselves lacking a comprehensive framework and have been relying on national regulations (Heuser, 2022).

Authors diversely define policy instruments for environmental governance, nuancing from public to market driven and being more or less voluntary or binding, resulting in a quite large range of options (Vatn, 2018). For instance, Piñeiro et al. (2020) divide incentives for sustainable agricultural practices in regulatory measures, market and non-market based incentives, and cross-compliance between payments and standards. The FAO provides a framework to display the numerous instruments available for environmental protection and remuneration, involving individuals, private and public sector, and considering their level of compulsoriness (Garrett and Neves, 2016). Ronchi et al. (2019) refer to *measures* for soil protection and individuate: regulatory, economic, information, monitoring and research and innovation. Juerges and Hansjürgens (2018) outline instruments for soil governance as: regulatory, planning, economic, informational, co-operative. For the sake of this study, we adopt the approach of Rogge and Reichardt (2016), that analyzed sustainability transitions and refer to policy instruments as tools to pursue a goal, dividing them into three catheogories: regulations, incentives, and information. Given that pursuit of soil health is currently high on the EU political agenda, we found the approach of linking policy instruments to wider objectives displayed in policy strategies (Rogge and Reichardt, 2016) as better suiting the purpose of this study. Hence, we define regulatory instruments as those applying restrictions, economic as those providing monetary resources and information as those producing and delivering knowledge. Table 1 provides an overview of the adopted definitions of policy instruments for soil governance.

3. MATERIALS AND METHODS

The aim of this study is to analyse the level of integration of the soil health narrative in EU soil governance. This broader objective is pursued firstly by exploring the conceptual integration of keywords related to soil health into policies, which can be done by conducting a content analysis on the explicit use of terminology (Neill et al., 2022). Secondly, by reviewing literature over available policy instruments that aim at incentivising soil health and the provision of related ecosystem services. To address these aims was adopted a twofold approach, based on i) content analysis of the integration of soil health along different EU policies and ii) narrative review of literature on existing shreds of evidence linking policy instruments to ES (Grant et al., 2009). The methodology consisting in analysing content of available EU policy instruments and existing evidences over policy instruments' effect on soil ES allowed to explore and understand the topic of soil health and frame it as the current policy narrative (Gonzalez Lago et al., 2019).

3.1. Content analysis of EU instruments

In the first phase, grey literature on EU regulatory instruments that tackle soil and land related issues was collected to compile a policy inventory. To do so we used as a reference the recent review by Heuser (2022), double checking with laws and strategies related to soil and land as indicated on the EU website (https://environment.ec.europa.eu/topics/soil-and-land_en), and finally integrating further regulations with citation chaining. Three main typologies of regulatory instruments were found: i) laws, directives and regulations, ii) Environment Action Plans (EAP), that set out goals and legislative proposals for EU environment policy and iii) horizontal strategies, that outline how to integrate SDG into EU policy priorities. A total of 28 regulatory instruments was finally included in the inventory.

Content analysis of the policy inventory was conducted by deductive coding (Saldaña, 2013) with the help of SketchEngine (Lexical Computing, 2003), free software for text analysis that allows to analyse frequency of keywords through large text bodies. Sticking to the EU definition of soil health, as the capacity to deliver as

Table 1. Definition of policy instruments for soil governance and related keywork search, adapted by the authors from Rogge and Reichardt (2016) and Garrett and Neves (2016).

Instrument category	Typology	Instrument definition Examples (and sources)	Keyword search
Regulation	Property rights and rights	Privatization of natural resources. Owners can be individuals, private entities, communities, large entities e.g. the state (Bartkowkski et al., 2018)	soil-health AND ecosystem-service* AND property OR property-use OR property-use-right
	Prohibition of use and mandatory farm set aside	Access to land is limited to certain land uses or partly given up for restoration and conservation (Bartkowkski et al., 2018)	soil-health AND ecosystem-service* AND prohibition-of-use OR prohibition
	Taxes / charges	Applied to land use or management practices that are not compatible with agro-environmental principles, e.g. taxation on pesticides (Ronchi et al., 2019)	soil-health AND ecosystem-service* AND tax OR taxes OR charge*
	Conservation	Used to reduce or compensate the costs of conservation of portions of land, e.g. by nonprofit organizations like land trust (Vatn, 2018)	soil-health AND ecosystem-service* AND conservation
	Permits and quotas	Quantified rights to use a natural resource and eventually trade the quotas, e.g. fishing quotas (Vatn, 2018)	soil-health AND ecosystem-service* AND permit* OR quota* OR cap OR carbon-market
	Subsidies	Governments link compliance to agro-environmental standards with direct payments, e.g. GAEC (Runge et al., 2022)	soil-health AND ecosystem-service* AND subsid*
	Offsets	Compensation for land development into (on/off) site environmental projects, e.g. planting forests (Vatn, 2018)	soil-health AND ecosystem-service* AND offset* OR offset-program OR emission-offset*
Information		Raising awareness and delivering knowledge by means of research, extension services or certification schemes to farmers, advisers, consumers (Juerges and Hansjürgens, 2018; Bampa et al., 2019)	soil-health AND ecosystem-service* AND research OR research-program* OR advisory OR advisory-service* OR extension-service* IR label* OR certific* OR standard*
Incentive	Payments for ES	Providers of specific ES are compensated for positive outcomes, e.g. farming practices respectful of water bodies (Vatn, 2018)	soil-health AND ecosystem-service AND payment* OR pes
	Voluntary farm set aside	Landowners give up part of land for restoration and conservation purposes in exchange of payments, e.g. 4% of non-productive arable land (Runge et al., 2022)	soil-health AND ecosystem-service* AND farm-set-aside OR set-aside
	Green Public procurement	Public authorities procure goods and services based on environmental requirements, e.g. ecolabel for school canteens (Neto et al., 2018)	soil-health AND ecosystem-service* AND green-public-procurement OR public-procurement
	Corporate social responsibility	Declaration of business strategies to contribute in benefitting the environment, e.g. NGO assessing corporations' activities (Vatn, 2018)	soil-health AND ecosystem-service AND corporate-social-responsibility OR CRS

many ES as possible, we included three main keywords in the coding, namely 'soil', 'soil health' and 'ecosystem services'.One further key word, i.e. 'carbon', emerged so frequently associated with soil (e.g. soil organic carbon) during the analysis that was finally added (complete overview in Appendix I, Figure 2).

3.2. Review of policy instruments

In a second phase, a narrative review of literature was conducted, to explore the connection between delivery of ES from healthy soils, and policy instruments to foster these practices. While systematic literature reviews hold a narrow scope and are used for investigating problems that have already been explored in literature, narrative reviews are most frequently applied to explore a topic that has a rather broad coverage and that is evolving through time (Byrne, 2016). Even if systematic review apply a more rigorous methodology, the flexibility of narrative reviews was beetter suitable for addressing the large range of keywords of incentives to be linked to soil ES, as well as the ever-changing understanding of the concept of soil health. Peer reviewed papers were searched on the Scopus database,

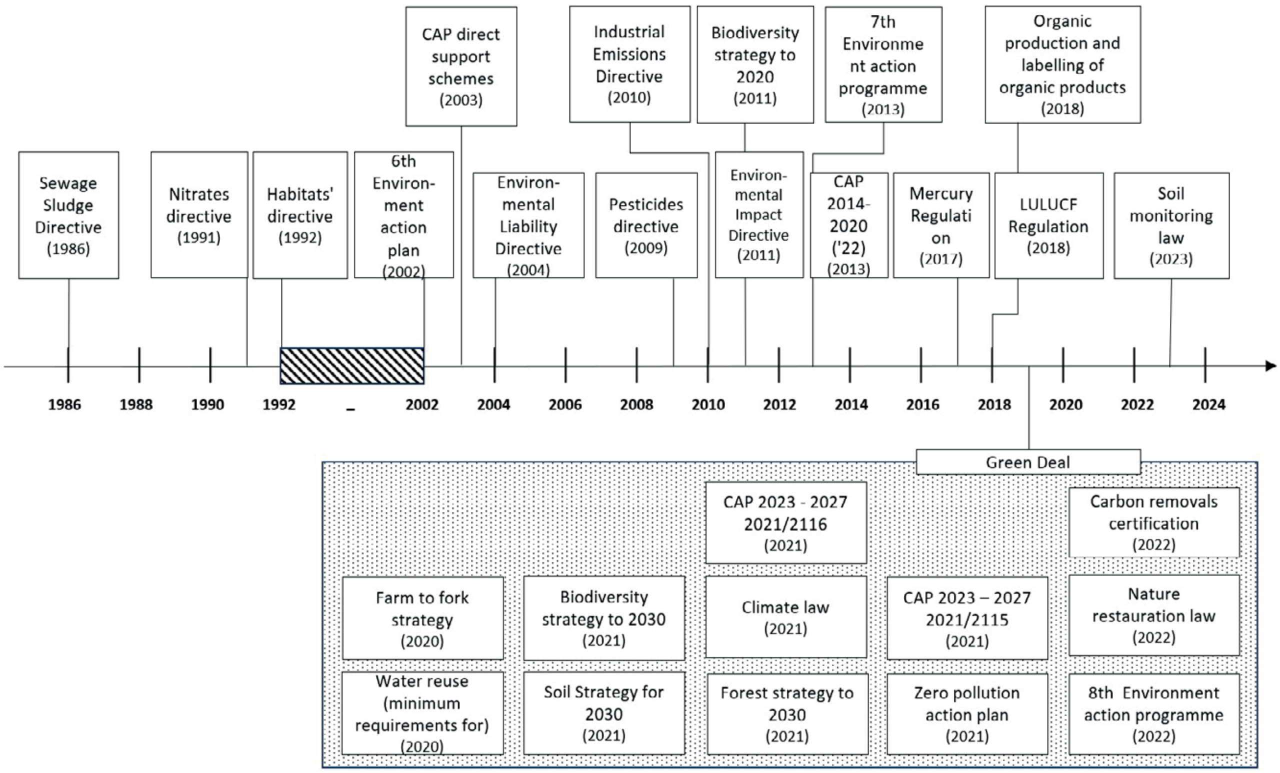

Figure 1. Overview of EU policy instruments relating to soils, source: authors' elaboration.

combining the keywords "soil-health" AND "ecosystem-services" AND policy instruments basing on the FAO indications over incentives for ES (Garrett and Neves, 2016); the complete overview of keywords' search is to be found earlier in Table 1. Searching criteria included search words in title, abstract and keywords, filtering was limited to papers and reviews published until 2023, accessibility and language were first criteria for exclusion . Secondly, relevance of the content was based on a first reading of methodologies and results, assessing whether ES had only been used as keyword in the abstract or also further addressed. Consequently, soil ES where counted as 1 every first mention and example were listed and divided into provisioning, regulating, cultural and supporting ES, following the MEA (2005) classification.

4. RESULTS

4.1. Content analysis: Integration of the soil health concept from a normative and narrative perspective

Soil in the EU started to be subject of policy almost 40 years ago, often implicitly integrated in different policy instruments during the past decades (Heuser et al., 2022; Ronchi et al., 2019). The timeline below (Figure 1) shows the different types of policy instruments that concern soil governance at EU level. Soils don't figure in the timespan between 1992 and 2002, thus for graphical purposes the decade was represented as a striped rectangle. As can be observed, integration of soils into several policy instruments increases in the latter part of the timeline, marked by the Green Deal set of policies, that during 2021 and 2022 delivered several strategies aiming to protect, conserve and enhance EU's natural capital, and safeguard the health and well-being of citizens from environment-related risks and impacts. The Soil Health strategy to 2030 (COM 2021/699) listed objectives that address different policy sectors including agriculture, forestry and urbanization, i.e. to reduce losses of nutrients and use of pesticides, to reduce emissions from land use and land use change and forestry sector (LULUCF); and more broadly natural and environmental management, i.e. to combat desertification, restore degraded carbon rich ecosystems; to improve status of water quality; to remediate contaminated sites).

In the upcoming paragraph some key findings on conceptual integration of soil health across different policy sectors will be presented, for a complete graphical overview please see Appendix I.

a. Agricultural sector

Policy instruments have been historically focusing on agricultural soils with two specific objectives: i) to decrease pollution and ii) to protect from erosion and loss of organic matter by enhancing soil fertility. The first directives aimed at protecting human health by *preventing* and *controlling* soil pollution from sewage sludge (86/278), nitrates (91/676), pesticides (2009/128) and industrial waste (2010/75). The Common Agricultural Policy (CAP), main instrument to support farmers, primarily focused on soil fertility. The past CAP (2013/1306) listed farming techniques to enhance good agricultural and environmental conditions (GAEC) to be pursued for soils (i.e. reduced tillage and burning, guaranteed minimum soil cover). The current CAP (2021/2115) further included crop rotation among the GAEC to guarantee soil protection and quality, and protection of wetland and peatlands to ensure organic C storage. Soils in the CAP are never explicitly linked to ES, except for one specific objective aiming at enhancement of ES and indicating as impact indicators an increased share of agricultural land covered by landscape features (2021/2116). Monitoring of soil conditions is required in the current CAP (2021/2116).

The organic farming law (848/2018) refers to enhancing soils' long-term fertility, stability, and biodiversity by reducing tillage and using only allowed fertilizers and conditioners, therefore improving soil ES. The Farm to Fork strategy (COM 2020/381) outlines reduction in use of pesticides and fertilizers and increase of organically farmed land but without listing any specific action connected to soil.

b. Forestry sector

The Forest strategy (COM 2021/572) refers to the contribution of forests to soil stabilization and explicitly relates healthy forest soils to the provision of ES, in particular to carbon sequestration, suggesting to-set up an ecosystem-based management approach and related payment schemes. Specific target to forests soils is also found in the LULUCF regulation (2018/841), addressing soil organic carbon as *sink* to mitigate GHG emissions, and the current CAP (2021/2115) aiming to support forest protection and management of ES. The older Biodiversity Strategy (COM 2011/244) related multifunctional forest management to payments for ES, albeit not referring their provision to soils.

c. Energy sector

The revised version of the renewable energy directive (2023/2413) contains reference to soils when it comes i) to harvesting forest products by maintaining soil quality (i.e. avoiding compaction) and biodiversity; and ii) to consider improvement of soil carbon and reduced green house gas emission (aka climate mitigation) by measuring or modeling changes in soil carbon amount.

d. Environmental regulations

The Habitat directive (91/676) and the Environmental liability directive (2004/35) marked the first steps for European natural environmental protection, soils however are almost absent from the text. Later on, the Environmental Action Plan (EAP), less binding instruments setting the ground for upcoming environmental policies, did target soils. The 6^{th}EAP (2002/1600) aims at protecting soil from erosion and pollution and calls for a soil strategy, by also mentioning their role as carbon sinks. 7^{th}EAP (1396/2013) lists water erosion, sealing and contamination to compromise soil ES, in particular biodiversity and water cycles, and addresses the need to increase knowledge and data collection on biodiversity to better value ES. The 8^{th} EAP (2022/591) relates an unspecified loss of ES to unsustainable land use management, soil sealing and pollution, and climate change and calls for a soil health law by 2023; furthermore it addresses a full integration on the One Health across all policy levels. Both latter call for improved natural capital accounting tools and market-based instruments – such as payments for ES.

The Zero Pollution action plan (2021/400) aims at *reducing* soil pollution to levels that are no longer harmful to human health and natural ecosystems, underlining the need to prevent and restore from contamination and regularly assess for their status, specifically agricultural soils for pesticide and nutrient reduction. Yet in the same year the Climate Law (2021/1119), – more legally binding instrument – never explicitly targets to soils, while on the other hand extensively refers to enhancement of carbon sinks by 2030. The recently approved Nature Restoration Law (2022/195) adds a time dimension that is relevant to soil, requiring long-term commitment to address degradation. Specific actions refer to increasing stocks of organic carbon in cropland mineral soils and restoring and rewetting organic carbon in peatlands. As for the Biodiversity Strategy to 2030 (COM 2020/380) points out the need to restore soils and terrestrial ecosystems, and related human wellbeing to specific soil ES provision: fertility, nutrient cycle, climate regulation.

Finally, two further regulations very relevant for soils are currently under discussion at EU level. On the one hand the Certification for Carbon Removals (2022) aims at improving soils' ES by increasing the stock of organic C in forest ecosystems and in cropland mineral soils in farming

Table 2. Summary of literature findings relating ES and soil health (number in brackets, colours refer to: red lower than 1; orange between 2 and 6; yellow between 7 and 16; green higher than 15).

Instrument typology	Sub-typology	Examples and count of ES, divided according to MEA (2005)				
		Provisioning	Regulatory	Cultural	Supporting	Total (# of ES) in instrument
Regulation	Property rights and use rights	Food Fodder (mixed-grazing, rotational grazing and reforestation; grassland) Biofuel (3)	Water retention Erosion Carbon storage (7)	-	Microbial biodiversity Nutrients' cycles (6)	16
	Conservation (easements and concessions)	Crop-livestock systems Forest plantation Biofuel from pastures and cropland (9)	Flood protection Carbon sequestration Protection of peri-urban green areas (10)	Land stewardship for socio-cultural wellbeing Educational and recreational purposes Indigenous knowledge (5)	Nutrients' cycles Water filtration Biodiversity Wildlife (11)	35
	Permits and quotas	Carbon farming Pastures (2)	Carbon sequestration Erosion protection (2)	Rural livelihood (1)	Soil organic carbon Soil biodiversity (2)	7
	Subsidies	Crops Cover crops Biofuel (2)	Water retention Carbon sequestration (2)	Adaptive farmers and citizen support (1)	Native biodiversity Soil organic carbon (3)	8
	Offsets	Carbon farming (1)	Carbon sequestration Erosion protection Water retention (3)	-	Soil organic carbon Biodiversity quality (2)	6
Incentive	Payments for ES	Cover crops Pastures Biofuel (3)	Carbon sequestration Reduced emissions Water retention Erosion protection Flood protection (8)	Landscape heritage conservation (1)	Biodiversity Water filtration Phosphorous recycling Soil organic carbon (7)	19
Total (# of ES) per typology		20	32	8	31	91

ecosystems. On the other hand the Soil Monitoring Law (2023) provides a definition of soil as vital, limited, non-renewable and irreplaceable resource and underlines need of monitoring, sustainable management, restoration of soil health and remediation of contaminated sites, but no definition or reference is made to connected ES.

e. Urbanization

No legally binding regulations exists at EU level, albeit soil sealing has been mentioned among the first causes of soil degradation in the past and current EAP and to minimize soil sealing is among objectives of both the biodiversity (COM 2020/380) and soil strategy (COM 2021/699) to 2030.

4.2. Availability of policy instruments' relating soil health to ES

Main findings are summarized below (Table 2), keywords that gave no results were not included in the table, namely: prohibition of use; farm set asides (both compulsory and voluntary); any information instrument; green public procurement; corporate social responsibility. The cells' color indicate a different amount of reference for each pair of ecosystem services and instrument typology. Overall, papers explicitly bridging soil ES to policy instruments for soil health were rather scarce, 23 articles were selected and can be found for a complete overview in Appendix II (since some of theme refereed to more than one policy instrument the list comprises a total of 29 references with repetions marked). Most literature was published in the last five years, showing an increasing interest in the topic.

Literature on property rights and land use rights mostly refers to ES of healthy soils (16) under different land use types, for instance grassland or forest, crops for food or fuel, but also investigates differences in agricultural practices, e.g. conventional or conservative, and pasture management, mixed or rotational. Those instruments highlight the role of regulating (7) and supporting (6) ES, and address trade-offs derived from different land use types. Conservation instruments show the greatest contribution to all ES (35), examples include governmental programs, at regional or local scale, and often refer to landscape level, i.e. forest, grassland. The regulatory and often compulsory character of conservation programs finds little support in terms of incentive instruments that could complement the action, compensating for the costs through governmental incentives or private buyer of ES. Improvement in market for ES was mentioned as key outlook for conservation easements (Eastburn et al., 2017).

Both property right and conservation instrument literature agree that the weak definition of property rights or poor enforcement of property rights in certain regions (such as South America or Africa), inequalities in the willingness to appropriate resources when new business opportunities emerge (i.e. biofuels or carbon sequestration), or among different farm typologies (i.e. smallholders and large properties), can lead to overconsumption of common-pool resources. Thus, this literature emphasises the importance of improving social capital for enhancing cooperation and common actions (Targetti et al., in press), both horizontally among farmers and vertically among supply chain actors (D'alberto, in press) as well as call for new institutions or enhance the capacity of existing institutions to design rules, and conservation strategies for common-pool resources (Lant et al., 2008).

Other regulation categories show lower amount of literature investigating the interplay between instrument and provision of ecosystem service. Examples of subsidies for soil health address regulating ES (2) and supporting ES (3) with the purpose of reducing erosion and increasing soil organic carbon. Tradeoffs emerged from provision of fuel instead of food (Gomiero, 2018) and from cover crops causing decreased production, having subsidies related to yield losses rather than to improved soil conditions (Deines et al., 2022). Offsets (6) and quotas (7) don't relate much to soil health but mostly to carbon farming, understood as a set of practices that increase soil organic carbon stored in farmland and should offset agricultural GHG emissions (Keenor et al, 2021).

Payments for ES reward farmers and landowners for improved regulating ES (8) and supporting (7) services, acting as compensatory mechanisms for investments, management practices and/or yield reduction. As for sources of financing, public sector is indicated as key funder, i.e. trough the form of direct payments but also private sector, e.g. industry was mentioned as source of finance, through compensation mechanisms (see for instance Lal et al., 2020).

Cultural ES are the most neglected from research (8), with the exception of conservation programs that provided some valuable insights (5). A recent study highlights the contribution of relating result-based payments also to cultural ES, such as preserving socio-cultural heritage at landscape level (Helena Guimarães et al., 2023). Among supporting services (31), biodiversity is frequently mentioned, though authors lack to specificy if it is below or underground, being the latter more relevant to soil.

Instruments related to information made no explicit reference to soil health as contributing to ecosystem services. Nevertheless, as of certification schemes and marketing labels, if no literature was found explicitly linking the topic of certification to soil health, it is probably a matter of time as increasing interest in carbon certification schemes is on the go (Keenor et al., 2021) and a soil certification is envisioned by the Soil Monitoring Law.

5. DISCUSSION OF RESULTS

5.1. Defining the narrative

Looking at the current policy setting available for soils in the EU, the agricultural sector has paid much attention to preserve soil fertility, showing a shift in narrative from protection against desertification and erosion towards an increase of soil organic matter in the form of organic carbon. Policy interventions remain rather designed at farms' level, as proven by the GAEC indicated in the CAP, as well as the approach to individual labeling of organic farmers, lacking to embed forms of coordination at territorial level that are more consistent with the scale of soil health (Janzen et al., 2021; Lehmann et al., 2020). Considering the definition of soil health as encompassing a wide range of ES, little instruments are to be found integrating the concept to the related loss of ES in agriculture, for instance considering the role that ploughing or excessive synthetic fertilizers play on soils' biodiversity (van Bruggen at al., 2019; Ingram et al., 2022). Moreover, the Farm to Fork strategy's attempt to broaden linkages between food security and environmental, soil health included, and at food system level by reducing nutrients' losses and use of pesticide is encountering notable resistance in its enforcement (Coderoni, 2023).

The forestry sector has shown greater linkages between sustainable forest management, increased soil ES – in the form of water retention, climate regulation and, most of all, carbon sequestration – and related incentives. Yet concentrating only on few ES, in particular provision of food and fibres or carbon sequestration, might result in insufficient targeting of other ES (Baveye et al., 2016) thus stepping out of the scale of action and scope of the soil health narrative (Lehmann et al., 2020). Improved forest management together with peatlands' maintenance and rewetting are depicted as carbon sinks in Forestry Strategy, Biodiversity Strategy, Climate Law, Nature Restauration Law. Those actions all focus prominently on carbon storage, but rarely further provide evidences to improvement of soil health to overall ecosystem health. While acknowledging the important role that carbon plays in key soils' functions, the risk of this narrow-scoped narrative is to only highlight the marketable and exchangeable value of carbon sequestration, while undermining the wider scope of the economic model for environmental preservation envisioned by ES, that greatly focused on biodiversity and habitat preservation in the beginning (Gómez-Baggethun et al., 2010). Instead of tackling single ES, approaches both in scientific studies and policy instruments encompassing bundles of ES (Bartkowski et al., 2018; Piñeiro et al., 2020) and minimum level of all ES (Bouma et al., 2022) could be more relevant to a soil health perspective.

Our results confirm previous findings claiming that EU policies have kept a rather sectoral approach to soil, mainly focusing on productive sectors and rather neglecting instruments related to natural areas (Löbmann et al., 2022; Ronchi et al., 2019). Moreover, we found that while soil sealing is listed among the causes of loss of soil ES (Panagos et al., 2021) and its reduction as key objective of recent strategies (e.g. COM 2021/699), no binding instruments to target the issue is available yet, while the Strategy for a Sustainable Built Environment is being discussed. A more coordinated approach along policy sectors could play a role in ensuring that soil health is pursued. Authors recently delving in the topic suggested that policy should focus on preserving and restoring actions, paying higher attention to soil *protection* in both regulatory (Heuser, 2022) and incentive instruments (Vysna et al., 2021). This implies also a greater understanding of EU soils' status and improvement, as aimed by the Soil monitoring law proposed in 2023. Yet, establishing reasonable and flexible indicators for highly diverse soils remains challenging, for instance when it comes to soil biodiversity (Lehmann et al., 2020) or to soil temporal dynamics that can only be over long-time spans (Baveye et al., 2016), including effects of degradation and conservation.

Last but not least, references to cultural ES, were almost absent from the current policy instruments, showing that much needs to be done to integrate in the soil health narrative a social dimension that attaches societal valuations and preferences over mere land use and functions (Janzen et al., 2021). Authors from various subject fields have suggested that a new understanding of the relationship (and reciprocity) between humans and soils could help tackle this issue. For instance, considering soils as natural cultural system to better value cultural ES provided by them (Costantini, 2023; Guimarães et al., 2023), or focusing on soil stewardship (Keith et al, 2016) and farmers' and land users' relational values (Friedrichsen et al., 2021) to further link environmental and social wellbeing to healthy soil management.

5.2. Orienting the instruments

Given the scarcity of results to this narrative review, we would firstly like to address methodological limitations concerning keyword selection and search databases, nevertheless the exploratory character of this study allows to expand the body of knowledge on soil policy and draw some key reflections that might be useful from an EU perspective. Few findings also highlight the little evidence to be found in scientific literature between soil health and related ES. This reinforces the previous finding that, despite being soil health part of the scientific discourse since longer (Lehmann et al., 2020), a significant gap emerges when it comes to policy instruments.

Soil health is not at the reach for most of the individuated instruments, while a stronger focus on soil fertility could be detected from this literature search, seen the frequency of carbon sequestration and soil organic carbon among mentioned regulating and supporting ES. This is true for public as well as for market driven instruments.

In the EU subsidies accessible through the CAP are currently the main instrument to incentivize farmers to fulfil environmental requirements, resulting in a hybrid form between regulation and incentive. As for soil they currently include i) direct payments for cross-compliance with GAEC concerning soil cover and organic matter, and ii) voluntary eco-schemes that include among areas of action additional "prevention of soil degradation, soil restoration, improvement of soil fertility and of nutrient management and soil biota" (2021/1115 p. 41). In addition, the second pillar, mainly through Agri-Environmental-Climate Schemes (AECS), addresses soil health either directly or indirectly (Mantino, 2022; Eichhorn et al., 2024a). For example, several Rural Development Programmes (RDPs) include measures to increase organic matter in the soil, promote cover crops and conservative agriculture, or invest in reducing soil erosion through repairing or rebuild dry stone walls or other landscape elements. Conversely, AECS incentivize measures that indirectly affect soil health, such as organic production or the maintenance and reintroduction of grasslands in mountain areas (Vergamini et al., 2024).

The current EU Common Agricultural Policy (CAP) could serve to test some initial result-based payments in AECS (Eichhorn et al., 2024b) and contribute to developing indicators to target ecosystem services (Bartkowski, 2018). The combination of command-and-control instruments and market-based instruments in the CAP could significantly affect soil health and the delivery of ES by farmers.

Conservation instruments seem more appropriate to the soil health narrative, compared to the field level more common to agricultural subsidies and regulations, for instance ES provided by forest soils, permanent grasslands as well as rewetted peatlands could contribute to the matter.

Regarding payments for ES, landowners – most typically farmers – could bekeen on generating ES that are marketable, as the case for carbon credits, yet a recent review shows that hybrid incentive mechanisms combining result and action based payments are more likely to be interesting to farmers (Raina et al., 2024). Payments for ES then will need to consider also mechanisms for distribution of benefits and incentives, to reduce the risk of having large landowners as main beneficiaries, attracting land accumulation and lobbing in areas where the land prices are low, thereby excluding small holders (Baveye et al., 2016). This is also tightly connected to length and typology of different land tenure arrangements, that might distort the trade-off between profitability and ES, given that long-term land tenure contract might also have the positive side effect of increasing commitment towards soil health and thus provisioning ES (Stevens, 2022).

Market regulation (i.e. carbon markets) are becoming the main solutions rather than compensation mechanisms parallel to emission reduction actions. Private financial institutions appear increasingly interested in mechanisms such as payments for ES or offsetting, this on one hand can provide new source of income for supporting those ES that are currently neglected. On the other the role of the public sector is relevant in making sure that market-based solutions are still tackling relevant objectives (Vatn, 2018), in this case the restoration of healthy soils in the EU by 2050. To overcome this issue key scholars in soil science suggested discussing the option to subsidize farmers based on a minimum level of all ES associated to soil health (Bouma et al., 2022). Level of detail on soil practices contributing to soil health seems for now limited but the concept of bundles of ES could further contribute to the discourse (Bartkowski et al., 2018).

In addition, our results highlight the need for improvements in developing new empirical and theoretical models that enable understanding causal effects between decision-makers' actions and their impact on multiple dimensions aimed at targeting various ecosystem services (ES). This would call the development of bioeconomic models to address both ex-ante and ex-post the complexity of interactions between economic behaviour and soil dynamics at different scales and spatial resolutions.

Finally, given the scarce results concerning information as a policy instruments, we would like to highlight the important role that this could play in the form of research and dissemination as well as extension services. A recent review by Arias-Navarro et al. (2023) has summarized key themes of past EU research over soils, primarily on regulating ES (erosion protection, soil contamination, soil and water, climate mitigation, carbon storage). Moreover soils are one of the five topics included in the EU *missions*, new instrument to support research and innovation in the period 2021-2027. "A soil deal for Europe" aims to reduce several soil degradation processes by addressing four operational objectives including: funding research and innovation; establishing living labs and lighthouses; develop a soil monitoring framework and raising people awareness (for more details on the Soil mission objectives please refer to EU Mission: A Soil Deal for Europe (European Commission, 2023)). This mission has allowed to finance a wide number on soil-related projects that are now running all over Europe, assessing their outcomes and contribuitions towards soil health might constitute a topic for future research. On the other hand, extension services mainly focus on soil fertility and show quite heterogenous approaches to advice, mostly lacking the holistic understanding of soil microbiology and chemistry embedded in the understanding of soil health (Ingram et al., 2022). Lack of information and evidence on which further ES might benefit from improved multi-functional soil management might prevent farmers from adopting practices that could benefit soil health, including accessing incentives and markets (Schröder et al., 2020).

There is a need to move the focus from a soil fertility and carbon-centered discourse to a landscape level understanding of soil uses, that embeds socio-cultural services provided to land users as well as the wider public (Guimarães et al., 2023; Friedrichsen et al., 2021).

6. CONCLUSIONS

This study contributes to the analysis of policy narratives, understood as the way an environmental problem becomes part of the policy discourse and agenda, by looking at the topic of soil health. It provides an insight over the integration of the soil health concept, intended as the delivery of a broad set of ES, throughout current EU policy instruments and scientific literature. The findings of this narrative review open up for a further, more careful investigation of incentives for soil ES, to improve the process we suggest some mitigation measures such as narrowing keyword selection to those policy incentives more relevant to soils, broadening search engines, and relying on the PRISMA flow for a systematic review process.

The agricultural sector enlists a set of incentives that promote a correct management of soils to guarantee greater fertility, well managed forest soils are found to improve soil structure and protect from erosion, yet soils are seen predominantly as substrate for primary production and carbon sinks. Overall, recognition of the value of ES related to soils in policy instruments was identified for primary production – food, fuel and fiber – and carbon storage, thus better fitting the scale of action of soil fertility and soil quality. Scientific literature also provided evidences of little availability of instruments explicitly tackling a range of ES that is understood for healthy soils. There is a need for integration of broader societal values connected to increased soil health, e.g. in the forms of safeguarded soil biodiversity or land users' wellbeing, including access and ownership to land.

The mix of policies and instruments currently available has so far not been able to tackle the issue of soil degradation, therefore a more coordinated effort among policy sectors is required to prioritize soil health. Given the prominent role of the private sector, future research could focus on the role of market instruments in pursuing soil health where more regulatory instruments have failed.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest. Fabio Bartolini, co-editor-in-chief of this journal, had no role in the editorial review process and decision-making for this article.

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APPENDIX I – CONTENT ANALYSIS

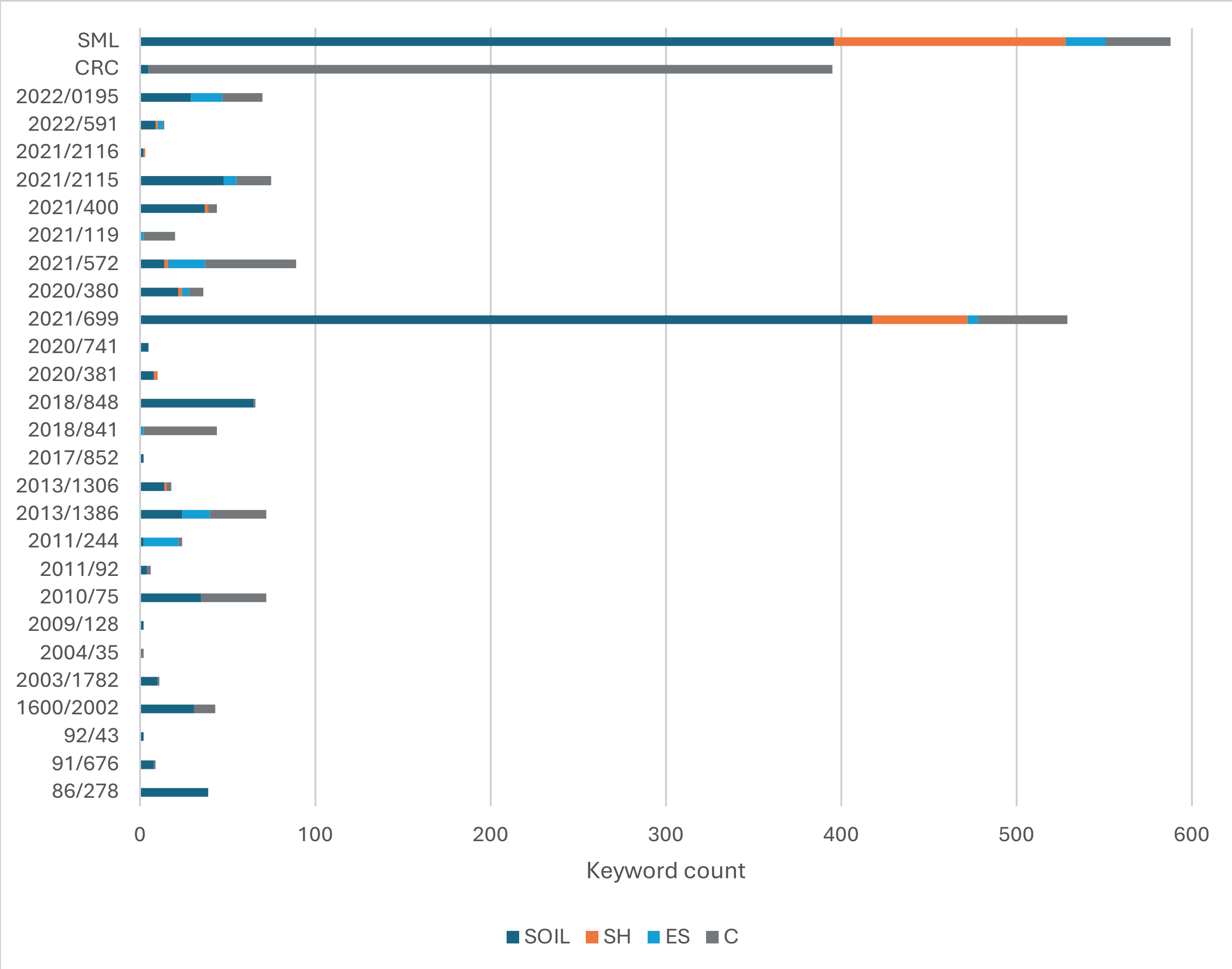

Figure A1. content analysis of n=28 EU policy instruments, codes in table A1. Colours refer to keywords soil, soil health (SH), ecosystem services (ES) and carbon (C).

Table A1. Policy inventory of 28 EU policy instruments and count of keywords: soil, soil health (SH), ecosystem services (ES) and carbon (C).

Code	Year	Law	SOIL	SH	ES	C
SML	2023	Soil monitoring law	396	132	23	37
CRC	2022	Carbon removals certification	5	0	0	390
2022/0195	2022	Nature restauration law	29	0	18	23
2022/591	2022	8th Environment action programm	9	1	3	1
2021/2116	2021	CAP 2023 - 2027	2	1	0	0
2021/2115	2021	CAP 2023 - 2027	48	0	7	20
2021/400	2021	Zero pollution action plan	37	2	0	5
2021/119	2021	Climate law	0	0	2	18
2021/572	2021	Forest strategy to 2030	14	2	21	52
2020/380	2021	Biodiversity strategy to 2030	22	2	4	8
2021/699	2021	Soil Strategy for 2030	418	54	6	51
2020/741	2020	Water reuse (minimum requirements for)	5	0	0	0
2020/381	2020	Farm to fork strategy	8	2	0	0
2018/848	2018	Organic production and labelling of organic products	65	0	0	1
2018/841	2018	LULUCF Regulation	1	0	1	42
2017/852	2017	Mercury Regulation	2	0	0	0
2013/1306	2013	CAP 2014-2020 (‘22)	14	1	0	3
2013/1386	2013	7th Environment action programm	24	0	16	32
2011/244	2011	Biodiversity strategy to 2020	2	0	20	2
2011/92	2011	Environmental Impact Directive	4	0	0	2
2010/75	2010	Industrial Emissions Directive	35	0	0	37
2009/128	2009	Pesticides directive	2	0	0	0
2004/35	2004	Environmental Liability Directive	1	0	0	1
2003/1782	2003	CAP direct support schemes	10	0	0	1
1600/2002	2002	6th Environment action plan	31	0	0	12
92/43	1992	Habitats’ directive	2	0	0	0
91/676	1991	Nitrates directive	8	0	0	1
86/278	1986	Sewage Sludge Directive	39	0	0	0

APPENDIX II - REFERENCES FROM REVIEW

Property rights and use rights

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