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Journal Contacts:
Silvia Coderoni, Dipartimento di Bioscienze e Tecnologie Agro-Alimentari e Ambientali, Via Balzarini 1, 64100 Teramo; E-mail: scoderoni@unite.it
Fabio Bartolini, Dipartimento di Scienze Chimiche, Farmaceutiche ed Agrarie, Via L. Borsari 46, 44121 Ferrara; E-mail: fabio.bartolini@unife.it

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Editorial

Reflections and new directions: An editorial retrospective and the launch of our new Policy Paper section

Fabio Bartolini, Silvia Coderoni

Over the past two years, *Bio-based and Applied Economics (BAE)* has consolidated the journal role as a platform for rigorous and innovative research at the intersection of economics, sustainability, agriculture, and bio-based systems. In a period marked by significant global transitions, ranging from climate change and biodiversity loss to disruptive technological shifts and geopolitical instabilities, our community of scholars has provided crucial insights into how bio-based economies can adapt, evolve, and contribute to sustainable development.

As a result of this commitment, we also received two important recognitions of the quality of the works published by the journal: BAE is now ranked Q1 in several subject categories and has been included in the list of "class A" journals for economics and political economy scientific sectors in Italy.

This editorial aims to offer both a retrospective overview of the journal's main contributions over the last two years and a prospective look at new directions.

Since our appointment as Editors in Chief, BAE has hosted a rich variety of contributions, spanning theoretical analyses, empirical applications, and interdisciplinary approaches. Among the most recurring themes we want to mention:

1. **Sustainability and Agricultural Economics** – Numerous papers have examined how farming systems can balance productivity with ecological stewardship. Topics such as agroecological transitions, carbon farming, and sustainable business models have been central.
2. **Circular and Bio-based Economies** – Research has increasingly focused on the transition towards circular models, with attention to waste valorisation, renewable bio-resources, and innovations in supply chains.
3. **Technological Innovation and Agriculture 4.0** – Several studies have addressed the adoption and socio-economic impacts of precision agriculture, digitalisation, and smart farming technologies, especially in Mediterranean and European contexts.
4. **Food Systems and Consumer Behaviour** – The journal has published relevant work on the transformation of food systems, including consumer attitudes towards sustainability labels, alternative proteins, and value chain governance.
5. **Climate and Resource Economics** – Contributions have deepened our understanding of climate change mitigation and adaptation strategies, the economics of soil and water management, and policy instruments to support resilience.
6. **Trade and Food Security** – contribution on investigating how the evolving trade dynamics, supply chain vulnerabilities, and geopolitical tensions shape the capacity of agri-food systems to ensure availability, accessibility, and stability of food supplies, with particular attention to both global interdependencies and local resilience.
7. **Agricultural and Rural Development Policies** –contributions have emphasised the role of agricultural and rural development policies in balancing productivity and sustainability, and supporting farmers' livelihoods within the broader transformation of rural areas.

Collectively, these research lines illustrate the breadth and relevance of BAE's mission: fostering knowledge that bridges economic science with pressing societal challenges.

Beyond thematic contributions, BAE has also been a space for methodological innovation. Authors have employed diverse approaches, from advanced econometric models to participatory scenario building, from experimental economics to multi-criteria decision analyses. These methods have enriched our ability to capture the complexity of bio-based and agricultural systems.

Equally important has been the increasing internationalisation of the journal. In the past two years, BAE has attracted submissions from across Europe, Latin America, Asia, and Africa, reflecting the global relevance of bio-based transitions. The diversity of contexts-from European Union policy frameworks to local farm-

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ing practices in emerging economies-has offered fertile ground for comparative analysis and cross-learning.

The growing engagement of early-career researchers has further expanded the vibrancy of our community. Their contributions, often interdisciplinary and problem-oriented, have underscored the evolving character of applied economics in addressing twenty-first-century challenges.

INTRODUCING THE NEW POLICY PAPER SECTION IN *BIO-BASED AND APPLIED ECONOMICS*

The global challenges surrounding climate change, biodiversity loss, food security, and sustainable rural development have increasingly highlighted the need for a stronger dialogue between academic research and policymaking. BAE has traditionally provided a platform for scholarly contributions that advance our understanding of agricultural, food, resource, and environmental economics. As these fields continue to expand and evolve, also the channels through which research is communicated, interpreted, and applied should.

With this issue, we are pleased to launch **a new section of the journal dedicated to Policy Papers**. This section is designed to bridge the gap between academic research and policy relevance, offering a space for concise, rigorous, and practice-oriented contributions that speak directly to current policy debates. The section will provide a venue for evidence-based, timely, and practice-oriented analyses with direct implications for decision-making.

While traditional research articles remain the backbone of scholarly communication, their structure and orientation often limit their accessibility to policymakers, practitioners, and wider stakeholders. Policy Papers provide a complementary format, explicitly tailored to highlight the implications of economic research for policy design and evaluation. They aim not only to report findings, but also to translate them into actionable insights that can inform real-world decision-making processes.

The agricultural and bio-based sectors are at the forefront of major societal transitions: the decarbonisation of economies, the digitalisation of production systems, the sustainable management of natural resources, and the pursuit of food system resilience. In all these areas, evidence-based policy support is indispensable. Policy Papers published in BAE will provide an opportunity for researchers to directly engage with these pressing challenges, while ensuring that scientific rigour remains the foundation of the journal's reputation.

Scope and characteristics

Policy Papers are expected to be shorter than research articles, typically ranging from 4,000 to 6,000 words, and should prioritise clarity, accessibility, and relevance over technical detail. While empirical evidence and methodological robustness are valued, the primary focus lies in the articulation of policy problems, the synthesis of available evidence, and the identification of feasible policy options.

Submissions may take different forms, including:

- Policy analyses, which assess the effectiveness of existing policies and highlight opportunities for reform.
- Evidence syntheses, which bring together insights from multiple studies to inform ongoing policy debates.
- Forward-looking perspectives, which explore new policy challenges emerging from technological, environmental, or social transitions.
- Comparative evaluations, which examine how different policy approaches perform across contexts and jurisdictions.

By launching the Policy Paper section, Bio-based and Applied Economics reinforces its mission of supporting both academic excellence and societal impact. We view this initiative as a contribution to a broader knowledge exchange ecosystem, in which researchers, decision-makers, and practitioners engage in a productive dialogue. Our aim is to stimulate a culture of evidence-informed policymaking, grounded in applied economics but open to interdisciplinary collaboration.

We hope that our readership will find in the Policy Paper section a source of inspiration, practical knowledge, and critical reflection on the directions of agricultural, environmental, and bio-based policy.

In establishing this new section, we reaffirm the belief that research must not remain confined to academic circles but must actively contribute to shaping a more sustainable, fair, and resilient future. The Policy Paper initiative represents a concrete step in this direction, and we look forward to the contributions and debates it will generate in the coming years.

The first paper of the section is published in this same issue and is the synthesis of the study day, which took place in Rome on 3rd April 2025, when more than twenty researchers have discussed the relevance and the implications of the Commission's Communication *A Vision for Agriculture and Food*" for Italy (Arfini et al., 2025).

As we look back with pride at the journal's recent trajectory and forward with ambition, we remain grateful to our authors, reviewers, and readers. Their dedication and engagement are the pillars of BAE's success. We invite the community to embrace this new phase, contributing not only new research but also impactful policy insights for a sustainable bio-based future.

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Policy Paper

Where is the Italian agriculture heading? A discussion in light of the prospects for the future CAP

Filippo Arfini[1,*], Fabio Bartolini[2], Anna Carbone[3], Tatiana Castellotti[4], Silvia Coderoni[5], Raffaele Cortignani[6], Raffaele D'Annolfo[4], Giovanni Dara Guccione[4], Michele Donati[1], Francesca Galli[7], Roberto Henke[4], Giampiero Mazzocchi[4], Alessandro Monteleone[4], Meri Raggi[8], Alessandra Pesce[4], Maria Rosaria Pupo D'Andrea[4], Benedetto Rocchi[9], Donato Romano[9], Roberta Sardone[4], Franco Sotte[10], Stefano Targetti[8], Catia Zumpano[4]

[1] *Università di Parma, Italy*
[2] *Università di Ferrara, Italy*
[3] *Unimercatorum, Italy*
[4] *CREA – Centro di ricerca Politiche e bioeconomia, Italy*
[5] *Università di Teramo, Italy*
[6] *Università della Tuscia, Italy*
[7] *Università di Pisa, Italy*
[8] *Università di Bologna, Italy*
[9] *Università di Firenze, Italy*
[10] *Socio emerito AIEAA, Italy*
*Corresponding author. E-mail: filippo.arfini@unipr.it

Abstract. In early 2025, the European Union launched a new phase of dialogue on the future of agricultural and food policies, aiming to move beyond the sustainability-centred narratives of the Green Deal and Farm to Fork strategy. The initiative, grounded in the "*Strategic Dialogue on the Future of EU Agriculture*" and the Commission's communication "*A Vision for Agriculture and Food*," reframes the role of agriculture within a broader geopolitical and socio-economic context. The Italian Council for Agricultural Research and Analysis of the Agricultural Economy and the Italian Association of Agricultural and Applied Economics convened a study day to examine the relevance and the implications of the EU's Vision for Italy. This paper presents a synthesis of the discussions and reflections, structured along four thematic pillars: economic, environmental, social, and institutional sustainability. The analysis highlights the structural weaknesses of Italian agriculture, the need for circular and diversified agricultural systems, the integration of agroecological and climate resilience strategies with competitiveness, the need for generational and social renewal, and the necessity for political reflection on the adequacy of the Italian agricultural policy governance system. By capturing the perspectives of researchers and academics, the paper contributes to the national debate on reshaping EU agricultural policy beyond 2027.

Keywords: Italian agriculture, CAP reform, sustainability, multiannual financial framework.
JEL codes: Q01, Q18.

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1. INTRODUCTION

Between the end of last year and the beginning of 2025, the European Union launched a new phase of debate around the future of policies for the agricultural and agrifood sectors. This latest phase aims to carry the strongly sustainability-focused approach - which had inspired the Green Deal and the Farm to Fork strategy - into a different perspective, in which the sectoral challenges are placed in a drastically changed global context and pursue the ambition of making the agricultural sector more attractive and responsive to the expectations of stakeholders.

The guidelines and recommendations for this new phase were outlined in the "*Strategic Dialogue on the Future of EU Agriculture*", a document resulting from a working group comprising approximately 30 European stakeholders from the agri-food sector, civil society, rural communities, and academia. The requests that emerged were taken up by the EU Commission with the publication of a strategic document, "*A Vision for Agriculture and Food. Shaping together an attractive farming and agri-food sector for future generations*", which placed the issue of agricultural policy renewal within a more ambitious agenda for food and the future of rural areas. A renewal program, based on further in-depth papers related to many unresolved issues, will be introduced in the coming months of 2025, with new emerging themes added.

The strategic vision document closes with an exhortation from the EU Commission, which "…*invites the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions, the social partners and all stakeholders to actively contribute to the development and delivery of the initiatives in this Communication*.". CREA – Research Centre for Agricultural Policies and Bioeconomy and AIEAA (Associazione Italiana di Economia Agraria e Applicata) jointly took up this idea and organised a study day, which took place in Rome on 3rd April 2025. More than twenty researchers, both academic and non-academic, experts in the various topics at the centre of the recent documents, actively participated in the event.

The work began with two general overview speeches: the first provided an in-depth analysis of the specificities of the Italian production system, drawing on the detailed sectoral analysis carried out by CREA PB in its Yearbook of Italian Agriculture (CREA, 2024); the second offered a reasoned summary of the contents of the EU Strategic Vision document. Then, the discussion was organised into four thematic tables, each focused on a dimension of sustainability — economic, environmental, social, and institutional — with as many coordinators as needed to guide the participants through a structured discussion on the issues of most significant relevance to Italy's national context.

The results and reflections arising from the debate are briefly reported in the following Sections, which represent a first contribution to the internal discussion on the future of agricultural and food policies, by a component of the Italian research world.

2. THE CAP POST-2027 IN THE VISION OF THE EUROPEAN COMMISSION

On February 19, 2025, the European Commission presented the Communication *"A Vision for Agriculture and Food,"* outlining a roadmap to 2040 that ensures future policies align with this Vision (European Commission, 2025a). The document sets the direction and outlines principles closely aligned with the recommendations of the *Strategic Dialogue* (2024), while also being strongly influenced by other strategic documents regarding the European Union's (EU) competitiveness, its repositioning in the changing global geo-economic and geopolitical context, and its capacity to respond to crises (Draghi, 2024; Niinistö, 2024; Letta, 2023; Spain's National Office of Foresight and Strategy, 2023).

The document was highly anticipated, as it traditionally outlines the Commission's orientations for the future of the Common Agricultural Policy (CAP) at the mid-point of the programming period. This was also the case in 2017, when the Communication (European Commission, 2017) paved the way for the New Delivery Model and CAP National Strategic Plans (NSP). In that document, the CAP was the focus, but agriculture and the broader agri-food system were largely absent from the debate on the future of the EU, except in budgetary issues. In 2025, by contrast, agriculture and food production are at the heart of the EU's political agenda, as they are considered strategic for maintaining economic and social stability, ensuring food security in times of crisis, and guaranteeing European food sovereignty. The Vision is therefore dedicated to securing their long-term competitiveness and sustainability, with the CAP being just one of several policies contributing to these goals, often not even the most important one.

The document focuses on four fundamental priority areas, which correspond to the three classic pillars of sustainability – economic, environmental, and social (the latter enriched by the food component) – alongside a fourth area focused on the sector's competitiveness and resilience. Generational renewal and innovation are cross-cutting themes throughout the Communication, with the former being a long-term priority due to the ageing farming population, and the latter a supporting element to facilitate a sustainable transition. Regarding sustainability, the document emphasises the need to integrate both economic challenges and ensure a socially just transition into the ecological transition, highlighting the importance of circular sustainability. According to this approach, environmental and economic sustainability enable the sector to remain competitive and meet society's expectations regarding food safety, food security, quality, vitality of rural areas, preservation of local cultures and traditions, animal welfare, and other related concerns.

In the priority area dedicated to economic sustainability, the most significant references to the CAP can be found. The document confirms the need to continue providing farmers with income support that should be more targeted and fairer, capable of attracting young and new farmers. Support should be more focused on farmers actively engaged in food production (with priority given to the production of agricultural products essential for the EU's strategic autonomy and resilience), on the economic vitality of farms, and on environmental protection. Furthermore, the document emphasises the need to streamline and simplify payments for ecosystem services, as well as to simplify conditionality by shifting from conditions to incentives, rewarding farmers who exceed mandatory requirements. However, there are not enough details to clarify how all this will impact the green architecture of the current CAP (which is not even mentioned in the document) or the resources required to remunerate farmers. The document also touches on the issue of flexibility – both for farmers, in defining practices best suited to their farms and contexts, and for Member States, in achieving the objectives of the post-2027 CAP.

The second priority area, focused on competitiveness, aims to ensure European food sovereignty by reducing critical dependencies (such as proteins, raw materials, and fertilisers), promoting fairer global competition, avoiding situations where European standards on food safety and sustainability place the EU at a disadvantage and lead to a loss of competitiveness, and strengthening EU's ability to respond to crises.

The priority area dedicated to environmental sustainability outlines the agricultural sector's contribution to the EU's 2040 climate target, considering its specific characteristics and the need to ensure both competitiveness and food security.

In the fourth priority area, focused on social sustainability, the document highlights the need to strengthen synergies and complementarities between the CAP and other policies, including the Cohesion policy, to provide adequate support and tangible impact in rural areas through integrated planning and implementation efforts. This aspect becomes particularly relevant when considered in light of the Communication on the future Multiannual Financial Framework (MFF) (European Commission, 2025b). In that document, the current budget structure, based on spending programs rather than policies, is shown to cause delays in planning and expenditure, as well as overlaps and gaps due to the lack of coordinated strategies for cross-cutting priorities. Therefore, the MFF Communication proposes a country-level plan focused on common priorities, including promoting economic, social, and territorial cohesion, as well as implementing key reforms and investments. Reading the two documents together reveals a desire for greater integration between Rural Development Policy and Cohesion Policy, although the extent of such integration, particularly in terms of policy autonomy, funding, and the role of public administrations, remains to be determined.

The Vision does not propose solutions but provides a broad overview of the transformations agriculture needs, promoting ongoing dialogue among stakeholders, institutions, and civil society, along with a combination of policies and institutional levels. It implicitly calls for the need, without explicitly naming it, for horizontal governance (among institutions at the same level with responsibilities over different policies) and vertical governance (among several institutions with responsibilities over the same policy) (Coderoni, 2023).

3. POINTS OF VIEW ABOUT ECONOMIC SUSTAINABILITY

The economic sustainability of the entire Italian agri-food system depends on both macro and micro aspects of the national system, including the structural characterisation of Italian agriculture and the strong trade interconnections within and outside Europe. These aspects depend on the ability to guarantee income, adequately remunerate production factors, ensure competitiveness, and employ workers. Among the various aspects that determine and influence economic sustainability, those relating to the international scenario and risk management are worth closer examination.

The economic sustainability of the entire Italian agri-food system strongly depends on the evolution of the international scenario in two interconnected aspects: one external and one internal to the Italian country system.

On the external side, Italian agriculture finds itself in the peculiar situation of being dependent on foreign markets for specific strategic production inputs (such as chemical inputs, soy, etc.). At the same time, the food industry exports high-quality, simple, and processed products, such as those with geographical indications, whose production cannot be outsourced (CREA, 2024). This situation has been achieved thanks to the advantages derived from the European Single Market, as well as a general climate of institutional and market stability, with the world's leading countries considered Italy's commercial partners. It is evident that situations of financial instability - linked to exchange rates -, economic instability - linked to tariffs -, or institutional instability - tied to unclear or no longer perceived as clear market governance rules - lead to repercussions that result in increased production costs, strain on the domestic market, and a decrease in prices and agricultural incomes.

On the internal side, within the Italian country system, the economic variables of the primary sector highlight that the profitability of land and labour has remained almost stable over the last decade, with only slight increases during the post-COVID years. These weak increases are less significant, especially on small-sized farms, due to the tensions recorded on international price markets, confirming that, despite the national production model's backbone being found in small-sized farms, the latter continue to be more vulnerable. The economic sustainability of the agricultural system, therefore, is closely linked to the structural dimension of farm holders' companies. Addressing this challenge also includes promoting generational turnover initiatives. In our country, the process of ageing has not suffered any setbacks in recent years, with a group of entrepreneurs over 60 years of age that largely exceeds that of entrepreneurs under 40 (CREA, 2024).

Considering these structural aspects of the agricultural production system, the organisational and coordination capacity of value chains is becoming increasingly important not only to define production quantities and selling prices, but especially to define quality levels aligned with the global market and to bring in financial and human resources capable of supporting innovation processes and the management of commercial strategies in both domestic and international markets (CREA, 2024). From this perspective, the Italian agri-food system is highly complex, encompassing businesses that vary in terms of ownership, corporate form, and strategy. Cooperative enterprises, family-owned companies, and multinationals compete in national and international markets. These latter companies have acquired all or part of the corporate structure of many Italian food companies, influencing the behaviour of the value chains they are part of, including their internationalisation strategies.

The economic sustainability of the Italian agri-food system increasingly depends on developing an efficient and modern industrial relations system, capable of providing timely guidance to supply chains and their operators. In this regard, forms of supply chain management related to inter-professional organisations would guarantee a management capacity suitable to face the economic challenges stemming from market instability and those arising from climate change, which, in turn, are embedded in international dynamics.

In a context marked by extreme weather events, market crises, and geopolitical instability, strengthening the resilience of Italian farms has become a priority. Two strategic levers in this direction are diversification and circularity. Diversification involves two main strategies. First, expanding the range of cultivated crops, for example, by introducing legumes or oilseeds such as sunflowers and rapeseed, can help better cope with the effects of climate change. Second, developing alternative sources of income for farmers, such as renewable energy production, agritourism, and direct sales, to help stabilise incomes during periods of market volatility. At the same time, promoting nutrient circularity is essential to reduce farm costs and mitigate the environmental impact of chemical fertilisers. Encouraging the reuse of nitrogen-rich livestock manure, adopting precision agriculture techniques, and integrating agroecological practices into production cycles can enhance farm sustainability and reduce reliance on imported fertilisers. Investing in diversification and circularity means building a more resilient and sustainable agricultural system that cannot only cope with external shocks but also adapt and evolve.

4. POINTS OF VIEW ABOUT ENVIRONMENTAL SUSTAINABILITY

The environmental dimension of sustainability is, in some respects, the most delicate as it implies negotiation and interaction between several actors (farmers and citizens) in managing different aspects that impact the environment and society itself. Even though the CAP in the past has introduced actions that go in the direction of creating a more environmentally sustainable production model, there are still numerous areas of intervention that include the adoption of more sustainable agricultural practices, the maintenance of high levels of biodiversity, the reduction of greenhouse gases, and the maintenance of certain limiting production factors (i.e. water, soil, inputs). The *Vision* document foresees achieving a higher level of environmental sustainability as a function of Science's ability to provide answers and develop interventions in several areas, including technological innovation, the evolution of agricultural production models, the development of supporting infrastructures, and increased consumer awareness.

The ongoing decline in biodiversity and accelerating climate change constitute one of the most pressing environmental challenges facing society. Despite significant financial resources allocated to environmental objectives, the effectiveness of EU agri-environmental and climate schemes in mitigating agriculture's impact on biodiversity remains questionable (Pe'er et al., 2022). In Italy, this situation highlights the need for innovative contractual solutions to improve policy efficiency. Among the most promising approaches are result-based schemes, in which farmers receive payments contingent upon achieving environmental outcomes, and collective approaches, in which groups of farmers commit to shared targets (Targetti et al., 2024). Nevertheless, key considerations include their capacity to attract private investment, the availability of enabling technologies, and the complexity they may entail.

In Italy, the agroecological transition requires a strong commitment from farmers, supported by robust institutional frameworks. Beyond the mere adoption of agroecological practices at farm and food system levels, it is essential to invest in training, advisory services, and knowledge exchange networks (Wezel, 2015). Reinforcing territorial governance mechanisms, such as Bio-Districts, and integrating local knowledge systems are also crucial (Dara Guccione et al., 2024). In light of the water crisis, agroecology presents a pivotal strategy for enhancing climate resilience. Therefore, full integration of agroecology within Italy's CAP NSP, with targeted support for Bio-districts and sustainable resource management, is essential. Despite the great emphasis on agroecology and Bio-districts and their potential contribution to a more sustainable agriculture, it must be admitted that this is a residual system in the Italian agricultural landscape, still far from becoming a reference model for many Italian farmers.

Although agricultural greenhouse gas (GHG) emissions in Italy have declined by 19% since 1990 (CREA, 2024), this reduction is mainly attributable to decreased production levels (Baldoni et al., 2017). Greater ambition in mitigation efforts is therefore required to attain climate neutrality without compromising productivity (Coderoni, 2023). Beyond the CAP, innovative policy instruments are being considered. The EU Regulation on carbon removals and carbon farming establishes quality criteria for certifying carbon credits generated from agricultural soils and forests, potentially stimulating voluntary carbon markets through private finance. Similarly, the introduction of an agricultural Emission Trading System, although highly questioned (Copa-Cogeca, 2024), could apply the polluter-pays principle within the sector, reducing emissions cost-effectively. In this context, Italy's availability of farm-level GHG estimates from FADN data (Coderoni & Vanino, 2022) could facilitate the identification of mitigation hot spots for targeted interventions, such as those supported by the Agrifood Just Transition Fund.

Soil health, a long-standing concern, has recently regained prominence through the EU's Soil Strategy, particularly via the Soil Deal and Soil Mission, which aims to reverse degradation currently affecting approximately two-thirds of EU soils. In Italy, pressing concerns include soil erosion, depletion of organic matter, biodiversity loss, and nutrient runoff. However, significant obstacles persist, including the dispersion of incentives across CAP measures, structural transformations within the sector, and institutional inadequacies (Winkler et al., 2025).

Dairy livestock farming represents a key sector in the decarbonisation agenda and is undergoing substantial transformation due to evolving consumption patterns and growing demand for sustainable dairy products (Coderoni, 2023). Although climate-smart innovations, such as robotic feeding systems, are enhancing efficiency, challenges remain concerning production standards and reliance on imported feed. Additionally, there is concern regarding the potential redistribution of costs along the supply chain under emerging policy regimes (Huber, 2024).

Agriculture is inherently circular, traditionally reusing by-products such as manure to maintain and enhance soil fertility. Beyond internal recycling, the sector holds significant potential to strengthen circularity through cross-sectoral synergies. Fertiliser use remains a primary environmental concern, accounting for approximately one-third of agriculture's CO_2 emissions and depending heavily on scarce and unevenly distributed natural resources. In response, the EU Regulation 2019/1009, which entered into force in 2022, promotes the use of organic and waste-derived fertilisers as part of a broader strategy to support sustainable agriculture. Nevertheless, adopting such alternatives remains limited, hindered by perceived high costs, concerns regarding potential contaminants, and cultural resistance (Ronzon et al., 2024). Facilitating this transition requires the development of industrial symbiosis initiatives, supported by policy instruments such as the EU's Integrated Nutrient Management Action Plan (Abitabile et al., 2025). Strengthening Agricultural Knowledge and Innovation Systems (AKIS) to enhance information dissemination and farmer skills, alongside improved monitoring through tools such as the Farm Sustainability Data Network (FSDN), is crucial for fostering a more circular and resilient agricultural sector.

5. POINTS OF VIEW ABOUT SOCIAL SUSTAINABILITY

Social sustainability lastly entered the debate on the European Union's agricultural policies. It is encouraging that this issue is now being addressed more concretely. In the *Strategic Dialogue*, seven principles address social sustainability, a significant step forward. Additionally, the Vision emphasises the importance of this topic, particularly in the context of generational renewal, which is seen as essential for the vitality of agriculture and rural areas. This is welcome news in Italy, where the issue is particularly acute (Carbone et al., 2024). It is also promising that the focus shifts from young to new entrants. Many young beneficiaries would likely enter farming anyway, while others seek to enter later in life, bringing valuable skills, capital, and networks.

New entrants, regardless of age, face land access issues, especially in densely populated Italy. Therefore, the mention of a European Observatory on Farmland is a positive development. Lack of infrastructure and services also prevents entries; thus, the broader, non-sectoral approach is a welcome development. We now await the *Generational Renewal Strategy*, as promised by 2025.

For Italy, promoting and enhancing social sustainability involves engaging with various aspects of agriculture and the food chain. Knowledge and skills are among the challenges recognised in the *Dialogue* as an opportunity to expand farmers' lifelong learning and revitalise extension services. Moreover, another challenge in the *Vision* document concerns "*Building an attractive sector that ensures a fair standard of living and leverages new income opportunities*". A focus on generational and entrepreneurial renewal should also consider the social diversity of the Italian agricultural system. Farming income contributes to the welfare of diverse entrepreneurs to varying extents. Farmers managing large holdings often belong to the highest income deciles. Small and medium farms, conversely, typically represent only one among several income sources for farming families, rather than being the primary one (Marino et al., 2024). Small and medium-sized activities still involve a significant number of people. In some rural contexts, they play a relevant social role, providing employment. Their support is likely to generate valuable social outcomes. However, the attractiveness of agriculture for small and medium-sized farms, as well as for young people and new entrants, strongly depends on the rural context in which they operate. More than direct farm income support, these farmers would need measures targeted at promoting farm business diversification, enabling household livelihood strategies based on «pluri-activity», simplifying bureaucracy in farm management, and promoting horizontal cooperation in marketing farm produce.

Social sustainability in Italian agriculture also requires a critical acknowledgement and systematic response to the economic and social inequalities embedded throughout the agri-food supply chain. These disparities disproportionately affect women and migrant labourers and are often neglected or tacitly accepted, despite constituting deep-rooted structural challenges (Zumpano,2020; Corrado and Zumpano, 2021). Thus far, the CAP has largely overlooked the social dimension, offering only broad, non-binding recommendations concerning gender equality, without establishing enforceable commitments (Zumpano, 2021). In the domain of labour rights, intervention has been limited to sanction-based mechanisms, which have proven insufficient and largely ineffective (Canfora & Leccese, 2022). The analysis of recent EU policy documents reveals little progress on these issues, particularly in terms of proposals. Persisting in this limited approach risks exacerbating rural decline, as individuals increasingly disengage from agricultural work and abandon rural territories. Building on the advances made in the CAP's environmental dimension, there is a need to support methodological frameworks that embed social sustainability into agricultural policy through the implementation of fairness schemes.

Another topic focused on the strategic dialogue is "*Making the healthy and sustainable choice the easy one*." This topic extends beyond the agricultural sector and encompasses the broader food system, aligning with the European Commission's recommendations (SAPEA, 2023). Appealing to consumers' rationality is not enough.

Different dimensions of the "*food environment*" need to be addressed to promote sustainable consumption. From a systemic perspective, four key aspects are of central importance: nutrition and diet, consumer information, public food procurement and the response to food poverty. Regarding the first aspect, Italy can valorise the heritage value of the Mediterranean diet (Dernini & Capone, 2024). However, it must deal with the decline in adherence and the rise in obesity, which raises the question of who should lead the change and with what incentives. In terms of information, the main challenge for sustainability labelling is to strike a balance between simplicity and comprehensiveness, considering the various social dimensions of sustainability (ranging from nutritional value to supply chain equity to animal welfare, etc.) (Sanye Mengual et al., 2024). Public procurement of food plays a strategic role in education and market orientation; however, the key issue remains defining effective sustainability criteria, which is the subject of ongoing debate (European Commission, 2024). Italy is widely recognised for its excellence in this area through the CAM (Minimum Environmental Criteria), which integrates environmental, territorial, and social sustainability criteria into public catering tenders. A widely shared call is to strengthen food literacy, meaning navigating a highly complex food environment. Finally, the importance of solidarity networks, such as food banks, is recognised to actively support food systems in addressing emergency food insecurity situations, provided that such networks are supported by appropriate policies (Galli et al., 2018).

However, the role of agriculture and rural areas is often nuanced or neglected (Mazzocchi et al., 2023). The reference to food waste remains rather vague: in the *Vision*, it is mentioned only once, without any specific target, merely as a general commitment to continue existing initiatives. This is problematic because the commercial dynamics that drive food waste behaviours are not recognised.

The introduction of elements that lead to considering agriculture in its social aspects, along with explicit measures, is a novelty that should be welcomed in the Italian agricultural landscape. However, the concrete impact of these measures depends on elements that require an evident willingness on the part of national policymakers to implement them.

6. POINTS OF VIEW ABOUT INSTITUTIONAL SUSTAINABILITY

Both the Strategic *Dialogue* and the *Vision* have highlighted some common elements that may influence the future policy governance for the agricultural sector and rural areas. First, budget simplification of the Multi-Annual Financial Framework (MFF) may require establishing a single fund for development policies and a plan for each country, which would contain key reforms and investments focused on common priorities.

Second, CAP is still a central tool for achieving the objectives of competitiveness and sustainability of the agricultural sector and rural areas. However, it should improve coordination with other policies to achieve a synergistic and more effective contribution (Coderoni, 2023).

Third, CAP's strategic approach to programming is still valid. However, some implementation mechanisms need to be simplified, while at the same time strengthening a target approach and the responsibility of Member States to ensure achievement of the set targets.

Finally, Cooperation with stakeholders needs to be improved at all stages of the programming cycle.

The discussion on institutional sustainability, however, must start with an analysis of the governance of programming, management and evaluation of the three main policy instruments that directly or indirectly affect the agricultural sector and rural areas in the 2023-2027 programming period: the CAP NSP, the National Recovery and Resilience Plan (NRRP) and the Partnership Agreement for Cohesion Policy.

The CAP NSP, which introduced unitary and national "program" for Pillar I and Pillar II and influenced the way interventions are programmed, consulted and approved, opening a broad debate on the role of the Ministry of Agriculture, the Regions and the paying agencies as Managing Authorities and in monitoring and evaluation responsibilities, necessitating the setting up of new coordinating "bodies". At the same time, the new objectives introduced with the "Farm to Fork" Strategy, new instruments (eco-schemes and social conditionality), the strengthening of bottom-up approaches, and mechanisms for performance assessment have introduced new actors and new "institutional" relationships.

The NRRP provided for "agricultural" interventions managed directly by the Ministry of Agriculture and other National administrations, firmly integrated with the NSP, but with different implementation and performance evaluation modalities and not always fully coordinated with CAP interventions.

Finally, the Partnership Agreement for Cohesion Policy provides for several national and regional interventions complementary to the CAP, in particular with regard to the development of inner areas, the promotion of human capital and environmental protection. Nevertheless, no formal coordination mechanism has been foreseen to ensure effective integration at territorial level.

A crucial aspect highlighted by the documents under the scanner is the stakeholders' dialogue: a process innovation tested for the first time in the CAP NSP through the Partnership Table (Henke et al., 2024). Italy is rich in experiences in this regard, carried out by local administrations collaborating with research institutions, the third sector, and private operators, through public participation mechanisms such as Food Councils, explicitly mentioned in the *Vision*.

On all these aspects, the progress of these new programming tools, their coherence, and integration capacity need to be monitored. A comparison at the EU level of the Member States' capacity to respond to the unitary programming inherent in the PSP would also be valuable and desirable.

The thematic discussion on institutional sustainability highlighted some assessments for possible Reform scenarios. A first element concerns the CAP's separation from other policies. From a strategic point of view, the Single Fund hypothesised in the budget reform could make it possible to improve the integration of the agricultural sector into the economic system on fundamental issues such as food, environment, land, and food security, where the complementary action of policies could be fundamental. The issue of the Single Fund is central, both because of the risks of resource loss for the sector and due to its effects on delivery mechanisms and performance assessment, which are already complex and impact policies in various ways. Participants in the discussion emphasised the need to change the approach and orient the CAP and future policies towards: i) tailored and targeted policies, given the heterogeneity of the recipients, with the need to accompany these processes with practical tools for evaluating results rather than inputs and performance; and ii) forward-looking aid oriented towards rewarding behaviour that can generate structural changes in the system, overcoming backwards-looking payments that tend to sustain the status quo and widen inequalities.

The other evidence that emerges from the discussion is the gap between the vision of agriculture, the relationship with traditional challenges (environmental sustainability, generational change, innovation) and that with the new challenges (food, health, labour, trade) and the role of incentive and regulation policies as opposed to "softer" forms of policies that are more suited to interventions in the more downstream components of the food system (education, information, transparency, addressing a proper food literacy, as advocated in *the Strategic Dialogue*). The tendency is to focus solely on the CAP, but it is necessary to discuss policies more broadly, to consider possible new beneficiaries, how to avoid conflicts between different objectives, and how to leverage synergies between actors.

Given the above scenario, especially for Italy, it becomes crucial to discuss the role of institutional actors involved and how these new processes can be governed within the already complex governance of policies due to the requirement of the Italian Constitution, which considers the Administrative Regions as responsible for setting up their regional policy for agriculture. Thus, in terms of institutional sustainability, there emerges the need to question how the national system should organise itself at the central level to interpret, measure and evaluate the system proposed to us by the EU, in terms of: i) integration and coherence of policies, in particular by looking at the programming tools that we have used in this programming, also with a comparison at the European level, and of the possible tools that may be proposed; ii) analysis of the trade-offs between the different objectives - inclusiveness, sustainability, productivity, resilience - and the visions of the different stakeholders; and iii) systematic implementation of mechanisms for evaluating policies, to allow real learning on the effectiveness and efficiency of the various interventions to achieve the set objectives.

The new European agricultural policy is undoubtedly more complex in terms of its political objectives and the inclusion of new stakeholders in the decision-making process. This increases the complexity of the governance process, requiring public decision-makers to have a greater capacity to understand the diverse needs of various stakeholders and, consequently, to allocate funds effectively. Given the current European context, which includes the prospect of a potential reduction in CAP funds, the vision of the political re-evaluation of the entire governance structure of Italian agricultural policy also becomes relevant.

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ORCID
GR: 0000-0002-1500-4579
DV: 0000-0001-9503-2977

Towards the knowledge and innovation system for the bioeconomy?

Giacomo Maria Rinaldi*, Davide Viaggi

Alma Mater Studiorum – University of Bologna, Via Zamboni 33, 40126, Bologna, Italy
*Corresponding author. Email: giacomomaria.rinald2@unibo.it

Abstract. The bioeconomy is a growing sector in both high- and low-income countries, closely linked to innovation. However, knowledge creation and innovation flows remain underexplored due to their complexity. This study aims to introduce the Knowledge and Innovation System for the Bioeconomy (KISB) to analyze sector dynamics. A systematic literature review examined its application, revealing the need for both technology- and collaboration-focused approaches. Key findings emphasize the importance of multi-actor and multidisciplinary strategies, with recent research prioritizing collaboration over innovation. Ethical and market challenges were noted in commercialization. Additionally, the concept of microKISB, operating at an organizational level, offers potential in business and policy research. Ultimately, KISB and microKISB serve as tools for policymakers, businesses, and researchers to drive bioeconomy advancements.

Keywords: bioeconomy, innovation system, knowledge development, innovation flows.
JEL codes: D85, O31, Q57.

1. INTRODUCTION

The bioeconomy represents an important segment of the economy of both high-income and low-income countries (Johnson et al., 2022; M'barek and Wesseler, 2023), gaining increasing popularity in recent years (M'barek and Wesseler, 2023). As pointed out by the systemic literature review in Wei et al. (2022), four stages of bioeconomy research can be identified, namely: the Infancy stage (1998-2002); the Exploring stage (2003-2012); the Blooming stage (2013-2017); and the Mature stage (2018-to date). Hence, the bioeconomy research can be considered in its maturity. Moreover, even from a policy perspective, the bioeconomy is considered an established and no longer emerging sector, with more than 60 specific strategies around the world (GBS, 2024).

Despite this maturity, the concept of bioeconomy is still subject to debate, both in policy and research fields (Vogelpohl and Töller, 2021; Wei et al., 2022), with different points of view that hinder a common vision (Johnson et al., 2022; Lewandowski, 2018; Viaggi et al., 2021). The main issue is that, based on local characteristics, each country (but even each continent) pushes for a different interpretation of the bioeconomy (M'barek and Wesseler, 2023). Several papers have tried to aggregate the main visions and approaches of the bioeconomy (e.g. Bugge et al., 2016; Vivien et al., 2019; Wei et al., 2022). However, regardless of the vision taken, there are some elements that are transversal and accepted as intrinsic to the bioeconomy. One of these is innovation (Viaggi et al., 2021). Nevertheless, few studies have focused on the innovative processes that regulate the bioeconomy and, in most cases, they emphasized practical rather than theoretical implications (Bröring et al., 2020; Faulkner et al., 2024; Van Lancker et al., 2016). Among the few examples of theoretical advancement, one is given by Van Lancker et al. (2016), who identified five factors and outlined the key characteristics of the innovation process. The five factors, called by the Authors "contextual factors" and defined as factors that "impact the implementation and management of innovation development processes in the context of the bioeconomy" (Van Lancker et al., 2016: 61) are: *Radical Innovation* (RI), *Complex Knowledge Base* (CKB), *Fragmented Policy* (FP), *Challenging Commercialisation* (CC), and *Intense Cooperation* (IC). These elements are considered by the authors as the basis on which innovation development processes are established, but they do not describe the wholeness of the development processes. A methodological approach that allows us to analyse, at the same time, the contextual factors and the development processes is that of Innovation Systems (IS). The IS perspective has its roots in the seminal works of Lundvall (1985; 1992), Nelson (1988; 1993) and Dosi (Dosi et al., 1988), who started to switch from a technology-based to a knowledge-based approach (Godin, 2006), replacing, in this way, the firm-centred vision of innovation with a systemic vision. The concept of IS is nowadays well-established (Rubach et al., 2017), with extensive literature on the topic (Pyka and Scharnhorst, 2009). In this framework, the socio-economic context and the relationships among organisations are considered key areas of research (Beckenbach et al., 2009; Garud et al., 2013). Consequently, with the inclusion of new economic and social variables within the innovation processes, the number of disciplines involved in the study of IS notably increased, moving the study of innovation into the domain of complexity science (Burmaoglu et al., 2019). Hence, in the last decades, following the varied backgrounds and the different research interests of the scholars, many different models to visualize innovation have been proposed.

One of the first models, widely accepted was outlined by Lundvall (1992), who introduced the concept of National Innovation Systems (NIS), shading the light on the impact of national institutions on the development of innovation processes (Russo and Rossi, 2009). Similarly, Cooke (1992) introduced the Regional Innovation Systems (RIS), underlining the local aspects of innovation and the importance of proximity (Boschma, 2004). Malerba (2002) focused on the Sectoral Systems of Innovation and Production. Merging the concepts of National and Sectoral Systems, Spielman and Birner (2008) developed a concept for a National Agricultural Innovation System, further developed by Klerkx et al. (2012) in the Agricultural Knowledge and Innovation System (AKIS). Instead, focusing on the typologies of actors that interact within the system, Etzkowitz and Leydesdorff (2000) identified three main categories, i.e. government, industry and academia, that establish mechanisms, more or less complex, of feedback and support for innovation. Referring to the double helix model of DNA, the Authors metaphorically called this three-actor model Triple Helix. Afterwards, the diffusion of this model in the scientific and political fields brought scholars to consider new categories. Hence, Carayannis and Campbell, first added the media and culture, affirming the Quadruple Helix model (Carayannis and Campbell, 2009), and then, introducing the natural environment, proposed the Quintuple Helix (Carayannis and Campbell, 2010).

Despite the academic debate toward these models, these theories have been favourably received by policymakers (Aragón et al., 2012). Indeed, in the field of innovation policy, the systemic approach has found increasing success, following and proceeding in parallel with the scientific debate (Aragón et al., 2012; Enger, 2018; Protogerou et al., 2010).

The aim of this paper is to identify if there is scope for a Knowledge and Innovation System for the Bioeconomy (KISB) framework and which may be its peculiarities. To do so, we decided to first explore what types of IS were adopted to describe the bioeconomy, and then to outline the main common characteristics.

Indeed, to the best of the Authors' knowledge, there are no specific literature reviews that assess the state of the art of IS framework in the bioeconomy. The originality of the present systematic literature review lies in its ability to assess, at the same time, the contextual factors of Van Lancker et al. (2016) and IS frameworks that mostly characterize the innovation literature in the bioeconomy.

The final results highlight there is no unique IS for the bioeconomy – as it happens in other sectors, such as agriculture – and that the contextual factors of Van Lancker et al. seem to be deficient in describing the complexity of the current innovation context.

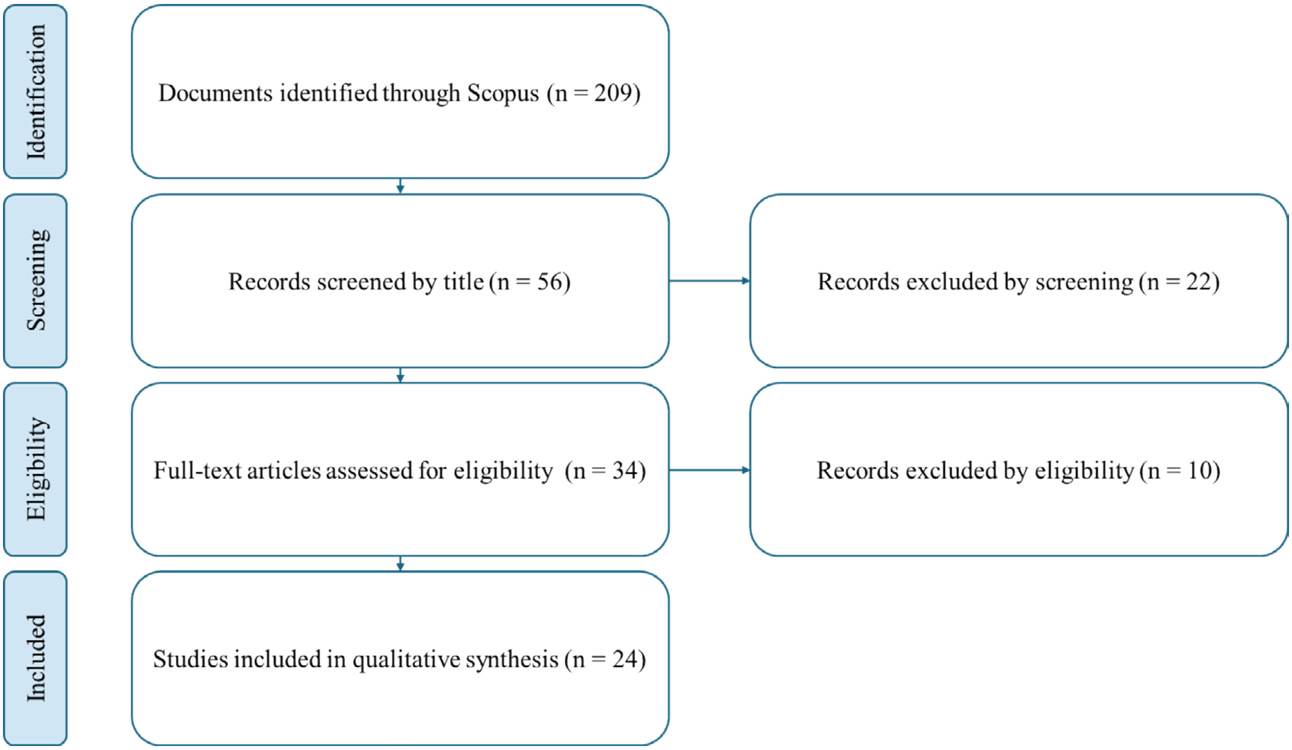

Figure 1. Overview of the process of document selection following the PRISMA method (Moher et al., 2009).

The paper is structured in the following way. In section 2, we present the material and methods adopted to carry out this study. In section 3, the results are reported in three main subsections, namely: general information about the papers; contextual factors identified; and categorization of the papers into four groups based on two dichotomies: collaborative-oriented vs. innovation-oriented and business-centred vs. policy-centred. These categories were then related to the contextual factors and the type of IS approach. In section 4 we discuss the results under the lens of a possible unique Knowledge and Innovation System for the Bioeconomy (KISB), similar to what happens in agriculture with the Agricultural Knowledge and Innovation System (AKIS). Finally, some conclusions are outlined in section 5.

2. MATERIAL AND METHODS

The present paper is conducted following the PRISMA (Preferred Reporting Items for SysteMAtic reviews) approach (Moher et al., 2009). This approach foresees several consequential steps. First, the identification of what to investigate (research question), where (sources, databases, etc.) and how to start (keywords, search strings, etc.). Second, the Authors determine specific preliminary criteria for including or excluding studies, for example, based on the typology of items (articles, reviews, book chapters, etc.) or only publications in a specific range of years. After that, a screening phase is carried out, reading titles and abstracts and identifying the match with the predetermined criteria. The final selection of the eligible articles is made by reading the full papers, rejecting the non-compliant ones that had passed the abstract-based selection. The last phase of the PRISMA approach is the qualitative review of the selected papers and the presentation of results.

Our research was conducted in July 2024. Based on the research question, we conducted our search in the Scopus database[1], using as a string: "(bioeconomy OR bio-based AND economy) AND innovation AND (system* OR network OR cluster)". This first query returned 209 documents (Fig. 1).

Hence, we filtered by subject area, keeping "Social Sciences", "Business, Management and Accounting", "Economics, Econometrics and Finance", and "Multidisciplinary." Based on the document type, we kept only articles and reviews. Then, we excluded Chinese as a language. Finally, according to our research question and the explained background, we selected only papers

[1] Scopus, Elsevier B.V., https://www.scopus.com/, last seen 04/02/2025

from 2017 to 2024 – the so-called *maturity stage* of the bioeconomy (Wei et al., 2022). In this way, a subtotal of 56 documents was found.

Based on the research question and the objective of this study, before starting to read titles, abstracts and, eventually, full papers, we defined some criteria:

– no papers with no focus/analysis of innovation processes;
– no papers on business opportunities/product-oriented (with no specific focuses on innovation systems);
– no papers on sustainability assessment;
– no papers on technology's impact on sustainability;
– no papers on circular economy with no reference to bioeconomy.

After the exclusion of non-compliant papers based on abstracts or full-paper reading or because the document was not findable, we conducted our qualitative research on the final number of 24 papers.

The qualitative analysis was conducted through four main steps:

i. Identification of general information, namely: Nationality of the Institution(s) of the Author(s); Paper's Topic; Sector(s) or Subsector(s) of the Bioeconomy considered; Study reference Scale; Methodology applied; Innovation Systems Framework adopted; and whether Case Study or not (if yes, where);
ii. Identification of the contextual factors (see Tab. 1 for the considered criteria);
iii. Classification of the papers based on four categories, contrasting on the vertical axis the collaborative-oriented and innovation-oriented papers, while on the horizontal axis the business-centred and policy-centred ones (Fig. 2). The assignment of a paper to one of the categories was concerned primarily with the paper's research objective. If the research objective was not clear enough, and doubts persisted, the analysis moved to results, discussion and conclusion. However, based on the main focus, none of the papers fell into multiple categories;
iv. Distribution of IS and contextual factors into the four previously identified groups.

In greater detail, the criteria listed in Tab. 1 are extrapolated by Van Lancker et al. (2016). Hence, to assign one factor to one paper, one or more than one of the criteria must be directly addressed in at least one of the sections of the paper. Thus, for example, to assign "challenging commercialisation", in at least one section there must be the identification of difficulties related to the commercialisation or adoption of bio-based products by other companies (B2B), by the final consumer (B2C) or both.

The classification of papers based on the identified four categories represents an original framework developed by the Authors. This framework, taking up the original distinction between technology-based and knowledge-based approaches, broadens its scope and contrasts innovation-oriented papers with collaboration-oriented ones. This choice was made to understand whether, in the study of the bioeconomy, linear approaches to innovation persist or whether, given the relatively recent birth of this sector, the collaborative and systemic model is prevalent in the analysis of the sector. Similarly, the contrast between firm/business-centred research and policy-centred research was adopted to understand the main point of view of today's research on the topic of innovation in the bioeconomy. The main scope of this contrast was to understand the distinctions in perspectives between two economic

Table 1. Criteria for selecting contextual factors.

Contextual factor	Criteria
Radical innovation	· Redesigned business models · Reconfigured supply chains · Setup new supply chains (new convergences of sectors)
Complex knowledge base	· Varieties of sciences and technologies
Intense cooperation	· Cooperation between different actors
Challenging commercialisation and adoption	· Challenging in B2B · Challenging in B2C
Policy schemes fragmented	· Different policy schemes · Different administrative levels · Legal limitations for biobased/biomass applications

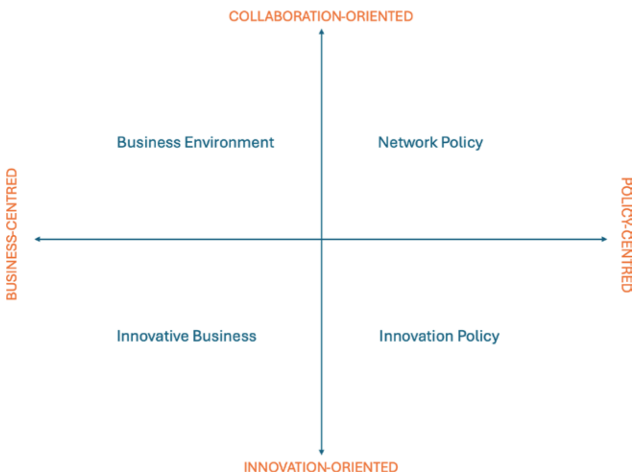

Figure 2. Papers grouped by main orientation (Collaboration vs Innovation) and research field (Business vs Policy).

branches (namely, business economics and economic policy) and to identify which of the two prevails when it comes to innovation in the bioeconomy. Furthermore, given the importance of these two perspectives, the analysis of the current literature on the topic provides insights in terms of knowledge gaps and future research. Hence, by placing these two contrasts on two axes, four different quadrants were identified, and each of them was named depending on the two dimensions involved. The four quadrants are: I) Network Policy (collaboration-oriented and policy-centred); II) Business Environment (collaboration-oriented and business-centred); III) Innovative Business (innovation-oriented and business-centred); and IV) Innovation Policy (innovation-oriented and policy-centred).Through these groups, it was possible to better understand the differences in IS framework adoption pathways and, focusing on the innovation process, the factors that characterise the bioeconomy context.

In the results section, after a general overview (subsection 3.1) and a description of the contextual factors identified (subsection 3.2), the four groups are used as a lens (subsection 3.3) to explore the relationship among them and IS frameworks adopted by scholars (subsubsection 3.3.1) and among them and contextual factors emerging from the papers (subsubsection 3.3.2).

3. RESULTS

3.1. General overview

Considering the geographical location of the authors' institutes, Europe has the most prominent role, with twenty papers out of twenty-four that involve only European institutes and two papers that involve European and non-European entities (however, in both cases the first Author belongs to a European country). Only in two cases, the Authors are not European, i.e. in one case from Brazil and in the other from Brazil and Australia. At the country level, the most represented country is Germany with 10 contributions, followed by Finland with 5 papers.

In terms of approach, the large majority of papers are applied research with eighteen of them that consider a case study. Lovrić et al. (2020) and Bueno et al. (2022) stand out as the sole studies where the Authors conducted practical research without analysing a specific case. Among the remaining three, two are literature reviews (Lang et al., 2023; Salvador et al., 2021) and one is a commentary (Losacker et al., 2023). Moreover, in terms of methodology, the most used methods are qualitative ones, namely focus groups, semi-structured interviews and questionnaires. Other methods comprise analysis of research projects, social network analysis, system dynamics and innovation systems approaches.

Looking at the reference scale, the National perspective is the most addressed, with twelve papers, followed by the Global perspective with five papers. Other scales, such as Regional or Continental are addressed as well, but respectively in three and two cases. The Municipal and mixed scale (i.e. National plus Regional) are referenced in one article each.

Regarding the bioeconomy sectors or subsectors considered in the papers, the main approach is that of considering the bioeconomy in its general complexity (Bogner and Dahlke, 2022; Chmielińskii and Wieliczko, 2022; Hurtado and Berbel, 2023; Lang et al., 2023; Losacker et al., 2023; Salvador et al., 2021), followed by forestry or wood-based bioeconomy (D'Amato et al., 2022; Giurca and Metz, 2018; Laasonen, 2023; Lovrić et al., 2020) and green chemistry or biofibre (Alfano et al., 2023; Kamath et al., 2023; Korhonen et al., 2020; Loos et al., 2018). Less common is the propensity to consider various sectors at the same time (Pyka, 2017; Scheiterle et al., 2018; Torre et al., 2023).

3.2. Contextual factors identified

Identifying the contextual factors as outlined by Van Lancker et al. (2016), we found that the most common one is i*ntensive cooperation*, a concept that emerged in almost all the papers considered (Fig. 3). Even the *complex knowledge base* is a widespread factor, discussed or addressed in almost 75% of papers. *Radical innovation* is covered in just over half of the papers, while slightly less than half examines the *challenging commercialisation*.

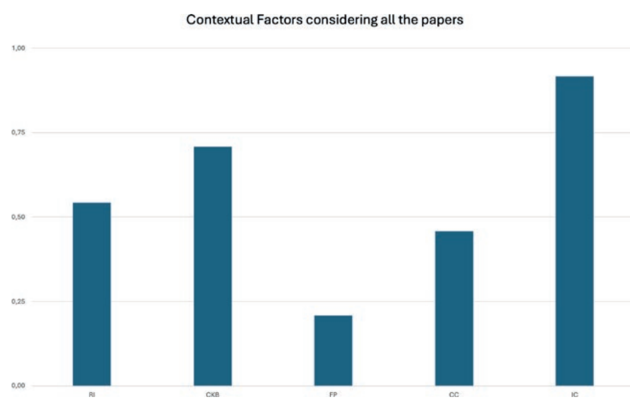

Figure 3. Contextual factors identified, in relative numbers, in the papers considered. Legend: RI = Radical Innovations; CKB = Complex Knowledge Base; FP = Fragmented Policy; CC = Challenging Commercialisation; IC = Intense Cooperation.

Finally, the least explored factor is that of *fragmented policy*, with less than a quarter of the articles focusing on it.

However, we also found some elements or critiques that, moving away from Van Lancker's definitions, may deepen the knowledge of the innovative context in the bioeconomy. These aspects are further discussed in the following sections.

3.2.1. Intense cooperation

This factor is the most addressed by different authors and no changes or modifications are reported in the concept: The idea of different actors that intensely cooperate in the bioeconomy innovation processes is widely perceived as one of the main characteristics of the sector. Furthermore, this result may suggest that, nowadays, the multi-stakeholder approach is perceived as more distinctive than the multidisciplinary approach (see next section on CKB). Bogner and Dahlke (2022) underline the importance of empowering and educating heterogeneous actors (different in age, gender, social and educational background) to stay actively engaged and participate in the innovation process with an *ex-ante* approach rather than an *ex-post* acceptance approach.

However, D'Amato et al. (2022) report the difficulty in the Finnish Wood-based Bioeconomy (WBE) to engage in cross-sectoral and cross-discipline knowledge co-production, pointing out the lack of collaborative skills, and organisational differences. Similarly, Laasonen (2023) highlights the positive effects of well-developed relational capabilities, and, on the other hand, the negative impact of their lack on the whole innovation system. A solution to these problems is pointed out by Alfano et al. (2023), which observe the role of clusters in aggregating different actors, that could act as intermediaries and help to overcome the collaboration issues.

Donner and de Vries (2023) underline the importance of small-scale initiatives in the circular bioeconomy business models and the role of geographical embeddedness and the relational proximity of actors. In this vein, the local-based innovation and the importance of local actors are pointed out also by Torre et al. (2023), in their study on rural development, and by Taffuri et al. (2021) in their paper on the urban management of biowaste. In the former, the Authors underline the effectiveness of knowledge exchange that the multi-level coordination (from national to local) made and the importance of long-term research programs to keep local actors embedded and aware of how collaborative research works. In the latter, the Authors highlight the complex web of stakeholders involved in the CBE paradigm even at the municipality level.

However, in some cases, the difference between IC and CKB is blurred. This is the case with some emerging concepts, such as *living labs*, where, in the case of Losacker et al. (2023), they are interpreted as places of interdisciplinary interaction, while in the case of Donner and de Vries (2023), they are seen, more in general, as "joint systemic co-creation approaches" (Donner and de Vries, 2023: 13). However, in both cases, the living labs are cited in the "future research" section, underlining the absence of studies in the direction of stable and, more or less, informal collaborations in the bioeconomy.

3.2.2. Complex knowledge base

Although the complex knowledge base of the bioeconomy is widely recognised (e.g. Bogner and Dahlke, 2022; Loos et al., 2018; Scheiterle et al., 2018) and still remains one of the peculiarities of this sector, the papers considered a greater tendency to identify this concept with the terms *multi-* or *interdisciplinarity* emerges (see for example Chmielińskii and Wieliczko, 2022; Orozco and Grundmann, 2022; Torre et al., 2023). Chmielińskii and Wieliczko (2022) identify interdisciplinary as a way to catch the overall complexity of the bioeconomy and render a holistic vision. This complexity is also pointed out when addressing the issue of lacking knowledge or capacity. For example, the case of Loos et al. (2018) points out the lack of capacity of the national system for the implementation of a biomass-based value web that involves several professionals and different know-how. In particular, the authors underline the poor awareness and evaluation of by-products as a resource and the need for coordination and support from public institutions. The latter should facilitate innovation diffusion, support applied R&D, and align institutions toward the commercialisation of plantain fibre (the byproduct analysed in the paper). Similarly, Drejerska et al. (2020), point out the lack of managerial know-how in implementing circular biowaste management. These two examples demonstrate how, through a systemic analysis, factors emerge that are difficult to identify in a mere technology-oriented or based on a linear approach. In this vein, in recent years some connected concepts are often addressed together with knowledge base, such as skills (e.g. Alfano et al., 2023) or education (e.g. Chmielińskii and Wieliczko, 2022; Hurtado and Berbel, 2023).

3.2.3. Radical innovation

In their paper, Van Lancker et al. (2016) state that "although some existing products and processes may only need some incremental, gradual innovations, the transition [towards the bioeconomy] will mainly require diverse, radically new and disruptive innovations" (Van Lancker et al., 2016: 61). This contrast between a more radical and a more moderate approach to innovation often emerges in the papers analysed, although with varying terminology. For example, Taffuri et al. (2021) apply an "improvement" perspective, by introducing bio-waste valorisation possibilities within the current Metropolitan Solid Waste Management System of a city in northern Italy (i.e. Turin). Kamath et al. (2023) contrast the "path-modernisation" with the "path-creation." The range of different types of innovation is also part of the work of Orozco and Grundmann (2022), who outline the variation from incremental to disruptive innovations. This latter concept, gains a wide consensus. Indeed, also Lovrić et al. (2020), Bueno et al. (2022), and Losacker et al. (2023) use the term "disruptive" to identify the most radical innovations. However, it is important to underline that, although both radical and disruptive are concepts that imply a deep change, they slightly differ from each other. In fact, the concept of disruptive innovation implies a modification of market dynamics through novel business models and low-end market capture, while the concept of radical innovation is more related to groundbreaking technological advancements (completely new ideas or products) that cause significant organizational transformations within companies (Hopp et al., 2018).

Closer to the concept of "radical" is the concept of "transformative knowledge" explored by Bogner and Dahlke (2022) in their paper on the German bioeconomy policy. Indeed, also in this case the main focus is on the policy side. However, the transition from "innovation" to "knowledge" implies a broadening of the overall vision of the phenomenon, with further dimensions analysed, such as "system knowledge", "normative knowledge", "techno-economic knowledge" and "transformative knowledge." Furthermore, this approach reconnects the concept of RI with that of CKB.

In the papers analysed, radical innovation is also seen from the business side, as emerged with the concept of disruptive innovation. In this field, Giurca and Metz (2018) consider the market formation, while Lazarevic et al. (2020) consider a niche market. Lang et al. (2023) underline the important connection between transformative innovation and the involvement of consumers in bio-based business models. Hence, even from a more business-oriented perspective, the importance of a systemic vision may help (e.g. the business model canvas developed by Salvador et al., 2021).

3.2.4. Challenging commercialisation

The aspect of how challenging is the commercialisation of innovations both for B2B and B2C is addressed both directly and indirectly in the papers considered. For example, Bogner and Dahlke (2022) indirectly address the problem by considering the projects that took place in Germany, documenting a strong focus on the market acceptance of products and processes related to the bioeconomy.

Chmielińskii and Wieliczko (2022) underline the difficulties that findings from research encounter in commercialisation. However, in their statement, the authors do not only imply the importance of convincing potential buyers, but they also call for engaging stakeholders across business, scientific, governmental, and consumer sectors and for using better education at all levels. In this way, they mix business and policy recommendations to systematically enhance the national bioeconomy.

Losacker (2023), more in line with van Lancker, refer to "technology legitimization." However, this concept encompasses social acceptability and broadens the discussion to a legal aspect. Moreover, Lang et al. (2023) discuss the active role of consumers in influencing business models, while, Korhonen et al. 2020 face the problem of the performativity of biomaterials compared to other materials and the importance of this issue in health risks for humans and the environment, stating that in some cases "it makes sense to use the most durable materials available, regardless of the material's environmental performance."

In other words, due to the large number of ethical challenges that the innovation processes have to face in the bioeconomy, it seems that the specific focus on the commercialisation side limits the capacity of this factor to describe the bioeconomy innovation context.

3.2.5. Fragmented policy

Due to the sectors convergence that characterise the bioeconomy (Lazarevic et al., 2020) the optimisation of policies still represents an issue (e.g. Korhonen et al., 2020). Anyhow, in addition to the low rate of papers that directly address this factor, we found that three policy issues are perceived as more compelling. First, a need for targeted policy interventions (Giurca and Metz, 2018), that implement the nowadays well-established and structured strategies for the bioeconomy (Bogner and Dahlke, 2022; Hurtado and Berbel, 2023). This is the case of the EU, where in addition to the strategy pointed out by the Commission (EC, 2018), almost all MS developed their own strategy (Joint Research Centre

European Commission, 2022). An example of successful policy intervention is outlined by Lovrić et al. (2020) in the case of Finnish WBE. In this context, the incremental change from a forestry to a wood-based bioeconomy policy has been perceived as a success for the stakeholders involved thanks to the reduced policy fragmentation.

The second policy issue is the lack of specific funds, considered under several aspects: D'Amato et al. (2022) indicate the limited funding opportunities for cooperating in cross-sectoral initiatives as one of the main tension factors in the Finnish WBE; in Laasonen (2023), the Finnish regional and business development agencies and the research and education organisations point out the need for external funding for R&D activities with other partners as one of the element to keep vital collaborations; Alfano et al. (2023) show that only a small percentage of the green investments made by Italian firms belonging to a *biocluster* is supported by public funds, with the highest percentage of investments financed by venture capital or traditional bank financing.

The third policy issue is a lack of legal frameworks for new technologies or services in the field of the bioeconomy, as emerged in the challenging commercialisation (see specific section).

Based on these findings, the fragmented policy factor does not describe the overall complexity of policy frameworks in the bioeconomy.

3.3. Papers classification

The highest number of papers belongs to the category of *Business environment*, with nine papers, followed by *Network policy* with eight (Fig. 4).

The *Innovation Policy* group and *Innovative Business* follow with, respectively, four and three papers. Hence, looking at the four dimensions considered, we found a higher number of papers directly focused on collaboration (seventeen papers) rather than innovation (seven articles), while between business and policy-centred papers we found a balance of twelve papers each.

3.3.1. Groups and Innovation Systems

Although the identification of the Innovation Systems (IS) Framework for each category did not yield significant results, some remarks can be made. In general, there is a wide range of frameworks adopted by different authors . In the first period (2017-2020) we notice a greater diffusion of innovation systems most known in the literature on innovation, i.e. National Innovation Systems (NIS), Regional Innovation Systems (RIS) and Technology Innovation Systems (TIS); while in a second phase (2020-2023) we notice a decline in these systems in favour of other frameworks, such as knowledge-based systems (e.g. Bogner and

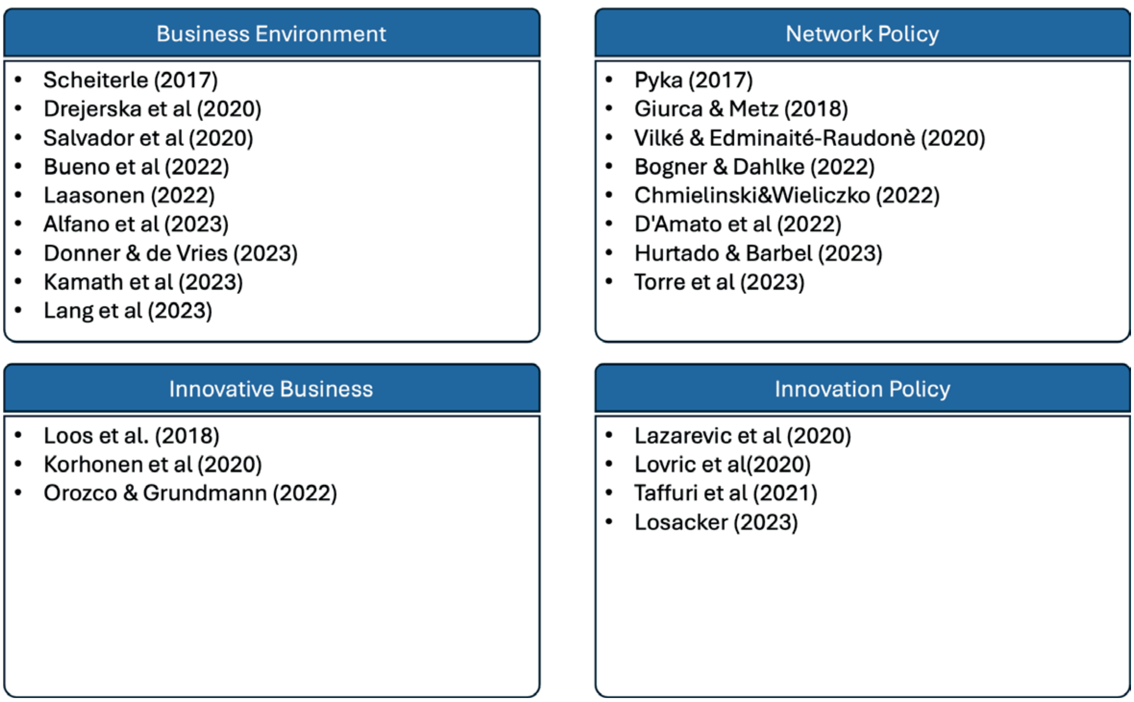

Figure 4. The selected papers classified based on the four different groups.

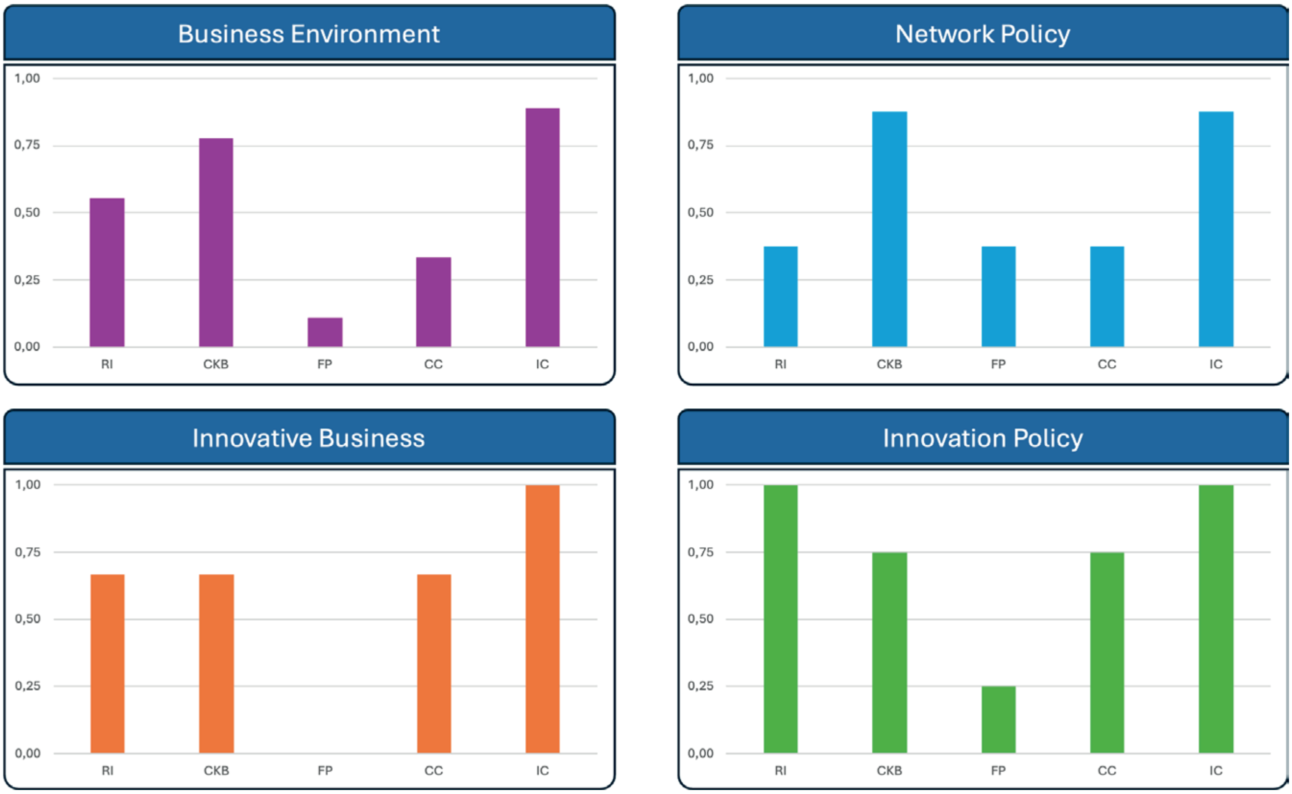

Figure 5. Contextual factors identified, in relative terms, in the four groups of papers considered.

Dahlke, 2022; D'Amato et al., 2022) or stakeholders analysis (Taffuri et al., 2021). More in detail, looking at the several IS frameworks, the NIS was more adopted in the business-centred (Loos et al., 2018; Scheiterle et al., 2018), TIS in policy-centred papers (Giurca and Metz, 2018; Lazarevic et al., 2020) and RIS in collaboration-oriented studies (Hurtado and Berbel, 2023; Kamath et al., 2023). No specific IS are adopted on the innovation-oriented side.

Delving into the specific groups, no remarks emerge from the *Innovative Business* and *Innovation Policy*, while in the case of *Business Environment* and *Network Policy,* we notice two peculiarities. In the *Business Environment* case, there is a tendency to focus with greater detail on sub-groups of the whole IS, adopting concepts like *networks* (Bueno et al, 2022) or *bioclusters* (Alfano et al., 2023; Kamath et al., 2023). Instead, the *Network Policy* group's peculiarity is the broadening of the vision towards a systemic approach of both innovation and knowledge. Indeed, only in this group, the concept of *knowledge* is used as a discriminant. For example, Bogner and Dahlke (2022) use different knowledge (i.e. transformative knowledge, system knowledge, normative knowledge and techno-economic knowledge) to identify the different types of policies, while D'Amato et al (2022) discuss the *Knowledge co-production* within the Finnish WBE. Finally, Chmielińskii and Wieliczko (2022) adopt the framework of *Innovation and Knowledge Systems,* which can be linked to the broad literature on Knowledge and Innovation Systems (KIS).

3.3.2. Groups and Contextual Factors

Apart from *Intense cooperation,* which is the most addressed factor in each category, other contextual factors are mostly in line with the IS frameworks outlined above (Fig. 5).

Indeed, *Complex Knowledge Base* is the most represented factor in collaborative-oriented research, in particular in the *Network Policy* group, where it is at the same level of *Intense Cooperation* and this confirms the aforementioned interest in the concept of knowledge in this group. Instead, in innovation-oriented studies, *Radical Innovation* has a prominent role in the *Innovation Policy* group, while in *Innovative Business,* it shares the same rate with *Complex Knowledge Base* and *Challenging Commercialisation*. In particular, this latter factor characterises innovation-oriented research more than collaborative-oriented one. The *Fragmented Policy* is addressed almost only in the policy-centred papers.

4. DISCUSSION

The variety of frameworks applied to describe the IS in the bioeconomy hinders the identification of a singular and unified framework. While this abundance of methodologies allows for the analysis of innovative systems from multiple perspectives, moving toward a unique, widely accepted IS may provide some advantages. An example might be provided by one of the most known and successful IS, the Agricultural Knowledge and Innovation System (AKIS) (Germundsson and Norrman, 2023; Ingram and Maye, 2020; Klerkx and Begemann, 2020). Rooted in the studies of Röling (Röling, 1988; Röling and Wagemakers, 1998), Arnold and Bell (2001) and Spielman and Birner (2008), the AKIS framework was supported by various supranational bodies, such as OECD (2012), World Bank (Julio and German, 2001), and EU (EU-SCAR, 2012, 2015, 2019). The latter, in particular, after a gradual introduction of this framework as a policy tool (EU-SCAR, 2012, 2015, 2019), decided to highlight the role of the AKIS introducing it in the Common Agricultural Policy (CAP) 2023-2027 (European Parliament and the Council of the European Union, 2021) and asking MS to assess how the different actors that compose the national AKIS interact and support the production and use of knowledge and innovation (EU CAP Network, 2023). Although this concept is still perceived by many political and administrative decision-makers as vague and there is difficulty in fully understanding it (Knierim and Birke, 2023), a well-functioning AKIS is seen as a way to strengthen the impact of funds and policy interventions, avoiding duplications and saving costs (EU-SCAR, 2019). In this sense, a unique IS for the bioeconomy, as the Knowledge and Innovation System for the Bioeconomy (KISB) proposed by Esposti (2012), might represent a way to determine coherent fund allocations and policy interventions, fulfilling the requests in this direction that we found in this review. In general, this vision might overcome the fragmented and sectorial policy framework that persists in the current bioeconomy. Furthermore, such a tool might be useful not only for policymakers but also for all the other components of the system (Knierim and Birke, 2023). For example, through the analysis of the KISB, several gaps in the system may emerge (e.g. missed brokers or missed technologies) and this may provide to extension services and firms interesting niche markets.

Nevertheless, it is fundamental to keep in mind that some profound differences persist between AKIS and KISB. First, due to its modernizing mission and its focus on increasing the sustainability of the rural world, AKIS's core components are *practitioners*, i.e. farmers, foresters, fishers, and food processors (Knierim and Birke, 2023), seen as implementers of practices that have a direct effect on the environment (Schmidt et al., 2022). Instead, as we saw in our findings, the current bioeconomy implies a vision that even overcomes Van Lancker's *Complex Knowledge Base*, incorporating knowledge-intensive, high-tech and high organisational and implementation skills. In this sense, the different typologies of practitioners involved in the bioeconomy (e.g. biomaterial producers, bioenergy producers, etc.) expands the audience of stakeholders involved, each with particular needs linked to their own area of interest and reference market. In addition, as we found in this review, the active role of primary producers in the innovation processes of KISB is little explored and, therefore, considered marginal.

Second, the current AKIS literature and the actual policy implementation are mainly focused on extension services (Amerani et al., 2024; Knierim and Birke, 2023), especially in their role as *innovation brokers*. Based on the papers we considered, this aspect cannot be focal of KISB nowadays because of the current lack of specific research on advisory services in the bioeconomy innovation process. Indeed, to date, research is mainly based on the helix approaches (triple, quadruple and rarely quintuple), considering only the main actors (e.g. business, academia and policymakers) and not connection figures. In this sense, it is not clear whether firms are directly linked to research institutions – with no need for intermediaries –, or if the high-tech innovations in the bioeconomy sector have equipped firms' in-house R&D with the necessary skills to avoid external advisory services.

Third, AKIS can be considered part of KISB if we consider that agriculture is part of the bioeconomy. Anyhow, the study of the interactions between these two systems is still in its infancy (Chmielińskii and Wieliczko, 2022; Vilkė and Gedminaitė-Raudonė, 2020), with several aspects to be further explored, such as the importance of the national AKIS within a national KISB or the interactions between AKIS and the other IS to form KISB. In particular, can we consider one system overarching the other, or are they synergistic or complementary?

Fourth, the different roles and importance of consumers. On this aspect, the KISB perspective gives a complexity that the contextual factors identified by Van Lancker et al. (2016) do not catch completely. Indeed, both the *Challenging Commercialisation* and *Intense Cooperation* do not focus directly on the challenging aspects that characterise the whole innovation process in the bioeconomy. For example, sustainability and circularity concepts are nowadays considered paramount for the bioeconomy (D'Amato and Korhonen, 2021; Drejerska et al., 2020; Lang et al., 2023; Salvador et al., 2021). In this vein, the use of biological resources inevitably raises ethical dilemmas (Viaggi, 2018; Viaggi et al., 2021). An example of this is the possible contrast between food production and the production of other crops (e.g. for biofibres or bioenergy), which is known as the *competing dilemma* (Asada et al., 2020). Another example is the well-known debate around genetic modifications (Hartung and Schiemann, 2014; Jacobsen et al., 2013; Weisenfeld et al., 2023), which strongly affects the biotechnological component of the bioeconomy (Wei et al., 2022). These two examples give an idea of the importance of stakeholders' engagement in the innovation development, in particular consumers, citizens and end-users. This could be also the reason why the *Intense cooperation* is the most accepted contextual factor as emerged from our results. However, many aspects of this cooperation are still unclear. Just to cite some unanswered questions: What are, nowadays, the main drivers? What bottom-up mechanisms characterize cooperation for innovation in the bioeconomy? Is this cooperation market-pushed or policy-driven? How does consumer behaviour influence the whole system in the transition towards new bio-products? What is the role and how do local actors contribute to the implementation of new bioeconomic value chains?

This latter aspect raises questions regarding the dispute that we found among researchers around the issue of *Radical innovation*. As we saw, researchers are mainly divided between a more moderate and incremental vision of how to implement the bioeconomy (e.g. Taffuri et al., 2021) and a more intense and radical one (e.g. Bogner and Dahlke, 2022). Although opposed, from a KISB perspective these two positions can be reconciled. Indeed, the path-modernisation and the path-creation (Kamath et al., 2023) are both part of the knowledge and innovation processes, with their own actors, mechanisms and characterising factors. Hence, both these two streams of research can contribute to a better understanding of the complexity of innovation in the bioeconomy.

Moreover, all the underlined aspects can benefit both from business-centred and policy-centred research. The business-centred research can largely contribute, through its attitude toward the *stakeholder* concept (Taffuri et al., 2021; Korhonen et al., 2020) and the sub-systems description (*bioclusters*, *networks,* etc.) (Alfano et al. 2023; Bueno et al., 2022; Kamath et al., 2023). Even in this case, the AKIS literature may provide a framework to explore many of the aspects underlined in the previous questions: microAKIS (Sutherland et al., 2023). This framework focuses on the innovation subset of the whole AKIS that operates at the farm's individual level or, using the description provided by Sutherland et al. (2022), "the sources of knowledge that farmers personally develop to pursue innovations and to manage their farms" (Sutherland et al., 2022: 40). The possibility of exploring the microKISB opens the room to further analysis in the business research, such as new business models, business environment and market creation with a firm-centred systemic perspective. It also allows for considerations in the field of policy-centred research. This stream of research can benefit from the micro-KISB perspective to draw conclusions about the role of local actors in the transition from national strategies to local implementations. Furthermore, the lack of analysis of the mechanisms of knowledge transmission in the whole system and the pressing requests to combine policy interventions and funds allocations – short and medium-term perspective – with bioeconomy strategies – long-term perspective – also questions the wider KISB perspective (more national-oriented). An example is provided by the emerging issue of education and training in the bioeconomy (Chmielińskii and Wieliczko, 2022; Hurtado and Berbel, 2023; Laasonen, 2023), which represents an interesting point of view for policy considerations to optimize the system's ability to absorb or generate knowledge (Buchmann and Pyka, 2015; Kurtsal et al., 2024). In this sense, the policy-centred research may merge *Intense cooperation* with *Fragmented policy*, showing that the system perspective can, at the same time, explain the mechanisms and propose pathways, as occurs in the study by Hurtado and Berbel (2023).

Hence, both KISB and microKISB can contribute to answering the unanswered questions, combining different levels of research (national, regional, local, etc.), and, at the same time, explaining the mechanisms that regulate all the contextual factors, taken both individually and together.

Finally, considering the least adopted contextual factors, i.e. CC and FP, we saw that in both cases they were limited in their ability to describe the overall complexity of the innovation development processes in the bioeconomy. This may partly explain why they are less explored by the papers considered. Hence, our suggestion is to enlarge both the concepts. The CC should become *commercialisation dilemmas* (or e*thical and market challenges in commercialisation*), extending the concept to the ethical aspects of the commercialisation of bioproducts. Instead, the FP should become a *complex policy and legal framework*, underlining the large mix of different levels of policies and norms that characterize the bioeconomy.

However, this study has some limitations. Excluding the linear approach of innovation from research criteria, part of the innovation processes are excluded. In this sense, future research may include this approach to enlarge the vision of the innovation processes. Similarly, future research may include contributions provided before 2017, the year we chose as the lower limit of our study. Indeed, earlier studies from the Infancy and Exploring stages of the bioeconomy literature may provide further insights for theoretical advancements in knowledge creation and innovation development in the field of bioeconomy.

Furthermore, no specific analysis has been conducted in terms of the current level of innovation in the field of the bioeconomy system. Specific research on this topic is deemed necessary in the future for a better knowledge of the sector and to understand how the bioeconomy fits into the main modern technological processes (e.g. digitalisation, nature-based solutions, etc.).

Finally, consulting a single scientific database (i.e. Scopus) can be considered a limitation of this research, which future research on the topic could overcome by consulting more databases.

5. CONCLUSION

In this study, we conducted a systematic literature review to explore the application of the IS framework in the field of the bioeconomy. In particular, the aim was to identify the scope and the characteristics of a KISB framework. We found that a unique framework is nowadays missed. Several approaches were adopted, but rarely with the aim of a theoretical advancement for the whole bioeconomy literature. Indeed, often the approach adopted was the one best fitting for the purpose of the research, with rare examples of the opposite, i.e. to seek a holistic framework that describes innovation processes within the bioeconomy.

However, one of the main results of this study is the possibility of applying and benefiting from a specific KISB. In fact, the mechanisms and dynamics examined in this study go further beyond the simple technology-oriented or linear approach to innovation, as we saw considering the complex amount of skills and professionals needed to implement bioeconomy processes (e.g. in biowaste management). Hence, based on the examined papers, some peculiarities should characterise the KISB. First, based on the result that *Intense Cooperation* (IC) and *Complex Knowledge Base* (CKB) are the most common factors, we outlined how the multi-actor and multidisciplinary approaches are fundamental in the bioeconomy innovation processes, and it is not possible to exclude them in the KISB. Second, we found a more intense stream of research in the field of collaborations rather than innovations. In this sense, the efforts made by scholars can strongly contribute to outlining a KISB, for example including the analysis of knowledge development. Third, even if less represented, the innovation-oriented papers add insights in terms of challenging aspects of commercialisation in the bioeconomy. Finally, we found that there is a wide scope for KISB and the connected concept of microKISB (i.e. the innovation subset of the whole KISB that operates at the organisation's individual level) in both business-centred and policy-centred research. Therefore, KISB and microKISB must be designed in such a way that they can represent an interesting and useful tool for all the actors involved in the bioeconomy innovation process, mainly policymakers, business actors, and researchers.

Furthermore, similarly to AKIS in the current CAP, even KISB may become a policy objective transversal to all the sectors involved. This would make all the operators aware of the actors involved in the knowledge and innovation system, and, on the other hand, the bioeconomy would benefit from a more systemic promotion and sharing of knowledge.

Moreover, looking at the contextual factors of Van Lancker et al. (2017), our suggestion is to enlarge the two less-represented concepts, i.e. *challenging commercialization* (CC) and fragmented *policy* (FP). The CC should become *commercialisation dilemmas* (or e*thical and market challenges in commercialisation*), extending the concept to the ethical aspects of the commercialisation of bioproducts. Instead, the FP should become a *complex policy and legal framework*, underlining the large mix of different levels of policies and norms that characterize the bioeconomy.

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ORCID
SM: 0000-0002-3627-8739

Impact of weather variability on crop yields and land use dynamics in Eastern India: Short- and long-term effects

Pratap Kumar Jena[1], Kirtti Ranjan Paltasingh[2], Souryabrata Mohapatra[3,*], Ashok Mishra[4]

[1] *Department of Economics, Maharaja Sriram Chandra Bhanjdeo University, Baripada, India*
[2] *Department of Economics, Ravenshaw University, Cuttack, India*
[3] *School of Liberal Arts, Indian Institute of Technology Jodhpur, Jheepasani, India*
[4] *Morrison School of Agribusiness, Arizona State University, Mesa, United States*
*Corresponding author. Email: smohapatra@iitj.ac.in

Abstract. Weather variability disrupts food grain production and agricultural sustainability. While existing literature highlights the stationary relationship between weather variables and agricultural outcomes, it often overlooks their bearing on land use changes. This study investigates the dynamic effects of weather variations on crop yields, land use and intensity in Odisha, Eastern India, using district-level data from 2001-18. By employing a ‘panel auto-regressive distributive lag (P-ARDL) model, we assess long- and short-term relationships between weather parameters and agricultural yields. Results reveal a negative marginal impact of rainfall deviation on yield, ranging from -0.16 for wheat to -0.48 for green gram in the long term. In the short term, however, the marginal impact is positive for some pulses (green gram, black gram) and oilseeds (groundnuts). Weather variability has adversely affected the intensity of land use but has induced crop diversification in both the short and long term.

Keywords: climate change, crop yield response, land use intensity, panel ARDL model, Odisha, India.
JEL codes: C33, Q15, Q18, Q54.

1. INTRODUCTION

Over the last two decades, the issue of weather fluctuations and their impacts has been debated intensively among policymakers, scientists and academia globally. Evidence shows varying effects of long-term changes in weather patterns in various regions, with some areas severely affected and others observed to have had observable positive effects (Mohapatra et al., 2023). The impact of weather variability differs across countries’ levels of development. It harms developing countries, whereas it carries possibly low to moderate impacts on developed countries, exacerbating the weather’s impact on inequality (Dudu and Çakmak, 2018; Asogwa et al., 2022; Xiang

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et al., 2022). Yet, this pattern is not universal. Some developed nations have endured significant damage; for example, the catastrophic floods in Japan in 2018 increased vulnerability, drove up healthcare costs and inflicted major losses in the manufacturing sector (Lin et al., 2020; Yamamoto and Naka, 2021; Yoshida et al., 2023). Similarly, devastating floods in Germany in 2021 and Spain in 2024 imposed substantial economic burdens on their capitalist economies (Martin-Moreno et al., 2025). Agricultural competitiveness increases the temperature among countries. For example, agrarian competition in developing countries has increased the temperature but declined in developed countries (Nugroho et al., 2023).

In addition, weather variations have considerably impacted crop production, food availability and quality. The dynamic effects of weather shocks on agricultural output in Peru show an adverse impact of weather shocks measured by excess heat or rainfall, which had a delayed negative impact on agricultural production, and its magnitude depends on various factors (Crofils et al., 2025). The connectedness and variability effects transmission between weather variables and agricultural productivity in Morocco suggest that weather variability increases the spillover effects transmitted to agriculture (Belcaid and El Ghini, 2020). The dynamic impact of weather changes on vegetable price fluctuations in China observed that the specific vegetable price was affected by changes in particular weather factors, which were time-varying (Yang et al., 2022).

However, in the case of developing countries like India, the consequence of weather variations is predicted to be harmful, and the impact could be severe in the near future. Agricultural productivity will be reduced by 4.5% with a 1°C increase in temperature in India, and it is predicted that the total factor productivity in agriculture will decline across all states by 2050 (Pattanayak et al., 2021). Several empirical studies have evidenced the deleterious impact of weather variations on farm production and productivity in India and some other countries (Arora, 2019; Xie et al., 2019; Chandio et al., 2020; Seven and Tumen, 2020; Mohapatra et al., 2025). However, research on the issue of weather variations and their dynamic impact on land use patterns and land use intensity is scarce. Indeed, this problem has been ignored in the case of Indian agriculture[1], specifically at the micro level in the agriculture of eastern India. In this paper, we thus attempt to answer the research question of how weather variations influence crop yields and land use dynamics in eastern India.

At the micro level, weather fluctuations significantly affect the exposure and vulnerability of one ecosystem by altering the water supply and food production, damaging infrastructure and causing morbidity and mortality, as noted by the Intergovernmental Panel on Climate Change (IPCC, 2014). All the outcomes have implications for land use. In the farm sector, the long-term changes in weather factors affect land use patterns and intensity through their impacts on crops' comparative advantage: yields or profits (Birthal et al., 2021). Farmers decide their acreage allocation after carefully analysing their prospects for profit (yield) during the weather shock and their ability to cope with it. Again, in developing economies, institutional mechanisms for managing weather risks, such as crop insurance, soil management practices (soil health cards) and so on, are inadequate and inaccessible to resource-poor smallholders. Thus, fluctuations in rainfall, a rise in mean temperature and frequent weather extremes severely threaten the food system and food security through changes in the pattern and intensity of land use (Opoku Mensah et al., 2023; Siotra and Kumari, 2024). Our study bridges the research gap by empirically assessing the dynamic impact of weather variations on land use patterns and intensity, contributing to better micro-level risk management strategies.

Odisha is a major agriculture-intensive state on the eastern front of India. The farming sector contributes about 9% of the total rice production and 4.22% of the total food grain production of Indian agriculture (Barik, 2023). The state's economy and the livelihood of most of its people depend extensively on agriculture and allied activities. The agriculture sector contributes about 20.6% of gross value added to Odisha's economy and supports about half of the state's total employment, as reported by the Government of Odisha (GOO, 2022). However, being a poor agricultural state on India's east coast, with about 30% of the population below the poverty line, the state is highly vulnerable to weather shocks (Rout, 2021). This case resonates with much of India and the surrounding South and Southeast Asian economies.

Furthermore, Odisha's location (extending from 17.31-22.31N latitude and 81.31-87.29E longitude) in the tropical zone makes it susceptible to high temperatures and humidity fluctuations. For instance, in recent decades, Odisha has frequently faced weather extremes, such as droughts, floods, storms, tropical cyclones and more (Srinivasa Rao et al., 2016). A limited number of studies in the literature have evaluated the impact of weather variations on the farm production and productivity of Odisha agriculture (Hoda et al., 2021; Senapati, 2022). However, the effects of weather variations on land use are yet to be examined. Hence, the paper discusses

[1] Except a recent study by Birthal et al. (2021).

the dynamic effects of weather variations on crop yields, land use and intensity in eastern India, setting it apart from traditional studies that primarily focus on the impact of climate on yields. The study uses the panel auto-regressive distributed lag (P-ARDL) method using district-level data[2] for 2001-2018, with 540 total observations. Land use is the ratio of land used for agriculture to non-agricultural uses. Finally, variables like crop diversification represent land use patterns, and cropping intensity represents land use intensity. The results underscore the significance of dynamic effects, revealing patterns and insights that static analyses would miss.

This study makes several significant contributions to the literature. First, it enhances our understanding of how land use patterns and intensity respond to long-term changes in precipitation and temperature, which is crucial for improving crop yields, productivity, food security and livelihood strategies in India and other developing and emerging economies. Second, the findings can assist policymakers in formulating incentives to encourage future adaptation strategies in response to increasing weather risks. Third, the study employs both short-term and long-term assessments, providing a sophisticated methodological approach. This helps in designing appropriate coping mechanisms to address the adverse impacts of weather variability and limited land. Finally, the findings are applicable to various other states in India, including West Bengal, Bihar, Assam and Andhra Pradesh, which share similar agro-weather zones and agricultural practices.

The rest of the paper is organised as follows: Section 2 reviews the literature, providing the background and context for the study; Section 3 describes the data sources and methodology used in the research, detailing the analytical techniques employed; Section 4 discusses the study's findings, interpreting the results and their implications; Section 5 concludes the paper, summarising the key insights and suggesting policy implications based on the findings.

2. BRIEF LITERATURE

The impact of weather variations is assessed by the effects of weather factors, like precipitation and temperature, on crop yields, and the magnitude of these effects is contingent upon the degree of change in these variables. Over the years, climate variability has influenced crop production in high-yield and high-technology agricultural areas, particularly in agriculturally based economies in developing countries (Lemi and Hailu, 2019). The impact of climate change on crop yields was different across crops in Thailand. Climate change negatively affected longan yield, whereas it positively affected maize and had no significant effect on rice yield. There was no effect of rainfall on crop yields (Kyaw et al., 2023). Crop yields are highly sensitive to temperature globally, whereas their extent varies in continents (Liu et al., 2020).

Furthermore, the combination of reduced precipitation and elevated temperatures has the potential to result in an escalation of global food prices. To mitigate this issue, farmers must use adaptive strategies to withstand the impacts of weather variations (Tuihedur Rahman et al., 2018). Studies found that compared with rainfall deficit, excess temperature negatively affects agricultural productivity more (Taraz, 2018; Zampieri et al., 2018). Tesfaye and Tirivayi (2020) noted a maximum temperature increase in the pre-monsoon period (i.e., April-June). Pattanayak and Kumar (2021) have estimated that agricultural productivity has reduced by 4.5% with a 1°C increase in temperature in India. In addition, they predicted the total factor productivity in agriculture would decline across all states by 2050. Moulkar and Peddi (2023) state that the effects of weather variables on crop yield vary in seasons and across crops. Generally, the monsoon and winter crop yields are more sensitive to temperature (minimum and maximum) and rainfall. Vogel et al. (2019) found that variation in crop yield is associated with temperature-related extremes. Climate change has threatened agricultural production in food-insecure regions of Asian countries (Habib-ur-Rahman et al., 2022).

In India, the growing threat of climate change – manifested through rising greenhouse gas emissions, erratic weather patterns, and increasing temperature anomalies – poses serious challenges to agricultural sustainability. The IPCC (2007) has underscored the long-term risks of continued fossil fuel reliance, projecting a global temperature rise of up to 6.4°C and a sea level increase of 59 cm by the century's end if current trends persist. Empirical evidence demonstrates a strong nexus between economic growth, energy use, and emissions: a 1% increase in fossil fuel consumption and GDP can raise CO_2 emissions by 0.67% and 0.61%, respectively, while a corresponding rise in renewable energy use and agricultural productivity reduces emissions by 3.65% and 0.41% (Raihan and Tuspekova, 2022). Both long-run and short-run relationships exist between agricultural production, economic growth, and CO_2 emissions (Ali et al., 2019). Greenhouse gas emissions tend to rise with the

[2] Districts serve as the primary administrative units within Indian states. India has approximately 766 districts, each with an average population of around 1.86 million. The state of Odisha comprises 30 districts. Accordingly, our dataset includes a total of 540 observations spanning an 18-year period.

intensification of agriculture and allied activities but can be mitigated through increased forest cover (Ahmed et al., 2025). In the Indian context, agricultural expansion and intensification are also linked to rising emissions. A study from Bangladesh shows that a 1% increase in agricultural land, crop output, and allied activities contribute to emissions growth of 0.25%, 0.29%, and 0.40%, respectively (Raihan et al., 2023). Since Bangladesh is nearer to Odisha and other states in Eastern India, the results are more relevant to the present study context.

The implications of this growth–energy–agriculture–climate nexus are particularly acute in India's agrarian economy, where rainfall-dependent farming remains dominant. Weather variability – particularly deviations in rainfall and evapotranspiration – has directly undermined crop yields, including key staples and pulses such as groundnut and chickpea. Despite being one of the most climate-sensitive sectors, agriculture continues to receive limited policy and investment attention (Belford et al., 2022). Climate-induced weather extremes, including droughts and heatwaves, disrupt food production, inflate prices, and depress consumption, ultimately worsening household welfare, especially among smallholders and marginal farmers (Alvi et al., 2021). In Sweden, such extremes cause major yield losses (Sjulgård et al., 2023). In India, rainfall and evapotranspiration negatively affect groundnut and chickpea yields.

Methodologically, studies assessing the agricultural impacts of climate variability in India employ two dominant approaches: general equilibrium and partial equilibrium models. While general equilibrium models offer system-wide analysis, their application is limited in developing contexts due to data and specification issues (Deressa, 2007). The partial equilibrium framework – particularly econometric models such as the Ricardian approach and crop simulation models – is more prevalent. The Ricardian model, grounded in Ricardo's (1817) theory of land rents and later adapted by Mendelsohn et al. (1994), estimates the net impact of climate variables on farmland values or productivity. It remains a widely used tool for assessing the welfare effects of climate change, though its application in India often requires careful calibration to account for heterogeneity in climate zones, cropping systems, and socio-economic conditions (Paltasingh and Goyari, 2015; Hashida and Lewis, 2022).

To address these challenges, India must adopt integrated climate adaptation strategies. These include educating farmers on climate risks, promoting diversified and resilient cropping patterns, strengthening agricultural markets, and improving access to weather forecasts and financial safety nets. As Tripathi and Mishra (2017) argue, effective adaptation requires locally contextualised measures grounded in an understanding of regional weather variability and its interaction with socio-economic drivers.

While existing literature predominantly addresses the climate impact on yields, this paper uniquely explores the dynamic effects of weather variation on crop yields, land utilisation patterns and intensity in eastern India. This study employs a P-ARDL model on micro-level data, a methodological innovation compared to previous studies. The chosen methodology allows for an in-depth analysis of dynamic effects, providing insights that static models fail to capture. First, the P-ARDL model is particularly well-suited for datasets where variables exhibit a mixed order of integration, i.e., a combination of the I(0) and I(1) series (Pesaran and Shin, 1998). This flexibility aligns with the nature of our data, as confirmed by the panel unit root tests. In contrast, dynamic panel data models (e.g., Arellano-Bond GMM) and panel cointegration techniques often require all series to be integrated in the same order, typically I(1), which was not the case in our study. Second, the P-ARDL framework allows for variable-specific lag structures, enabling us to more accurately capture the dynamic relationships among variables with differing temporal responses. Conversely, models such as dynamic fixed effects or traditional panel cointegration models generally impose uniform lag lengths across variables, which may lead to model misspecification when applied to heterogeneous datasets like ours. Third, the P-ARDL model provides a clear and tractable single-equation framework that simultaneously estimates both short-run dynamics and long-run equilibrium relationships (Pesaran et al., 1999). This dual capability simplifies interpretation and policy relevance. In contrast, cointegration-based models (e.g., Pedroni, Kao, Westerlund tests) and system-based approaches often involve more complex estimations, with increased computational burden and interpretation challenges, especially in applied settings. Last, P-ARDL is well-suited for panels with a moderate time dimension and limited cross-sections, such as ours (T = 18 years; N = 30 districts), and performs robustly in small samples. In contrast, GMM-based dynamic panel data models can suffer from finite-sample bias and over-identification problems, especially when the number of instruments exceeds the number of cross-sectional units.

3. MATERIALS AND METHODS

3.1 Data sources and variable construction

The study uses data from 30 districts of Odisha (see Figure 1) from 2001 to 2018 from various second-

Figure 1. The shaded area within the map of India indicates the study region, Odisha. *Source*: Authors' illustration. *Note*: The map delineates the state borders.

ary sources such as the Department of Agriculture and Farmers' Empowerment (Odisha Agriculture Statistics 2001-18), ENVIS Centre of Odisha's State of Environment and the Crop Production Statistics Information System (CPSIS).

This study uses specific data on the area, production and yield of nine major crops – rice, wheat, maize, horse gram, green gram, black gram, groundnut, rapeseed and sesamum – these crops are among the major seasonal crops produced in Odisha, India[3]. Furthermore, the study uses other control variables, such as fertiliser consumption and agricultural credit, along with a group of weather factors, such as rainfall and maximum and minimum temperatures. We use the rainfall deviation from the normal rainfall ($\underline{R}$) instead of rainfall itself. The expression is standardised as $RD_{it} = \frac{(R_{it} - \underline{R})}{\sigma_R}$, where σ_R is the standard deviation of rainfall (see Table 1 for variable description).

Data on weather factors related to the Monsoon cropping season are collected from secondary sources, comprising different phenological stages of crop growth, such as sowing and growing. The crop yield of all major crops is taken as the dependent variable in different crop yield response models. The study uses three definitions of agricultural land use patterns: (1) cropping intensity, (2) crop diversification, and (3) ratio of land use to non-farm land use pattern. Cropping intensity is the ratio of gross cropped area to net sown area as $CI_t = \frac{GCA_t}{NSA_t}$, where GCA is the gross cropped area, and NSA is the net sown area in Odisha's agriculture, which measures how intensively the land is used for farming purposes.

The second definition is crop diversification. Crop diversification is a measure that indicates the degree of diverse patterns of land use in a farming system. Usually, farmers adopt crop diversification as a traditional strategy to minimise weather risks. This helps stabilise farm income volatility and augments income levels (Basantaray et al., 2022). It also helps retain and revive soil health. Several diversification measures are available in the literature, but we use the Composite Entropy Index[4], defined as: $CEI_t = -\left[\sum_{i=1}^{N} P_i log_N P_i\right] \bullet \left\{1 - \left(\frac{1}{N}\right)\right\}$, where CEI has two components: distribution and number of crops (N) or diversity. Here P_i is the share of i th crop in total operational landholding.

The value of the CEI increases with the rise in the number of crops and decreases in concentration. The value of CEI ranges between zero and one, indicating no diversification to perfect diversification. The third variable that captures the land use rate is the rate of agricultural use of land, which is defined again as the ratio of total cultivable (000' ha) land under agricultural use to non-agricultural use and is formally expressed as $ALU = \frac{LA_t}{LNA_t}$ where ALU stands for the rate of agricultural use of land, LA_t is the total land under agricultural use, and LNA_t is the total land under non-agricultural use. This measure gives us a broad idea of how the cultivable landmass is used for farming purposes and the trend over time. All these variables are gathered annually, and the total observations are 540. All variables and their definitions are described in Table A1.

3.2 Empirical estimation methods

To prepare for the panel ARDL estimation, we first conduct descriptive statistics and correlation analysis

[3] *Cereals*: Rice and wheat – the two primary food grains, forming the staple diet and occupying the largest share of cultivated land. *Pulses*: Green gram, black gram, and horse gram – important protein sources, particularly in rainfed and marginal areas. These legumes also contribute to soil nitrogen fixation and improve cropping system sustainability. *Oilseeds*: Groundnut, rapeseed, and sesamum – key oil-producing crops suited to Odisha's agro-climatic conditions, cultivated for edible oil and as cash crops.

[4] This CEI, a modified version of Shannon-Weaver index, rectifies its drawbacks and assesses both richness and evenness which makes it possible to compare crop diversity across different places (Tesfaye and Tirivayi, 2020). So, it is an improved measure of diversification.

to examine the central tendencies, dispersion, and pairwise relationships among the study variables – namely, crop yield, land use, rainfall deviation, and temperature variation. To assess the stationarity of these variables, we apply panel unit root tests, including the Levin-Lin-Chu (LLC) test (Levin et al., 2002) and the Im-Pesaran-Shin (IPS) test (Im et al., 2003), both of which are extensions of the augmented Dickey-Fuller (ADF) test and assume cross-sectional independence. The P-ARDL model is suitable when the panel data series are either I(0), I(1), or a combination of both, but not I(2). If any variable is found to be integrated with order two (I(2)), we exclude it from the estimation to maintain model validity. The panel ADF unit-root test estimates the following model:

$$\Delta y_{i,t} = \rho_i y_{i,t-1} + \sum_{p=1}^{pi} \varphi_{pi}\, \Delta\, y_{i,t-p} + \theta_{ij} D_{ij} + \varepsilon_{it} \quad (1)$$

where in Eq. (1), y_t is the random process of one variable, the period t = 1, 2..., T and i = 1, 2,...,N represents the cross-sectional units/groups. If the unit-root test results show that the variables are stationary, either in I(0) or I(1) or mixed order of integration, then the P-ARDL model is applied to explore the impact of weather variations and other factors on crop yields, rate, pattern and intensity of land use. Otherwise, in the case of non-stationary or stationary in different order, either I(1) or I(2), the Todo-Yamato causality test and vector error-correction (VEC) model are appropriate to measure the effects. We estimated the following baseline model using panel ARDL to carry out our objective as we get mixed stationarity conditions of variables:

$$y_{it} = f(HYVA_{it}, FERT_{it}, CRD_{it}, RAIN\_DEV_{it}, MAX\_T_t, MIN\_T_t) \quad (2)$$

The dependent variable y_{it} is estimated for all nine major crops and three different forms of land use. The other control variables, such as areas under high-yielding varieties (HYVA), total fertiliser consumption (FERT) and agricultural credit from banks (CRD), are also modelled. Although the variables are in different units, they are taken in logarithmic values to estimate the log-linear model from Eq. (2) for better analysis of results. The coefficients can be directly interpreted as elasticity values.

3.3 P-ARDL model specification

To term a P-ARDL model, we must first determine the optimal lag length. This has been done using the Schwarz information criterion (SIC), which indicates one lag as the optimum lag for use in the P-ARDL model, which estimates both long-term and short-term relationships between variables[5]. Moreover, the dynamic heterogeneous P-ARDL model developed by Pesaran and Shin (1998) and Pesaran et al. (1999) can be expressed within the (p,q) lag approach. The period t=1, 2…T and groups i=1, 2…N. It is expressed as:

$$y_{it} = \sum_{j=1}^{p} \beta_{ij} y_{i,t-j} + \sum_{j=0}^{q} \gamma_{ij} x_{i,t-j} + \mu_t + \varepsilon_{it} \quad (3)$$

where y_{it} is the dependent variable (crop yields, cropping intensity and rate of land use), x_{it} is $(K\times 1)$ vector of explanatory variables. The parameter vector β_{ij} of the order $(K\times 1)$ is the coefficient vector of the lagged dependent variable, γ_{ij} is the vector of coefficients of all explanatory variables to be estimated, μ_t is a unit-specific fixed effect and ε_t is an error term. Both p and q are optimal lag orders.

If the variables in Eq. (3) are I(1) and cointegrated, formerly, the error term is an I(0) for all i. A salient feature of cointegrated variables is that they respond to any deviation in the long-term equilibrium relationship. This means that the deviation from the long-term equilibrium captured by the error correction model (ECM) reveals the short-term dynamics of the variables. Hence, the short-term relationship between the study variables, the error correction model (ECM), is estimated based on the framework of (p, q) as:

$$\Delta y_{it} = \sum_{j=1}^{p-1} \beta^*_{ij} y_{i,t-j} + \sum_{j=0}^{q-1} \gamma^*_{ij} \Delta x_{i,t-j} + \varphi_i \left(y_{i,t-1} - \gamma'_{ij} x_{i,t}\right) + \mu_i + \varepsilon_{it} \quad (4)$$

where

$\varphi_i = -\left(1 - \sum_{j=1}^{p} \beta_{ij}\right)$;

$\beta_i = \sum_{j=1}^{q} \gamma_{ij} / (1 - \sum_k \beta_{ik})$;

$\beta^*_{ij} = -\sum_{m=J+1}^{p} \beta_{im}$; j = 1, 2, …p-1 and

$\gamma^*_{ij} = -\sum_{m=J+1}^{q} \gamma_{im}$; j=1, 2, 3…q-1.

In the above Eq. (4), φ_i is the ECM coefficient for each unit, and its value indicates the adjustment rate to the long-term equilibrium. The term should be negative and significant. If $\varphi_i = 0$, then we don't have a long-term relationship. Pesaran, Shin and Smith (1999) developed a pooled mean group (PMG) estimator that combines mean and pooling residuals, and this test incorporates the intercept, short-term coefficients and different error variances across the groups. However, based on this test,

[5] This estimation can be conducted using STATA, EVIEWS, or any suitable statistical software for time series or panel data analysis. For this study, we employed EVIEWS 13. The underlying code used in the analysis is available from the corresponding author upon reasonable request.

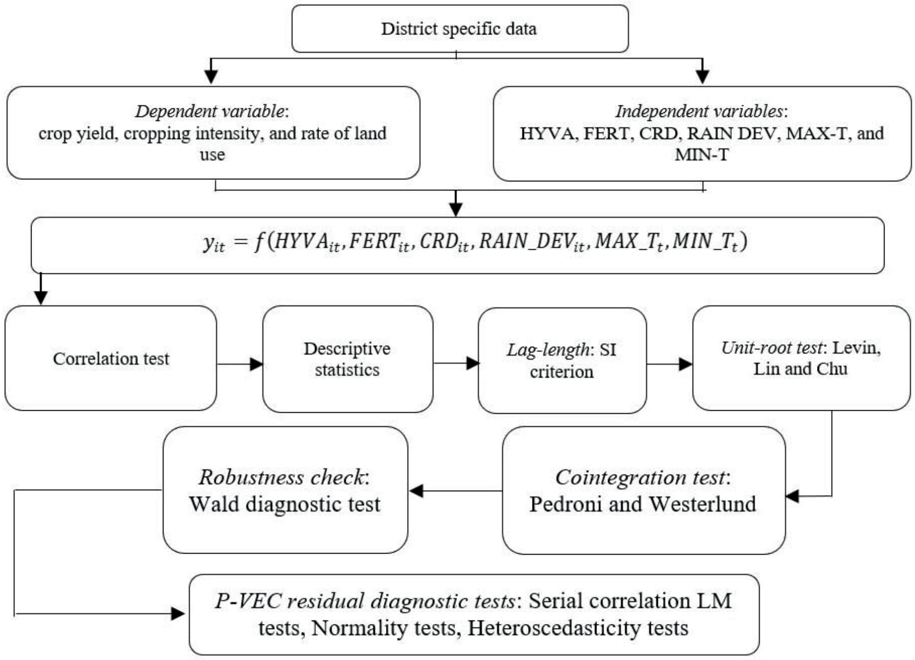

Figure 2. Flowchart illustrating data diagnosis. *Source*: Authors' illustration. *Note*: P-ARDL specification is excluded.

long-term coefficients are assumed to be equal across the groups, like fixed effect estimators. This P-ARDL model can be applied when variables are of the order I (0), I (1) or a mix of both. A flowchart showing related data diagnosis is presented in Figure 2. All estimations, including the P-ARDL model and diagnostic tests[6], were carried out using EVIEWS-13 software.

4. RESULTS AND DISCUSSION

4.1 Results of descriptive statistics

Table 1 reports the descriptive statistics of the study variables[7]. The results indicate that among the cereal crops, rice yield has the highest mean value (1580.30 kg/ha) and the standard deviation (589.85), followed by wheat and maize yields (1393.79 kg/ha and 1376.35 kg/ha), and wheat yield has the lowest standard deviation (521.79). The pulse crop yield indicates that horse gram yield has a higher mean value of (317.35 kg/ha) than green gram yield (297.08 kg/ha) and black gram yield (290.69 kg/ha), but horse gram has a lower standard deviation (99.10) than other pulse productions. Among the oilseeds, groundnut has a higher mean value (1145 kg/ha) and standard deviation (411.85) than rapeseed and sesamum seeds. The skewness values of all crops' productions are negative, except for maize and rapeseed, and kurtosis values are positive, indicating negatively skewed crop production. Similarly, the crop yield statistics indicate that the mean value of rice, wheat, maize and groundnut yields are positive and other crop yields are negative. The standard deviation of maize yield is the highest (802.86 kg/ha), followed by rice yield, whereas the least standard deviation is found in horse gram (99.10). Among the weather variables, rainfall has higher mean and standard deviation values (153.15 mm and 2.10mm) than temperatures. The mean values of fertiliser consumption and agriculture land use are (320.83kg/ha and 0.26). The mean values of cropping intensity and its standard deviation values are positive. The skewness and kurtosis values are also positive and very high.

The cross-correlations between study-selected crop yields and other variables are reported in Table A2, which indicates that all crop yields are positively influenced by their production, fertiliser consumption, agricultural credit and agricultural land use. Among the weather variables, rainfall positively correlates with crop yields, whereas the temperature correlation varies among crops.

[6] In the case of omitted variable bias or endogeneity problem, the P-ARDL model has advantage as it takes care of endogeneity by selecting the optimal time lag in the model estimation. The problem of serial correlation, normality and heteroscadasticity can be performed in diagnostic tests.

[7] The definition of study variables with their units of measurement are shown in Table A1.

Table 1. Variables tags and descriptive statistics

Variables	Mean	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Probability
Rice yield (RICEY)	1580.30	589.85	0.37	3.15	13.02	0.00
Wheat yield (WHEATY)	1393.79	521.79	0.15	8.18	606.32	0.00
Maize yield (MAIZEY)	1376.35	802.86	2.95	20.12	7376.99	0.00
Horse gram yield (HGRAMY)	317.80	99.10	0.86	6.49	339.92	0.00
Green gram yield (MONGY)	297.08	114.94	1.03	5.23	207.45	0.00
Urad yield (URADY)	290.69	109.84	0.97	4.99	174.19	0.00
Groundnut yield (GNUTY)	1145.17	411.85	1.73	8.97	1069.40	0.00
Rapeseed yield (RPSEEDY)	832.24	144.51	3.17	37.92	6486.00	0.00
Sesamum yield (SESAY)	255.92	105.98	0.64	3.49	41.95	0.00
Credit (CR.)	2.03	0.53	-0.24	2.48	11.04	0.00
Fertiliser consumption (FERT)	320.83	268.14	20.24	43.73	4615.00	0.00
Rainfall deviation (RAIN_DEV)	153.15	2.10	0.88	10.89	1414.87	0.00
Maximum temperature (MAX_T)	35.25	0.03	-0.05	2.58	3.92	0.14
Minimum temperature (MIN_T)	23.00	0.05	-0.43	3.89	33.34	0.00
Cropping intensity (CROPINT)	2.32	2.73	3.77	19.14	6879.20	0.00
Rate of agr. Land use (ALU)	0.26	0.39	0.52	5.18	126.44	0.00
Crop diversification (CEI)	0.21	0.11	0.29	2.19	21.77	0.00

Source: Authors' calculation. *Note*: Initial data is parenthesis.

The maximum temperature negatively correlates with the crop yields, except for the wheat yield. On the other hand, the minimum temperature[8] positively correlates with crop yields except for wheat and rapeseed crops. The cropping intensity is positively correlated with rice, wheat, maize and groundnut, and it is harmful to other crop yields. The Jarque-Beara test statistics and their respective probability values indicate that except for the Max_T variable, all variables are significant at a 1% significance level, which means the study variables are normally distributed.

4.2 Results of the unit-root test and VAR lag selection

Before applying the P-ARDL model, it is necessary to test the stationarity condition of variables by using unit-root tests, which will determine the reliability of the subsequent model to determine whether variables are I(0) or I(1) or a mixed order of both, but should not be I(2). The stationarity of all variables is checked using Im et al. (2003), and Levin et al. (2002), and the results are reported in Table A3. Table A3 reveals that the crop production and yields are stationary at their level values except for wheat yield, maize, horse gram and sesamum yields, and all of them are stationary at their first difference.

Other variables like fertiliser consumption, agricultural credit, weather variables like rainfall deviation and temperatures, crop diversification, cropping intensity and rate of agricultural land use are stationary at their level. We find a mixed order of stationarity of variables from the estimated unit-root test results, which suggests the suitability of the P-ARDL model. The estimation of the P-ARDL model needs an appropriate lag length. The lag selection criteria decide the optimum lag length in model estimation. Table A4 reports the results of the optimum lag selection criteria, where the SIC suggests that one is the optimum lag, the least lag among all other criteria. We use one lag, as indicated by the SIC.

4.3 Crop yield response to weather variation

Table 2 reports both the long-term relationship between the study variables and the error correction results for the short-term relations between the variables. From the long-term equation, it is found that agricultural credit significantly and positively influences all crop yields, which means if agricultural credit increases by 1%, rice yield will increase by 0.04%, wheat yield by 0.13%, horse gram yield by 0.08%, green gram (moong) yield by 0.19%, black gram yield by 0.16%, groundnut yield by 0.08%, rapeseed yield by 0.11% and sesamum seed by 0.09%. Similarly, weather variables, such as rainfall deviation and temperatures, have mixed effects on crop yields. If rainfall deviation (both excess or defi-

[8] The minimum temperature is the minimum annual average temperature. In Odisha, for that matter in India, this minimum temperature 23 °C is absolutely normal during monsoon season. The max goes to 40-42 °C here during summer and around 30-35 °C during most of time in a year.

Table 2. Results of P-ARDL model

	Rice	Wheat	Maize	Horse gram	Moong	Urad	Groundnut	Rapeseed	Sesa
Long term Elasticities									
HYVA	0.87***	0.08***	0.11***	0.12***	0.22***	0.15***	-0.03*	0.05***	0.03***
	(0.02)	(0.01)	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.01)	(0.01)
FERT	-0.07**	-0.06*	0.16***	0.15***	0.07	-0.14***	0.14**	-0.12***	0.04
	(0.04)	(0.03)	(0.04)	(0.03)	(0.06)	(0.03)	(0.05)	(0.02)	(0.04)
CRD	0.04***	0.13***	0.01	0.08***	0.19***	0.16***	0.08***	0.11***	0.09***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.001)	(0.01)
RAIN_DEV	-0.05	-0.16***	-0.46***	0.15***	-0.48***	-0.06*	0.06	-0.28***	-0.35***
	(0.04)	(0.05)	(0.09)	(0.05)	(0.10)	(0.03)	(0.05)	(0.03)	(0.04)
MAX_T	1.48***	-0.48*	0.66**	-0.49**	0.40	-1.54***	-1.83**	-0.78**	0.90**
	(0.40)	(0.27)	(0.34)	(0.23)	(0.53)	(0.18)	(0.40)	(0.30)	(0.37)
MIN_T	0.94***	-0.89***	-0.08	0.17	-0.67***	0.61***	0.15	-0.87***	-0.48***
	(0.15)	(0.15)	(0.16)	(0.12)	(0.22)	(0.04)	(0.11)	(0.17)	(0.14)
Short term Elasticities									
ECM(-1)	-0.69***	-0.80***	-0.33***	-0.60***	-0.46***	-0.35***	-0.46***	-0.46***	-0.71***
	(0.09)	(0.08)	(0.06)	(0.08)	(0.05)	(0.05)	(0.07)	(0.10)	(0.14)
Δ (HYVA)	0.11	0.02	0.17***	0.23***	0.15***	0.27***	0.15***	0.20***	0.16***
	(0.09)	(0.02)	(0.03)	(0.03)	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)
Δ(FERT)	-0.04	-0.11*	0.15	0.04	0.05	0.05	0.11	-0.03	0.01
	(0.08)	(0.06)	(0.11)	(0.08)	(0.06)	(0.06)	(0.09)	(0.08)	(0.13)
Δ(CR.)	-0.02	-0.04	-0.08	-0.03	0.001	-0.09**	-0.03	-0.08	-0.05
	(0.06)	(0.06)	(0.05)	(0.06)	(0.03)	(0.04)	(0.03)	(0.05)	(0.06)
Δ(RAIN_DEV)	0.14	0.25***	0.07	-0.04	0.18***	0.14***	0.15***	0.11	0.18*
	(0.07)	(0.07)	(0.09)	(0.06)	(0.06)	(0.06)	(0.05)	(0.06)	(0.11)
Δ(MAX_T)	-0.67***	-0.17***	-0.94	0.5	-1.20***	-2.63***	0.86	0.02	0.81
	(0.09)	(1.27)	(1.01)	(0.37)	(0.60)	(0.74)	(0.83)	(0.83)	(0.84)
Δ(MIN_T)	0.01	0.09	0.3	0.69*	-0.28	-0.54	0.41	1.01*	-0.31
	(0.90)	(0.47)	(0.73)	(0.40)	(0.46)	(0.51)	(0.62)	(0.59)	(0.72)
Const.	-5.31***	1.62	0.27***	-0.30***	0.21***	0.07***	1.27***	0.91	-0.26***
	(0.73)	(0.16)	(0.05)	(0.03)	(0.03)	(0.01)	(0.20)	(0.20)	(0.05)

Source: Authors' calculation. *Note*: *** P < 0.01%, ** P< 0.05% and * P < 0.10. The coefficients of lagged values of yields are not reported. Standard errors in parenthesis.

cit) increases by 1%, yields of wheat decrease by 0.16%, maize by 0.46%, green gram by 0.48%, black gram by 0.06%, rapeseed by 0.28% and sesamum seed by 0.35%, but the yield of horse gram increases by 0.15%. Rainfall deviation has no significant impact on the yields of rice and groundnut. This is because rice is a water-guzzling crop, and any positive or negative deviation in rainfall affects its yield the least unless there is a large variation. Odisha agriculture is highly dominated by rice, and farmers mostly grow modern varieties that are either drought- or flood-resistant, depending on the state's agro-weather zone. Similarly, a 1°C increase in maximum temperature significantly increases rice yield by 1.28%, maize by 0.66% and sesamum by 0.90%.

On the other hand, a 1°C increase in maximum temperature leads to a decrease in the yields of wheat by 0.48%, horse gram by 0.49%, black gram by 1.54%, groundnut by 1.83% and rapeseed by 0.78%; there is no significant impact on the green gram yield. The minimum temperature increase negatively affects wheat, green gram, rapeseed and sesamum yields but positively impacts rice and black gram yields. Except for agricultural credit and weather factors, other variables, such as the area under high-yield-variety seeds and fertiliser consumption, significantly affect crop yields. It is found that the HYVA coefficients are significant and positive except for groundnut, which means if the area under high-yield-variety crops increases by 1%, the yield of rice increases by 0.87%, wheat by 0.08%, maize by 0.11%, moong by 0.22%, black gram by 0.15%, rapeseed by 0.05% and sesamum seed by 0.03%. In contrast, groundnut yield decreases by 0.03%. Similarly, suppose fertiliser consumption increases by 1%. In that case, crop yields decrease, such as rice yield decreasing by 0.07%, wheat yield decreasing by 0.06%, black gram yield decreasing by 0.14% and rapeseed yield decreasing by 12%.

The results of the short-term equation (Eq. 4) show that the ECM coefficients are significantly negative in all crop yields, indicating a need for short-term adjustment for a long-term equilibrium relationship between the study variables. The coefficient of agricultural credit is significantly negative only on the black gram yield, whereas there is no significant effect in all other crop yield models. The rainfall deviation significantly positively impacts green gram, black gram, groundnut, wheat and sesamum yields. Since these are mostly pulses and oilseeds grown in rain-fed areas, they consume less water. So, any negative deviation may not harm their yield to a great extent. However, any positive deviation may positively affect their yield because it offers the required amount of moisture rather than creating a flood-like situation. These crops are grown when the monsoon period is over. So, the positive deviation over the normal trend helps the crops rather than creating a flood-like situation and reaps better yields of these dry-area crops. The maximum temperature significantly negatively impacts rice, wheat, green gram (moong) and black gram yields.

Similarly, the minimum temperature significantly and positively affects the horse gram and rapeseed yield, but it has no significant effect on all other crops. Fertiliser consumption is significantly negative only in wheat yield. The high-yielding-variety coefficients are significant and positive for almost all crops, which indicates that if the area under high-yielding varieties increases in the short term by 1%, the yields of maize, horse gram, moong, black gram, groundnut, rapeseed and sesamum seed rise.

Table 3. Results for Land Use Response Model, P-ARDL, Odisha, India

	CROPINT	ALU	CEI
Long term elasticities			
FERT	0.08*** (0.02)	0.53*** (0.08)	0.07 (0.06)
CRED	0.02*** (0.01)	0.19*** (0.02)	0.19** (0.06)
RAIN_DEV	-0.16*** (0.03)	-0.20* (0.11)	0.11** (0.05)
MAX_T	-0.68*** (0.16)	-1.36** (0.68)	0.29*** (0.01)
MIN_T	-0.01 (0.07)	-1.06*** (0.29)	0.58 (0.61)
Short term elasticities			
ECM (-1)	-0.52*** (0.05)	-0.66*** (0.08)	-61*** (0.06)
Δ(CROINT (-1))	-0.338 *** (0.044)		
Δ(ALU (-1))		-0.449*** (0.042)	
Δ(CEI (-1))			-0.584*** (0.049)
Δ(FERT)	0.01 (0.02)	0.16 (0.12)	0.21* (0.12)
Δ(CRD)	0.03* (0.01)	-0.05 (0.08)	0.02 (0.05)
Δ(RAIN_DEV)	-0.01 (0.01)	-0.15 (0.11)	0.88*** (0.12)
Δ(MAX_T)	-0.14 (0.23)	-2.96* (1.59)	1.12* (0.56)
Δ(MIN_T)	-0.20* (0.10)	-0.28 (1.36)	-0.56 (0.41)
Const.	1.53 (0.14)	-2.28*** (0.26)	1.47** (0.65)

Source: Authors' calculation. *Note*: *** P < 0.01%, ** P < 0.05% and * P < 0.10. Variables are naturally log-transformed. In case of rainfall deviation, the absolute value is taken for log transformation. Standard errors in parenthesis.

4.4 Land use response to weather variation

Table 3 reports the P-ARDL results of the impact of weather factors and other control variables on land use patterns and intensity. Since we have used three variables representing the rate, pattern and intensity of land use, i.e., rate of land use (ALU), crop diversification (CEI) and cropping intensity (CROPINT), we present the results separately. Here, we also have both long-term and short-term dynamics. We offer the long-term results first and then the short-term effects.

We observed that rainfall deviation significantly harms cropping intensity. More specifically, its elasticity coefficient indicates an additional 1% increase in rainfall deviation, reducing the cropping intensity by 0.16%. It hampers both the gross cropped area and the net sown area. However, it affects the gross cropped area more than the net sown area, reducing the cropping intensity. This is because rainfall deviation, either upward or downward, creates a flood- or drought-like situation affecting farming practices and ultimately decreasing the gross cropped area.

On the other hand, the net sown area is somewhat determined by the irrigation potential being used. So, it reduces the numerator of the ratio more than the denominator, reducing the cropping intensity. Sometimes, delays in the arrival of monsoons also adversely affect soil preparation and sowing/planting of seedlings. This also harms farming by reducing the gross cropped area. Naturally, a delayed monsoon will have more deviations in precipitation by disturbing its spatiotemporal distribution. Our result aligns with other studies in African countries, such as those of Duku et al. (2018).

Similarly, as the negative elasticity coefficient of maximum temperature suggests, a 1% increase in maximum temperature (MAX_T) may reduce the cropping intensity (CROPINT) by 0.68% over the long term. A plausible explanation is that a rise in temperature reduces the yields of certain crops, discouraging the allotment of land to those crops (Birthal and Hazrana, 2019). Similarly, Zampieri et al. (2018) argued that excess temperatures and heatwaves affect crop yield more than drought and rainfall deviation in arid and semi-arid tropical zones. Our results are consistent with Birthal et al. (2021).

Similarly, looking into the long-term impact of weather factors on crop diversification (CEI) and rate of land use (ALU), we observe that most weather factors significantly induce crop diversification but harm the rate of land use in the long term. In fact, the elasticity coefficient of rainfall deviation concerning crop diversification shows that an additional 1% deviation in rainfall induces 0.11% more crop diversification. This is because farmers adopt diversification as an ex-ante coping mechanism to counter the production shock due to weather variations (Gouraram et al., 2022). A diversified crop portfolio helps farmers increase the resilience of their farm production system and considerably lower their exposure and vulnerability to the harmful effects of changing environmental conditions (Basantaray et al., 2022). Even in rainfed agriculture, vertical diversification[9] is adopted as an effective risk management strategy (Prasada, 2020).

Similarly, maximum temperature also positively influences crop diversification. Higher temperatures reduce soil moisture and cause dryness. So, farmers shift the cropping pattern toward pulses, which require less water and little moisture in the soil (Zampieri et al., 2018). The elasticity coefficient is 0.29, implying that an additional increase in average temperature by 1°C can induce crop diversification by 29% during the Monsoon season on a long-term basis. Moniruzzaman (2019) found similar evidence in neighbouring Bangladesh. The author simulated that increased temperature increased crop diversification over the baseline scenario of temperature and rainfall during the rainy and summer seasons.

However, rainfall deviation (RAIN_DEV) and temperature (both MAX_T and MIN_T) adversely affect the rate of land use (ALU) in the long term. As observed from the elasticity coefficient, an additional 1% increase in deviation reduces the rate of agricultural use of land by 0.20%. Rainfall deviations harm the intensity of land use and thereby affect farm production. As stressed above, any deviation from the normal level affects soil preparation and the intensive use of land for cultivation. Similarly, if the average temperatures (MAX_T and MIN_T) increase by 1°C, agricultural use of land decreases by 1.36% and 1.06%, respectively, which indicates that deviations from normal temperature levels have a severe adverse impact on the rate of agricultural use of land.

Along with weather factors, we observed that over the long term, fertiliser consumption and agricultural credit affect cropping intensity, crop diversification and rate of agricultural land use. This is because easy and smooth access to credit facilitates the investment in necessary inputs, such as seeds and other equipment, and helps prepare the soil in advance. So, this positively impacts cropping intensity and crop diversification, leading to a rise in land use.

Regarding the short-term results, we observed that all forms of land use are negatively affected by their lagged values, which is counterintuitive as per the rational expectation theory. Observing the weather factors, we find that rainfall deviation does not significantly affect cropping intensity and rate of land use in the short term, though the coefficients are intuitively negative. However, rainfall deviation does induce a substantially higher degree of diversification. The elasticity coefficient indicates that a 1% rise in rainfall deviation brings 0.88% more crop diversification. This may be attributed to the fact that a greater deviation (either positive or negative) has immediate implications for crops.

A positive deviation leads to the submergence of crops, while a shortfall of rainfall from the normal level creates a drought-like situation, leading to crop failure. In both cases, it induces more diversification as an immediate strategy in the short term to counter the crop loss caused by weather variation. Many empirical studies argue that greater agro-biodiversity contributes to increased crop yield and reduced production risk (Di Falco and Veronesi, 2014). Even farmers adopt crop diversification as an *ex-ante* measure to cope with weather-induced income shocks (Moniruzzaman, 2019). So, rainfall deviation has a positive impact on crop diversification. The minimum temperature significantly affects the rate of agricultural land use and crop diversification, while its elasticity coefficient in the case of cropping intensity is statistically insignificant. However, the maximum temperature adversely affects the rate of agricultural land use, while its impact on crop diversification is positive. Among other variables, we observed that credit access significantly impacts cropping intensity in the short term, while fertiliser consumption significantly induces a higher degree

[9] Refers to the combination of multiple cropping and industrialization. Farmers invest in horticulture, agroforestry, livestock raising, the cultivation of fragrant herbs and more, as part of this type of diversification.

of crop diversification. Both elasticity coefficients are statistically significant only at a 10% probability level.

4.5 Diagnostic checks

The P-ARDL model results are diagnosed using the Wald diagnostic test. This has the null hypothesis that the covariate's coefficient is equal to zero. The Wald coefficient diagnostic test results of crop yields and land use patterns are reported in Tables A5 and A6, which indicate that the estimated F-statistic values are highly significant, meaning that the variables are significant to the model fit. We used different model residual diagnostic tests, such as the serial correlation LM test, normality tests, and heteroscedasticity test, to check the model's diagnostic. Table A7 presents the results of model residual diagnostic tests. All the test results indicate that all null hypotheses of all tests are statistically significant at a 1% level. That means there is a rejection of the null hypothesis concerning land use variables in all three models, which means the models are free from serial correlation and heteroscedasticity and are normally distributed.

5. CONCLUSIONS

The novelty of this study lies in considering, first, the heterogeneous impact of weather variables such as rainfall deviation and temperature, which vary among crops under study, similar to the evidence found by Guntukula and Goyari (2020). Second, rainfall deviation harms the rate and intensity of land use over both the long and short terms, but rainfall deviation induces more crop diversification. So, weather variations may distort the rate and intensity of land use, but the change in land use patterns is favourable.

The study findings have significant implications for food security and the long-term viability of the industrial system. Because almost all crop yields have been negatively damaged, predictions for food security and the sustainability of food production appear bleak. However, based on the findings, we make policy recommendations to reduce the impact of weather variations on agricultural production in the study area. Adaptive policies, strategies and weather financing must be implemented. Because temperatures and the timing and amount of necessary rainfall have changed and are expected to vary in the study region, farmers must adopt new crop types and greater diversification techniques to combat weather hazards. By highlighting dynamic effects, this study provides a more nuanced understanding of weather-induced changes in land-use intensity; the policy suggestions hover around land management and efficient use of resources. This implies developing and initiating widespread adoption of modern stress-tolerant cultivars resilient to various weather-induced stresses and making an optimal crop choice – crop diversification strategies. Such adoption should be followed by acreage allocation, considering the expected weather shocks. To help farmers, the government could invest in research and development activities to develop crop varieties resilient to extreme weather shocks.

Policymakers could provide funding for renovating the extension network to disseminate early weather warnings, thus helping sustain the optimal acreage allocation and intensity of land use. Crop diversification is an effective *ex-ante* coping mechanism to counter the harms induced by weather variation. However, government policy has not been conducive to a diversified production system since we somehow promote a monoculture of certain crops that the Green Revolution initiated. Odisha agriculture used to be diversified indigenously. But after the Green Revolution of the 1960s, rice has become the staple crop grown here at the expense of pulses. Though some recent concerted efforts have been made to promote crop diversification and return to indigenous cropping patterns, they have not been widely promoted. The "Millet Mission" is one such effort by the government of Odisha, but we need more such schemes that encourage diversification. We, too, found that weather variations would induce more diversification ex-post, but adopting diversification as an *ex-ante* strategy will be more effective. Agriculture in Odisha was traditionally characterised by a highly diversified cropping pattern. However, following the 1960s, it became increasingly concentrated around rice cultivation. A return to diversified farming systems is proposed, encouraging the cultivation of millets, pulses, and other traditional crops to restore balance and resilience in the agricultural landscape. In addition, smallholders must be covered by crop insurance and hedging as part of the formal modern weather risk-mitigating mechanism. The paper's emphasis on dynamic effects provides a critical contribution to the field, paving the way for future studies to explore these dimensions further.

Despite the robustness of the empirical strategy and the authenticity of the data sources, this study has certain limitations. The analysis is confined to 30 districts in Odisha, which may limit the generalisability of the findings to other Indian states or agro-climatic zones. While all variables were sourced from the ENVIS Centre of Odisha's State of Environment – an authoritative platform supported by the Ministry of Environment, Forest and Climate Change – certain critical variables such as irrigation infrastructure, mechanisation, and technological adoption were not included. These factors can influence crop yield, cropping intensity, and land use, and their omission may lead to potential biases. Moreover, the weather variables used – rainfall deviation and average temperature – do not capture the full spectrum of extreme events, intra-seasonal variability, or asymmetric effects of droughts and floods. Additionally, while the panel ARDL framework accommodates dynamic relationships, concerns related to endogeneity and omitted variables, such as input prices or market access, remain. The focus on major crops also excludes the vulnerability of minor crops and allied sectors, while the lack of socio-economic disaggregation restricts the insights for targeted policy interventions.

These limitations offer avenues for future research. Subsequent studies could incorporate more granular weather data, such as temperature thresholds, rainfall timing, or extreme weather indices, alongside farm-level primary data to better capture farmer behaviour and adaptation responses. Expanding the spatial scope to include other states with similar agro-ecological characteristics would enhance the external validity of the results. Furthermore, integrating irrigation access, mechanisation levels, crop insurance coverage, and institutional support would provide a more comprehensive understanding of the drivers of land use decisions and crop productivity under climate stress. The proposed model could also be assessed for its effectiveness in medium-term out-of-sample forecasting using approaches such as the Auto-Regressive Integrated Moving Average with exogenous variables (ARIMAX) model (Kozicka et al., 2018; Mantziaris et al., 2024) offering insights into yield responses under future weather variability, which would be of interest to both policymakers and potential investors. Future research could also explore gender- and caste-based vulnerability to weather shocks, assess the role of policy instruments such as PM-KISAN or the Millet Mission, and apply structural models or simulations to evaluate the effectiveness of proposed adaptation strategies. Taken together, the integrated approach provides valuable insights that can inform future agricultural adaptation strategies in weather-sensitive regions, thereby enriching the empirical base for designing climate-resilient agricultural policies.

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APPENDIX

Table A1. Description of study variables.

Variables	Definitions	Hypothetical sign
Dependent variable		
YLD	Crop yield (kg/hectare)	
CI	Cropping intensity is defined as the ratio of gross cropped area to net sown area (Index)	
CEI	Crop diversification is measured by the composite entropy index	
ALU	Rate of agricultural land use is defined as the ratio of land used for agriculture to non-agricultural use (Index)	
Independent variables		
FERT	Total fertiliser consumption (kg/ha)	+
HYVA	Area under HYV or modern variety seeds (000' acres)	+
CRD	Agricultural credit from banks (Rs. billion)	+
RAIN_DEV	Standardised deviation of average rainfall during the Kharif season (millimetres) from its historical normal value	+/-
MAX_T	Average maximum temperature during Kharif season (Celsius)	-
MIN_T	Average minimum temperature during Kharif season (Celsius)	-

Source: Authors' annotation. *Note*: Complied from ENVIS Centre of Odisha's State of Environment, Odisha Agriculture Statistics (various issues) and other sources.

Table A2. Relationship between crops and key variables.

	Cereals			Pulses			Oilseeds		
	Rice	Wheat	Maize	Horse gram	Moong	Urad	Groundnut	Rapeseeds	Sesamum
HYVA	0.52	0.40	0.22	0.03	0.22	0.32	0.33	0.51	0.08
FERT	0.22	0.02	0.26	0.25	0.40	0.34	0.00	0.30	0.14
CRD	0.27	0.23	0.49	0.37	0.53	0.47	0.30	0.34	0.35
RAIN_DEV	0.26	0.01	0.02	0.12	0.08	0.13	0.12	0.09	0.06
MAX_T	-0.05	0.00	-0.08	-0.05	-0.06	-0.04	-0.02	-0.05	-0.22
MIN_T	0.01	-0.06	0.05	0.01	0.01	0.07	0.18	-0.12	0.09
CROPINT	0.11	0.03	0.03	-0.19	-0.05	-0.14	0.06	-0.15	-0.31
AL	0.45	0.07	0.18	0.24	0.29	0.30	0.38	0.12	0.25

Source: Authors' estimation.

Table A3. Results of unit root test of study variables.

	Levin, Lin & Chu t*				Im, Pesaran and Shin W-stat			
	Intercept		Intercept with Trend		Intercept		Intercept with Trend	
	Level	1st Difference	Level	1st Difference	Level	1st difference	Level	1st Difference
RiceY	-7.84***	-	-6.49***	-	-6.65***	-	-5.12***	-
RiceP	-6.36***	-	-1.86**	-	-7.97***	-	-5.76***	-
WheatY	-1.09	-8.40***	-2.30**	-	-3.87***	-	-5.13***	-
WheatP	-3.91***	-	-4.31***	-	-3.76***	-	-3.26***	-
MaizeY	-2.46**	-	-1.74**	-	-1.31	-13.75**	-3.02***	-
MaizeP	-1.28	-11.38***	-1.05	-8.99***	-2.66***	-	-1.66*	-

(Continued)

Table A3. (Continued).

	Levin, Lin & Chu t*				Im, Pesaran and Shin W-stat			
	Intercept		Intercept with Trend		Intercept		Intercept with Trend	
	Level	1^{st} Difference	Level	1^{st} Difference	Level	1^{st} difference	Level	1^{st} Difference
HgramY	-6.43***	-	-6.46***	-	-6.04***	-	-7.21***	-
HgramP	0.55	-8.64***	-4.01***	-	0.3	-13.71**	-3.42***	-
MoongY	-3.66***	-	-8.17***	-	-1.18	-18.08**	-6.41***	-
MoongP	-5.54***	-	-3.12***	-	-6.69***	-	-3.87***	-
UradY	-3.15***	-	-4.57***	-	-2.43***	-	-5.17***	-
UradP	-4.36***	-	-4.49***	-	-4.46***	-	-4.71***	-
GnutY	-5.14***	-	-6.96***	-	-3.46***	-	-4.66***	-
GnutP	-5.14***	-	-2.33**	-	-3.46***	-	-0.92	-10.14***
RapeseedY	-3.34***	-	-5.96***	-	-2.21**	-	-6.19***	-
RpseedP	-6.16***	-	-7.27***	-	-6.73***	-	-7.38***	-
SesaY	-4.58***	-	-6.67***	-	-6.05***	-	-7.23***	-
SesaP	1.90	-5.98***	-0.97	-4.07***	1.03	-11.81***	-0.96	-10.1***
FERT	-5.38***	-	-1.08	-1.93**	-2.83***	-	-1.55*	-
CR	-5.95***	-	-3.05***		-0.02	-8.68***	0.82	-6.92***
RAIN_DEV	-4.62***	-	-1.67	2.25**	-7.71***	-	-5***	-
MAX_T	-8.53***	-	-6.92***	-	-6.96***	-	-4.76***	-
MIN_T	-4.95***	-	-3.46***	-	-4.78***	-	-1.86**	-
CROPINT	-5.85***	-	-2.98***	-	-4.17***	-	0.29	-7.52***
LN	-9.55***		-10.90***		-5.84***		-6.87***	

Source: Authors' estimation. *Note*: *, ** and *** denote 10%, 5% and 1% significance levels, respectively.

Table A4. Wald test results of crop yields.

	Rice	Wheat	Maize	Horse-gram	Green-gram	Urad	Groundnut	Rapeseeds	Sesamum
F-stat	603.01***	87.07***	18.34***	43.51***	57.83***	183.42***	25.79***	1130.29***	1156.39***
Chi-sqr	4221.08***	609.50***	128.39***	304.57***	404.80***	1283.94***	180.50***	7912.02***	8094.75***
Null Hypothesis: C (1) = C (2) = C (3) = C (4) = C (5) = C (6) = C (7) = 0									
C (1)	0.87	0.08	0.11	0.12	0.22	0.15	-0.03	0.05	0.44
	0.02	0.01	0.03	0.02	0.03	0.02	0.02	0.01	0.03
C (2)	-0.07	-0.06	0.16	0.15	0.07	-0.14	0.14	-0.12	-0.12
	0.04	0.03	0.04	0.03	0.06	0.03	0.05	0.02	0.02
C (3)	-0.04	0.13	0.01	0.08	0.19	0.16	0.08	0.11	0.14
	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.00	0.01
C (4)	0.30	0.10	0.07	0.03	-0.01	0.09	0.12	0.04	0.06
	0.01	0.02	0.04	0.02	0.04	0.02	0.02	0.01	0.01
C (5)	-0.05	-0.16	-0.46	0.15	-0.48	-0.06	0.06	-0.28	-0.29
	0.04	0.05	0.09	0.05	0.10	0.03	0.05	0.03	0.02
C (6)	1.48	-0.48	0.66	-0.49	0.40	-1.54	-1.83	-0.78	0.48
	0.40	0.27	0.34	0.23	0.53	0.18	0.40	0.30	0.17
C (7)	0.94	-0.89	-0.08	0.17	-0.67	0.61	0.15	-0.87	0.10
	0.15	0.15	0.16	0.12	0.22	0.04	0.11	0.17	0.05

Source: Authors' estimation. *Note*: *, **, and *** denote 10%, 5% and 1% significance levels, respectively.

Table A5. Wald test results of land use.

	CROPINT	ALU	CEI
F-statistic	30.17***	59.26	33.17***
Chi-square	150.83***	296.28	165.83***
Null Hypothesis: C (1) = C (2) = C (3) = C (4) = C (5) = 0			
C (1)	0.08	0.53	0.09
	0.02	0.08	0.01
C (2)	0.02	0.19	0.04
	0.01	0.02	0.01
C (3)	0.16	0.20	0.12
	0.03	0.11	0.03
C (4)	-0.68	1.36	-0.61
	0.16	0.68	0.19
C (5)	-0.01	1.06	-0.02
	0.07	0.29	0.09

Source: Authors' estimation. *Note*: *** denotes a 1% significance level.

Table A6. P-VEC model residual diagnostic test.

	CROPINT	ALU	CEI
Serial Correlation LM Tests (H_0: no serial correlation at lag order h)			
Lag 1	164.39***	155.64***	112.67***
Lag 2	189.35***	197.83***	129.22***
Normality Tests (Orthogonalisation: Cholesky)			
Null hypothesis: residuals are multivariate normal			
Skewness (Chi-sq)	334.89***	399.75***	418.05***
Kurtosis (Chi-sq)	11744.56***	15727.93***	8789.53***
Jarque-Bera	12079.44***	16127.68***	9207.58***
Heteroskedasticity Tests: No Cross Terms			
Chi-square statistics	1075.67***	1200.50***	1492.41***

Source: Authors' estimation. *Note*: *** denotes a 1% significance level.

Table A7. P-VEC model residual diagnostic test.

	CROPINT	ALU	CEI
Serial Correlation LM Tests (H_0: no serial correlation at lag order h)			
Lag 1	164.39***	155.64***	112.67***
Lag 2	189.35***	197.83***	129.22***
Normality Tests (Orthogonalisation: Cholesky)			
Null hypothesis: residuals are multivariate normal			
Skewness (Chi-sq)	334.89***	399.75***	418.05***
Kurtosis (Chi-sq)	11744.56***	15727.93***	8789.53***
Jarque-Bera	12079.44***	16127.68***	9207.58***
Heteroskedasticity Tests: No Cross Terms			
Chi-square statistics	1075.67***	1200.50***	1492.41***

Source: Authors' estimation. *Note*: *** denotes a 1% significance level.

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Editor in chief: Silvia Coderoni
Associated editor: Laura Garcia Herrero

ORCID
AMJ: 0000-0002-6239-6122
DF: 0000-0003-2969-4440
HR: 0000-0002-5981-4469
JD: 0000-0003-2517-7905

Rebuilding strategies for food self-sufficiency: Portugal's past patterns and future ambitions

Alexandre Macedo João[1,*], Dulce Freire[2], Humberto Rocha[3], Joana Dias[4]

[1] *Center for Interdisciplinary Studies, University of Coimbra, Portugal*
[2] *Center for Interdisciplinary Studies, Faculty of Economics, University of Coimbra, Portugal*
[3] *Centre for Business and Economics Research, Faculty of Economics, University of Coimbra, Portugal*
[4] *Institute for Systems Engineering and Computers at Coimbra, Faculty of Economics, University of Coimbra, Portugal*
*Corresponding author. Email: j.alexjoao@gmail.com

Abstract. This study analyses Portugal's wheat productive capacity, exploring the reasons behind its recent steady decline despite achieving self-sufficiency in the 20th century. Using Multivariate Adaptive Regression Splines (MARS), which proved to be highly effective in the development of forecasting models, the research provides valuable insights for countries facing similar challenges in defining production strategies. By employing this approach, decision-makers can improve resource allocation, ensure food security, and foster a resilient agricultural sector. The findings highlight the importance of understanding wheat production dynamics within the European Union and aligning national strategies with the Union's goals and policies. The analysis indicates that achieving self-sufficiency is possible, supported by productivity improvements and increased cultivation areas. However, realizing significant production growth demands the adoption of sustainable strategies. This research contributes to shaping informed agricultural policies, enhancing decision-making processes, and promoting a more sustainable and efficient food production system to meet future challenges.

Keywords: wheat production, self-sufficiency, productivity, forecasting models, policy making.
JEL Codes: E21, E23, E27, Q10.

ABBREVIATIONS

EEC/EU: European Economic Community/European Union
MARS: Multivariate Adaptive Regression Splines
CAP: Common Agricultural Policy

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INTRODUCTION

Cereal production and consumption have been central issues for the world economy. The main similarity between the subsistence bases of ancient states was the fact that their economy was based on cereal production (Scott, 2017). During the second half of the 20th century wheat production and productivity per hectare increased steadily, reflecting its status as the main cereal for human consumption. However, in recent decades, the increases in production of several major cereal crops have slowed down, and in several countries, yields started to stagnate (Michel & Makowski, 2013). To further aggravate this situation, the armed conflict affecting the Ukrainian territory caused international wheat prices to rise to all-time highs. In the case of European countries, this confrontation was especially harsh, given that a lot of countries were dependent on cereals imported from Russia and Ukraine (Zhang et al., 2024). Given the strategic relevance that wheat has in societies, how can each State respond to these domestic supply threats? Departing from the analysis of Portugal, this paper aims to answer a question that is arising in many countries.

The main objective of this study is to analyse historical wheat production and consumption data and to project trends for 2022–2032, in order to find out if Portugal has the capacity to become self-sufficient in wheat production, something that was already achieved in the 20th century, particularly during the "Wheat Campaign". We adopt the Multivariate Adaptive Regression Splines (MARS) machine learning model, validated in time-series forecasting (Nayana et al., 2022). By employing the predictions resulting from MARS in scenarios with different cultivated areas, we assessed the implications of land use adjustments on future wheat production. Although this study is focused on the Portuguese case, the method employed can be applied to other countries. This scenario-based approach provides informed guidance to policymakers, identifying realistic and sustainable strategies to optimize production efficiency, strengthen national food security and support informed planning based on each country's production potential.

Portugal was the chosen country because it has been, throughout history, very dependent on the agricultural sector. Furthermore, the country has witnessed periods of self-sufficiency and also of very low levels of self-supply in wheat production. But in recent decades, production has dropped to alarming numbers. If in 1989 the degree of self-supply was around 60%, in 2021 this value had dropped to 6.1%. As a result, Portugal became a country very dependent on imports. In order to invert this trend, the Portuguese government created the *National Strategy for the Promotion of Cereal Production (NSPCP)*, which set self-supply goals in cereal production for the period between 2018 and 2023. The degree of self-supply defined by the NSPCP was 38% for all cereals and 20% for wheat (Barreiros, 2018). Since the NSPCP has already ended, we can confirm that its objectives were not achieved. Regardless, and in order to have defined goals with political relevance, its targets will serve as a basis to build one of the three production scenarios discussed in this study. Two prediction models were developed, one for the *per capita* consumption and other for the production per hectare.

This study is structured as follows. The next section presents the data collected, as well as the chosen methodology. Section 3 discusses the results, drawing three scenarios for production. Finally, section 4 presents the main conclusions of this study: Self-sufficiency, although difficult to achieve, would still be possible given the area that was once cultivated in Portugal.

DATA SOURCES

This study is based on quantitative data and qualitative information obtained from scientific studies and relevant historical documents. Data is available for the whole Portuguese continental territory, but after a preliminary analysis, we observed that 8 districts (out of 18) were responsible for 92% of the national wheat production from 1920 to 2021. These districts are: Beja, Bragança, Évora, Faro, Lisbon, Portalegre, Santarém and Setúbal (Figure 1). Considering that these districts contributed the most to national production, it is plausible to assume that this trend will continue and consequently, the analysis focuses on them. Unfortunately, some of the data for the districts, like the cultivated area and the climatic variables, were only available from 1943 onwards. So, although at a national level the available data started in 1920, when looking at the district level the available data only considers the period from 1943.

As shown by Figure 1, we can observe the discrepancies in production between the chosen districts and the rest of the country. The districts that completely make up the Alentejo region (Beja, Évora and Portalegre), are the three main contributors and together represent 64% of total production.

We collected data on total consumption, *per capita* consumption, population, total production, productivity per hectare, cultivated area and climatic variables (temperature and precipitation). The data used in this study were produced by several certified national and international entities: National Statistics Institute (NSI), Portu-

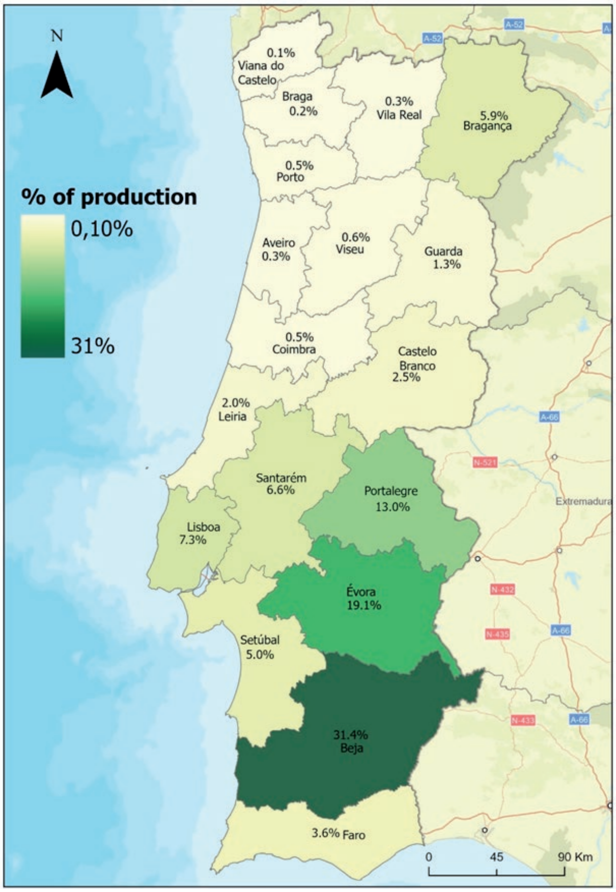

Figure 1. Percentage of national production by district (1920-2021). Source: own processing based on data from the NSI using ArcGIS.

guese Institute of the Sea and Atmosphere (PISA), United Nations (UN), Climate Portal (CP) and Pordata.

Production values at district level were calculated by Viana et al. (2021). This data required extensive research, since the sources where it was published have different territorial units over the years. Therefore, it was necessary to transform the values so that they were all measured using the same territorial unit. This transformation was done by applying an area-weighting technique that allows the transfer of data from a set of units in the territory to a second set of units, with which the first ones overlap. This method assumes a spatially homogeneous relationship between the source unit and the target unit, meaning that the variable is assumed to be equally distributed across the source unit (Viana et al., 2021). The evolution of wheat production in Portugal has not been consistent over the last century, as can be seen in Figure 2. Although there have been periods in which production has come close to and, in some cases, even exceeded consumption, the insufficiency of national production has been a constant in Portuguese history (Pais et al., 1978; Freire & Lains, 2017). In recent decades, the situation has worsened with production capacity declining at an alarming rate.

The cultivated area was also calculated by applying the same method used for production and can also be seen in Figure 2. The decrease in cultivated area is pointed out as one of the main reasons why Portugal has seen such large production losses in recent decades. The NSI estimated, for the year of 2022, an area of about 103 thousand hectares dedicated to cereal cultivation, the lowest value in the last 100 years. In comparison, 322 thousand hectares of wheat were cultivated in 1989, a year in which the degree of self-supply reached 60%.

Wheat consumption in Portugal has increased over the last century but has stagnated since the beginning of the 21st century. While the consumption registered in 2021 is below its peak, it is still very high when compared to historical values. It's important to note that the growth in consumption was achieved through an increase in wheat imports and not production (Freire & Lains, 2017). In our analysis, the consumption values are of total consumption, which include human, animal, and other uses. The evolution of total consumption can also be observed in Figure 2.

The population of each country constitutes another essential variable in this analysis, as it directly affects the calculation of self-supply. Therefore, we collected data on the total Portuguese population at the end of each year between 1920 and 2021. For the period 2022 to 2032, we used the population forecasts available in the United Nations database (Gaigbe-Togbe et al., 2022).

Productivity per hectare is more relevant at district level because it enables us to analyse which districts have the highest yields and where production can be more efficient and profitable. Historically, productivity levels in Portugal have been low, and experts argue that this is mainly due to poor soil and adverse climatic conditions suitable for increasing productive efficiency in a competitive market. In addition, the soils with productive potential have been progressively occupied by more efficient and profitable crops, such as vineyards, olive groves and almond trees (Pais et al., 1978; Faisca 2019). The evolution of productivity per hectare is shown in Figure 3.

Climatic variables are essential for understanding the performance of agricultural production, as crops are vulnerable to inter-annual climatic variability (Gouveia & Trigo, 2008). Despite technological advances, modern agriculture is still heavily dependent on weather conditions, which poses a significant risk to production due to short-term variability and future climate changes. Jambekar et al. (2018) used data mining techniques to model

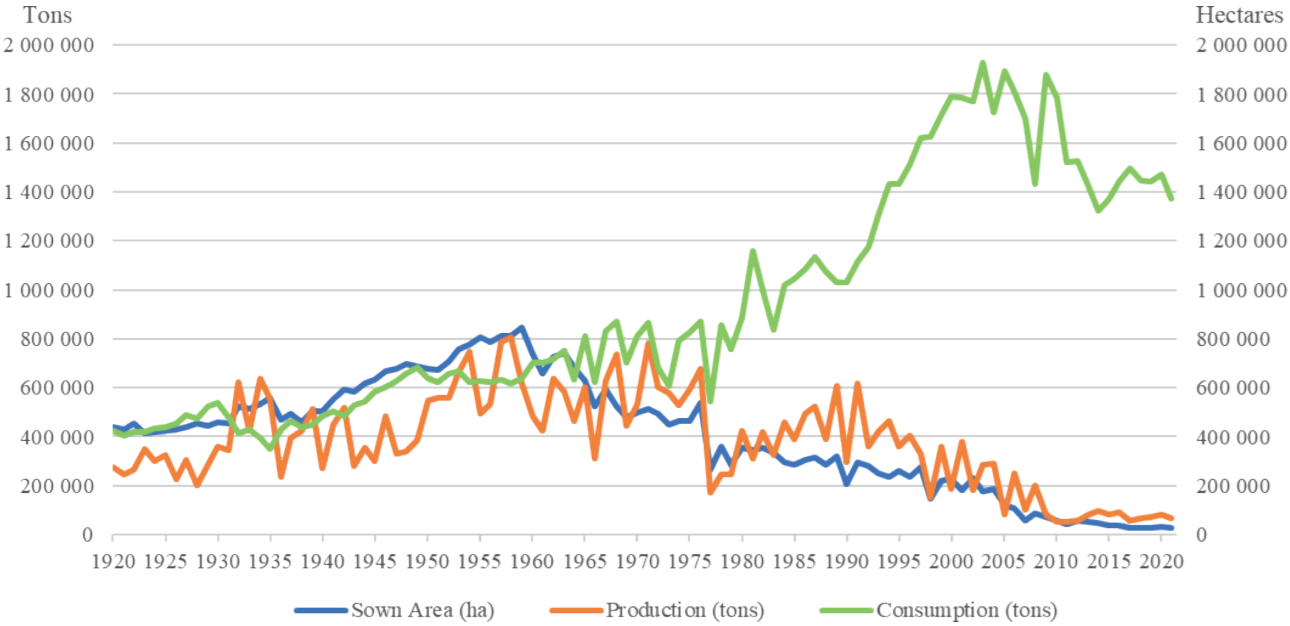

Figure 2. Production, consumption and sown area in continental Portugal (1920-2021). Source: own processing based on data from the NSI.

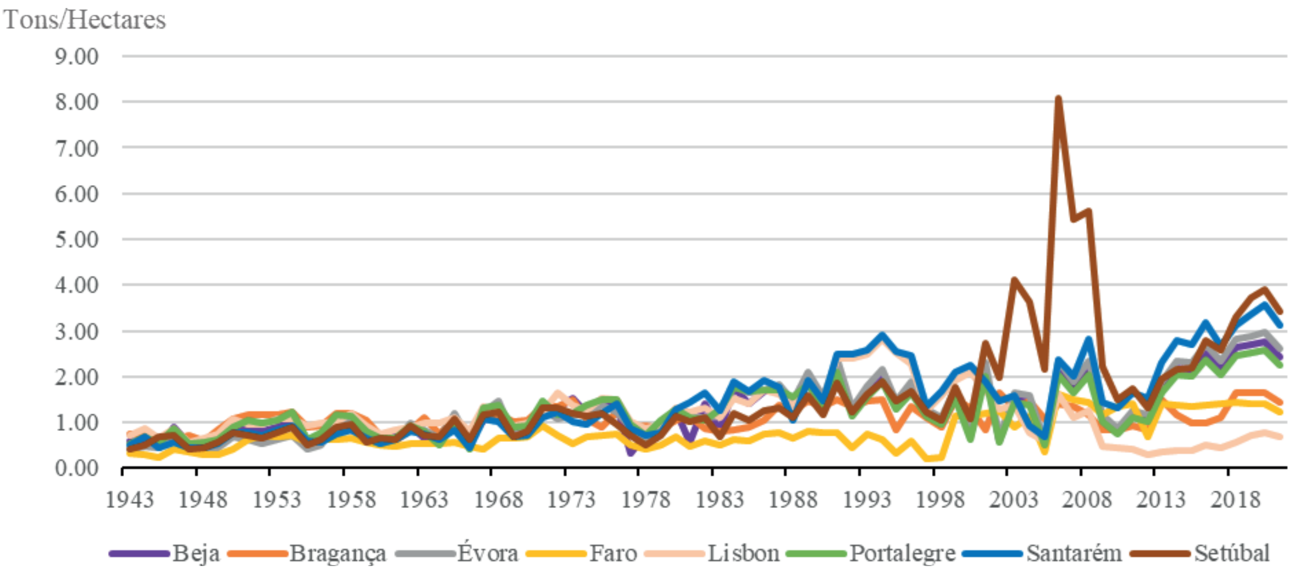

Figure 3. Productivity of the 8 major wheat producing districts (1943-2021). Source: own processing based on data from the NSI.

wheat production in India, showing that climatic variables are one of the main predictive factors. Rocha & Dias (2019) observed that low precipitation and its seasonality distribution can explain as much as 75% of the wheat yield variability. Garrido-Lestache et al. (2005) concluded that the quality of certain varieties of wheat under Mediterranean conditions is mainly affected by precipitation and temperature. We have values for annual temperatures (average, maximum and minimum) and precipitation. These figures cover the period from 1943 to 2021. As we are forecasting future yields, it is also necessary to obtain forecasts for the climatic variables, which are available in the CP database. The data is shown in Figures 4 and 5.

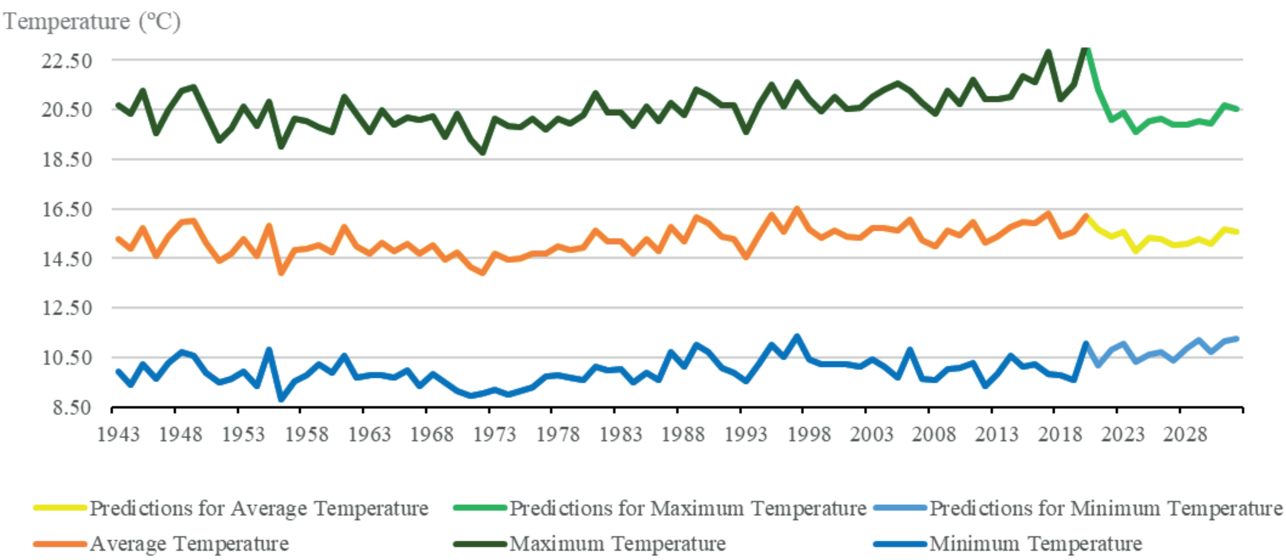

Figure 4. Average, maximum and minimum annual temperature in Portugal with forecasts (1920-2032). Source: own processing based on data from the PISA and the CP.

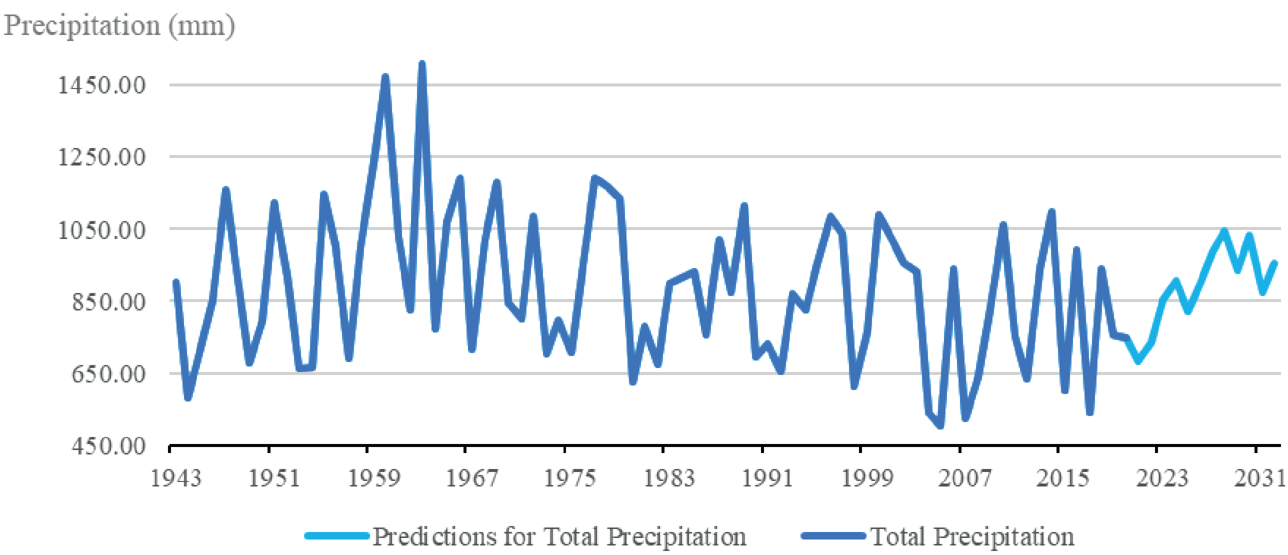

Figure 5. Total annual precipitation in Portugal with forecasts (1920-2032). Source: own processing based on data from the PISA and the CP.

METHODOLOGY

Based on the available data, two different forecasting models were developed: one for production and the other for consumption. It is assumed that future consumption will be influenced mainly by historical consumption and population's trend. In the case of production, the forecast model includes variables with a direct impact on wheat yield, namely the cultivated area, temperature and precipitation.

The method used in both models was MARS, developed by Friedman, J. (1988). It is similar to linear regression as it aims to model the relationship between the dependent and the independent variables. However, unlike linear regression, which uses a single coefficient to represent the relationship between the variables, MARS uses a series of spline functions, with their own set of parameters to model this relationship. Each spline function represents a segment of the overall relationship, and the combination of these functions can approximate a wide range of non-linear relationships between the predictor variables and the dependent variable. It automatically identifies important interactions in the data which it fits into a model to capture these interactions (Nayana et al., 2022). Its ability to automatically identify and capture complex relationships in the data, especially for situations where the functional form of the relationship is difficult to specify, as well as its ability to handle large data, make it a very useful tool for data modelling and analysis.

The choice of MARS over more conventional methods, such as linear regression or ARIMA, is justified by its demonstrated predictive accuracy and robustness in previous studies, as well as its growing momentum as a tool for developing predictive models in complex data mining applications and challenging scenarios (Nayana et al., 2022). Dias & Rocha (2019) tested different modelling approaches for wheat price forecast in the USA, one of which was MARS, using only past values of the time series. Their study concluded that the most consistent results were obtained with MARS. Nayana et al. (2022) used MARS to predict wheat yield in India. The results showed that MARS was an effective approach for predicting wheat yield, achieving high levels of accuracy. Jambekar et al. (2018) conducted a study aimed at predicting crop production using different data mining techniques in India, exploring datasets containing information on the production of wheat, climatic variables, and area under cultivation. Their results demonstrated that MARS was the most effective technique for predicting crop production. Overall, these studies highlight the growing relevance of MARS in agricultural research, particularly in settings where the underlying data relationships are difficult to specify. Its proven effectiveness reinforces its suitability for the present study, which deals with forecasting under structural and historical complexity. By supporting more accurate predictions, MARS contributes to better-informed decisions in crop management, resource allocation and policy design.

FORECASTING MODELS

Per capita *consumption*

The consumption of a given product depends on many variables, such as price, alternatives, availability and *per capita* income. Based on the available data and given the lack of additional information allowing a more detailed analysis of the evolution of consumption, it is assumed that the historical values of the series represent, in an integrated manner, the set of variables that influence consumption. Any structural change in the Portuguese economy that has occurred during the period from 1920 to 2021, with a significant impact on the variation in consumption, is reflected in the historical records of total consumption. This approach is therefore considered the most suitable for generating viable and realistic forecasts, within the limitations of the available data. These values can therefore be used as a basis for forecasting values. In other words, MARS was employed to predict *per capita* consumption using an autoregressive model, which is a model that uses past values of the dependent variable as forecasting variables.

As in any autoregressive model, it is necessary to decide which past values will be considered to estimate the values of the future series (the figure in the future period will be calculated based on known past values from $t - n_1$ to $t - n_2$). The choice of the past values is made automatically by an optimization algorithm that studies the different possibilities, choosing the one that leads to a smaller prediction error considering the data. The sliding window concept is used, in which it is considered that not all the data of the series are known, predicting these values based on the lag interval to be evaluated. As the aim is to estimate the period from 2022 to 2032, while forecasting each year individually, multiple forecasting models were developed, one for each year under analysis. The lagged values that may be the best for predicting consumption figures for next year may not be the best for predicting two years into the future. To create these models, we resorted to existing libraries that implement these methods in the R studio software (Dias & Rocha, 2019). The predictions of the *per capita* consumption are represented in Figure 6.

As expected, the predictions point to an increase in *per capita* consumption. Even with some setbacks and a somewhat uneven evolution, *per capita* consumption will end 2032 at 156.97 kilos consumed per inhabitant. These values were calculated in kilos per inhabitant, but the total figure is measured in tonnes so that a comparison can be made with production values. Obtaining these values for the *per capita* consumption forecast and combining them with the population forecast for Portugal, we calculated the value of national consumption, which is presented in Table 1.

We can see that the population in Portugal will decrease over the period analysed, which is in line with the trend of recent decades. Despite this, as we can see from the figures presented, wheat consumption in Portugal is expected to continue to increase. In 2021, national wheat consumption was approximately 1 335 million tonnes. This figure, compared to the range of values forecasted up to 2032, shows that despite the decrease in population, total consumption in Portugal will increase by around 18% over this period.

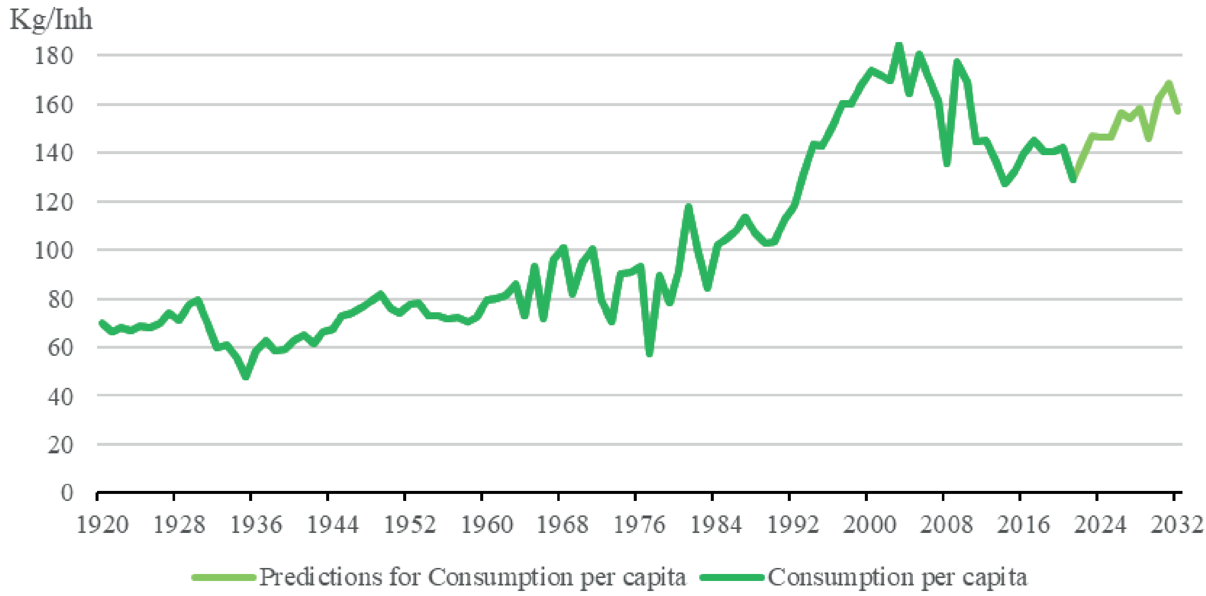

Figure 6. *Per capita* consumption (1920-2032). Source: own processing based on data from the NSI.

Table 1. Population, *per capita* consumption and total consumption (2022-2032).

Year	Total consumption (ton)	Population	*Per capita* consumption (kg/inh)
2022	1 411 132	10 282 222	137.24
2023	1 508 353	10 259 508	147.02
2024	1 498 097	10 235 702	146.36
2025	1 493 358	10 210 995	146.25
2026	1 593 684	10 185 237	156.47
2027	1 568 546	10 158 975	154.40
2028	1 606 847	10 132 084	158.59
2029	1 471 144	10 104 703	145.59
2030	1 637 633	10 076 502	162.52
2031	1 692 462	10 047 864	168.44
2032	1 572 636	10 018 702	156.97

Source: Based on Data from PorData and UN.

Productivity per hectare

In the case of the model for productivity per hectare, the use of MARS was applied differently. As mentioned previously, 8 districts accounted for 92% of the production over the last century. Thus, we will estimate the productivity per hectare of these districts individually, providing a way for determining the districts where it is most advantageous to concentrate production.

In our first attempt, we only considered climatic variables as independent variables: annual temperature (average, maximum and minimum) and precipitation. However, these climatic variables were found to have little explanatory power with regard to productivity trends. This might be caused by the fact that only annual values of these variables were included, which is not the most optimal level of aggregation, as it does not allow for capturing monthly values and variations that have a significant impact on output. Additionally, technological and biotechnological innovations in agriculture significantly influence yields and productivity per hectare, a factor that is not captured by climatic variables, highlighting the importance of considering technological change in analysing dynamics of productivity over time.

Different categories of innovation, including mechanical, biological, chemical, agronomic, and computer technologies, have profoundly transformed the structure of the agricultural sector (Sunding & Zilberman, 2001). After the Second World War, there were major advances in mechanization and biological innovations, and fertilizer consumption increased significantly around the world (Federico, 2010). At the beginning of the 21st century, the sector experienced a new technological revolution, driven by advances in biotechnology and precision agriculture (Sunding & Zilberman, 2001). However, while innovation is rightly highlighted as a key driver of productivity growth, it is essential to recognize the practical challenges associated with adopting new technologies, particularly in regions with limited financial resources, aging agricultural populations or underdeveloped infrastructures. This is particularly evident in the Portuguese case, where several authors have shown the historical and structural difficulties in adopting agricultural innovations (Freire & Lains, 2017, Lains et al., 2024). Despite significant transformations in recent decades, Portugal continues to face challenges, which make it more difficult to apply advanced solutions (Soares, 2005). As such, although innovation is a driver of agricultural productivity growth, it is important to always consider the geographical and infrastructural context in which it is implemented.

Given that climatic variables alone could not accurately predict future productivity and assuming that, with the constant advances in innovation, average productivity will continue to increase, it was decided to include the year as an explanatory variable. The inclusion of this variable captures the progressive effect of time on productivity and therefore captures the impact of innovations. By including the year as an independent variable, models with acceptable explanatory power were obtained.

Analysing the results presented in Table 2 reveals that climatic variables have good explanatory power over productivity per hectare in certain districts, such as Bragança, Faro, Lisbon and Santarém. The forecasts displayed in Table 3 indicate a significant increase in productivity per hectare over the period analysed. According to the trends observed, Beja, Évora, Portalegre, Santarém and Setúbal are the districts with the biggest increases. Not coincidentally, they are all neighbours and belong to the Ribatejo and Alentejo regions, located in the south of Portugal. On the other hand, the districts of Bragança, Faro and Lisbon show a slower evolution and seem to be entering a period of stagnation or even decline in productivity, as can be seen in the last three years of the series.

Table 2. Explanatory power of climatic variables.

Districts	Explanatory power of climatic variables for predicting productivity	
Beja	74.2%	climatic variables are not significant
Bragança	55.8%	maximum and average temperature are significant
Évora	74.2%	climatic variables are not significant
Faro	76.1%	all climatic variables are significant
Lisbon	84.8%	maximum temperature is significant
Portalegre	64.1%	climatic variables are not significant
Santarém	86.6%	maximum temperature is significant
Setúbal	80.1%	climatic variables are not significant

Source: author's calculation using Rstudio.

PRODUCTION SCENARIOS

This section examines whether it is possible for Portugal to achieve wheat self-sufficiency over the analysed period. To assess this possibility, three different scenarios of cultivated area are considered:

- First scenario: the area in 2021 remains constant;
- Second scenario: the area corresponds to its maximum value since 1943;
- Third scenario: the necessary area to reach the 20% target defined in the NSPCP.

By combining the predicted yields per hectare obtained from MARS with the proposed cultivated area in each of these three scenarios, we can determine the potential for wheat production in Portugal. Table 4 shows the values for the cultivated area for each scenario. In the case of the third scenario, since the sown area was calculated based on the productivity figures predicted for the 2022-2032 period, an average was calculated to provide a single approximate value that represents the

Table 3. Prediction of productivity per hectare per district (T/Ha) (2021-2032).

Year	Beja	Bragança	Évora	Faro	Lisbon	Portalegre	Santarém	Setúbal
2022	3.14	1.74	3.36	1.13	0.81	2.93	3.58	4.49
2023	3.32	1.81	3.55	1.42	0.53	3.09	3.63	4.84
2024	3.49	1.87	3.74	1.38	0.87	3.25	3.84	5.19
2025	3.67	1.93	3.92	1.58	0.90	3.42	3.92	5.53
2026	3.85	1.99	4.11	1.44	0.93	3.58	4.06	5.88
2027	4.02	2.06	4.30	1.58	0.97	3.74	4.15	6.23
2028	4.20	2.12	4.49	1.37	1.00	3.91	4.28	6.58
2029	4.38	2.18	4.67	1.63	1.03	4.07	4.37	6.93
2030	4.56	2.25	4.86	1.43	1.06	4.23	4.46	7.28
2031	4.73	2.31	5.05	1.50	1.09	4.39	4.48	7.62
2032	4.91	2.37	5.24	1.19	1.02	4.56	4.59	7.97

Source: author's calculation using Rstudio.

area needed to achieve 20% self-supply over the entire period. Table 4 clearly show that Beja stands out as the district with the largest cultivated area across all scenarios, followed by Évora and Portalegre. Lisbon, Setúbal, and Faro consistently show the smallest cultivated areas. The second scenario, which represents the maximum expansion, presents values significantly higher than the other two.

First scenario

Agricultural production dynamics have undergone significant changes over the past decades. In several countries, the area allocated to agriculture has declined and the workforce in the sector has also fallen significantly (Federico, 2010). Portugal has followed this trend, as evidenced by the data from the last few decades. Increasing production depends largely on expanding the agricultural land and as wheat is considered a very demanding crop in terms of natural resources, namely fertile soils, expanding the cultivated area is a huge challenge. In 2021, the area allocated to wheat production in the 8 districts was 27 374 hectares, corresponding to 95% of the entire cultivated area. This number is one of the lowest of the last century, being only higher than the values recorded in 2018 and 2019. The figures for the cultivated area with wheat in 2021 were used to estimate the amount of output that can be achieved.

The production numbers recorded in Table 5 show a continuous increase during the series, which can be attributed to productivity gains driven by innovations, as mentioned earlier. Despite having the third smallest cultivated area in the last century, the increase in production, even with the land remaining constant, demonstrates Portugal's productive potential. Given that the highest self- supply figure achieved was 8% in 2032, the results show that Portugal does not have the capacity to guarantee 20% self-supply, which means that it cannot meet the target set by the NSPCP. This indicates that Portugal cannot rely exclusively on innovation advances to increase productivity. It is also necessary to look at the possibility of expanding the cultivated area.

Table 4. Area cultivated in each district for all three scenarios (Ha).

District	First Scenario	Second Scenario	Third Scenario
Beja	9 787	275 363	28 967
Bragança	2 907	56 545	9 962
Évora	6 859	149 344	20 369
Faro	717	65 089	3 065
Lisbon	772	71 374	2 861
Portalegre	3 840	86 219	11 418
Santarém	1 318	64 649	4 872
Setúbal	1 174	46 151	3 202
Total	27 374	814 734	84 717

Source: based on data from the NSI and author's calculation.

Second scenario

In the second scenario, production was calculated based on the largest sown area recorded since 1943. Once again, the districts of Beja, Évora and Portalegre recorded the largest areas, while the districts with the smallest were Bragança and Setúbal. The sum of the figures presented in Table 4 corresponds to 814 734 hectares, a figure higher than that recorded at the peak of the Wheat Campaign, when self-sufficiency was achieved. The importance of mentioning the Wheat

Table 5. Production with constant area in tons (2022-2032).

Year	Beja	Bragança	Évora	Faro	Lisbon	Portalegre	Santarém	Setúbal	Total	Self-Supply
2022	30 730	5 058	23 048	811	625	11 250	4 717	5 271	81 510	5.8%
2023	32 492	5 261	24 351	1 019	409	11 865	4 783	5 682	85 861	5.7%
2024	34 155	5 436	25 655	990	672	12 479	5 059	6 093	90 539	6.0%
2025	35 917	5 610	26 889	1 133	695	13 132	5 165	6 492	95 033	6.4%
2026	37 679	5 785	28 193	1 033	718	13 746	5 349	6 903	99 405	6.2%
2027	39 342	5 988	29 496	1 133	749	14 361	5 468	7 313	103 851	6.6%
2028	41 104	6 163	30 799	983	772	15 013	5 639	7 724	108 197	6.7%
2029	42 866	6 337	32 034	1 169	795	15 628	5 758	8 135	112 722	7.7%
2030	44 627	6 540	33 337	1 026	818	16 242	5 876	8 546	117 013	7.1%
2031	46 291	6 715	34 640	1 076	842	16 857	5 902	8 945	121 268	7.2%
2032	48 054	6 890	35 941	853	787	17 510	6 050	9 357	125 442	8.0%

Source: author's calculation using Rstudio.

Table 6. Production with the maximum area in tons (2022-2032).

Year	Beja	Bragança	Évora	Faro	Lisbon	Portalegre	Santarém	Setúbal	Total	Self-Supply
2022	864 640	98 388	501 796	73 551	57 813	252 622	231 443	207 218	2 287 471	162%
2023	914 205	102 346	530 171	92 426	37 828	266 417	234 676	223 371	2 401 441	159%
2024	961 017	105 739	558 547	89 823	62 095	280 212	248 252	239 524	2 545 208	170%
2025	1 010 582	109 132	585 428	102 841	64 237	294 869	253 424	255 215	2 675 728	179%
2026	1 060 148	112 525	613 804	93 728	66 378	308 664	262 475	271 368	2 789 089	175%
2027	1 106 959	116 483	642 179	102 841	69 233	322 459	268 293	287 521	2 915 968	186%
2028	1 156 525	119 875	670 555	89 172	71 374	337 116	276 698	303 674	3 024 988	188%
2029	1 206 090	123 268	697 436	106 095	73 515	350 911	282 516	319 826	3 159 659	215%
2030	1 255 655	127 226	725 812	93 077	75 656	364 706	288 335	335 979	3 266 447	199%
2031	1 302 467	130 619	754 187	97 634	77 798	378 501	289 628	351 671	3 382 504	200%
2032	1 352 032	134 012	782 563	77 456	72 801	393 159	296 739	367 823	3 476 585	221%

Source: author's calculation using Rstudio.

Campaign lies in the fact that it was the period in which the highest levels of self-sufficiency were achieved, demonstrating that it is possible to place Portugal in a comfortable situation in terms of domestic supply.

Following the public policies applied by fascist Italy, the Portuguese government launched the Wheat Campaign in 1929. It was established due to two main factors: the insufficiency of national production to meet consumption needs and the implementation of protectionist policies by the countries to which Portugal depended on for its supply (Freire, 2008). The measures implemented were successful in the sense that, between the years 1931 and 1935, wheat production exceeded domestic consumption and made it possible to create surpluses (Pais et al., 1978). The highest degree of self-sufficiency recorded was 161.29% in the year 1934.

Both testimonies of time and historians recognise that wheat self-sufficiency was difficult to achieve in the following decades. One of the reasons that explains this fall in production in the decades following the Wheat Campaign is the fact that most of the incentives granted by the Portuguese state during the campaign was primarily aimed at increasing the cultivated area (Freire, 2008), rather than promoting investment in innovation and new cultivation techniques. However, with the implementation of new technologies that have altered the structure of the agricultural sector and increased productivity, it is relevant to compare the figures recorded during the Wheat Campaign with those of this second scenario, since self-sufficiency is achieved in both.

According to the data presented in Table 6, production is significantly higher than consumption forecasts, which suggests that Portugal would be able to achieve self-sufficiency if it recuperated the area that was once allocated to growing wheat. In 2022, Portugal would reach an output corresponding to 162% of consumption and in 2032, this figure increased to 221%. However, it is unlikely that this land can be repurposed for wheat production due to the occupation of much of it by urban uses, more profitable crops or because it no longer has the required fertility levels (van Vliet et al., 2017). During the period in which these maximum areas were recorded, it was clear that they were driven by strong state support, which encouraged producers to occupy their land with wheat. However, given the comparative disadvantages and the fact that the agricultural sector is no longer governed by national policies, but by the Common Agricultural Policy (CAP), this type of guideline is no longer available and probably won't be in the future.

Third scenario

In the third scenario, it was tested the situation in which Portugal reaches the 20% target of self-supply. In 2017, the Portuguese Ministry of Agriculture, Forestry and Rural Development announced the creation of the NSPCP, which defined several mains goals, like the increase of cereal production, the reduction of external dependence and the achievement of a stronger and more efficient agricultural sector in the period between 2018-2023. The strategy was based on three pillars: strengthening the role of producer associations, focusing on innovation and transfer of knowledge, and better organization along the production chain (Barreiros, 2018). The production of the districts was calculated based on the percentage of total national production achieved by each district in 2021, and is shown in Table 7.

According to the results, the total wheat production required to meet the self-supply target in 2032 is approximately 10% higher than in 2022, primarily due to the

Table 7. Production required to achieve 20% self-supply in tons (2022-2032).

Year	Beja	Bragança	Évora	Faro	Lisbon	Portalegre	Santarém	Setúbal	Total
2022	104 573	18 546	78 573	3 929	2 340	38 346	18 221	17 698	282 226
2023	111 779	19 823	83 986	4 200	2 502	40 988	19 476	18 918	301 671
2024	111 019	19 689	83 415	4 171	2 485	40 709	19 343	18 789	299 619
2025	110 668	19 626	83 151	4 158	2 477	40 580	19 282	18 729	298 672
2026	118 102	20 945	88 738	4 437	2 643	43 306	20 578	19 988	318 737
2027	116 239	20 614	87 338	4 367	2 601	42 623	20 253	19 672	313 709
2028	119 078	21 118	89 471	4 474	2 665	43 664	20 748	20 153	321 369
2029	109 021	19 334	81 915	4 096	2 440	39 977	18 995	18 451	294 229
2030	121 359	21 522	91 185	4 559	2 716	44 501	21 145	20 539	327 527
2031	125 422	22 243	94 238	4 712	2 807	45 991	21 853	21 227	338 492
2032	116 543	20 668	87 566	4 379	2 608	42 735	20 306	19 724	314 527

Source: author's calculation using Rstudio.

projected increase in national consumption. This trend underscores the importance of continuing to invest in strategies to boost wheat production, as the target will continue to rise steadily. In contrast, the required cultivated area gradually decreases over the same period, reflecting the positive impact of innovation-driven gains in productivity.

DISCUSSION

Portuguese productive capacity

As other European countries, from the second half of the 19th century onwards (Federico, 2010; Lains et al., 2024), Portugal experienced growing State intervention, particularly in the most important agricultural subsectors for human consumption, like cereals. The Wheat Campaign is part of this trend of national protectionist policies (Freire, 2008). In Portugal, this kind of policies lasted until the country's entry into the European Economic Community (EEC), in 1986, where the CAP came into effect. The policy changes had a very particular impact on wheat, because in the 20th century it was the crop that deserved the most protection (Freire & Lains, 2017). The implementation of the CAP changed the structure of the Portuguese agricultural sector and has been considered detrimental to the sector's evolution. Indeed, it can be observed that agriculture has struggled to generate new dynamics capable of counteracting the structural impacts of the CAP reforms, notably failing to devise development strategies, engage new stakeholders, and harness productive potential (Cunha, 2010). Following the decline in incentives for wheat cultivation, output sharply declined nationwide, since it was state intervention that rendered production economically attractive to farmers. Combining these changes in the orientation of incentives with the opening of international markets and the integration into the EEC, imports were favoured in order to make up for the national consumption deficit.

The findings of the second scenario suggest that Portugal could become self-sufficient if it manages to recover a large part of the land once used to produce wheat. In fact, the lower degree of self-supply recorded in this scenario, 159% in 2023, allows us to understand that there is room for production gains through increases in the cultivated area. However, the assumption that the maximum areas historically cultivated can be recovered does not fully consider current constraints, such as urbanization, land abandonment, soil degradation and shifts to more profitable crops (van Vliet et al., 2017). These structural changes in land use reduced the feasibility of fully recovering former wheat production areas. This complexity must be acknowledged when interpreting the results. However, the analysis also shows that a consistent and stable increase in cultivated area, combined with productivity gains driven by technological innovation, could significantly improve self-supply. Although self-sufficiency is unlikely to be achieved in the short term due to climatic, environmental and political constraints, the third scenario emerges as a more realistic benchmark. To be more specific, the year in which the area necessary to reach 20% is lowest is 2032, and to reach that point it would be necessary to increase the area by 44 300 hectares, an increase of 162% over the 2021 figure.

Another significant takeaway from the analysis of the results is the identification of the most favourable districts for wheat production. It has already been mentioned that most of the Portuguese territory does not have favourable conditions for wheat production and that only a few regions are capable of meeting the necessary conditions to produce it efficiently (Freire & Lains, 2017). The Alentejo and Ribatejo regions, composed by five districts (Beja, Évora, Portalegre, Santarém and Setúbal), emerge as the most productive zones. Setúbal, which is the district with the highest productivity, should have production concentrated mainly in municipalities outside the Setúbal peninsula, due to the high residential density in this zone, which are a part of the Lisbon metropolitan area. The district of Santarém, with the second highest productivity, has historically concentrated production in the municipalities located on the left bank of the Tagus river, which is close to the Alentejo region. Although Beja, Évora and Portalegre have lower productivity levels than these two, they are still the districts with the highest concentration of production and should continue to be prioritised. During several centuries, wheat was the main crop of the Alentejo region (Faísca, 2019). In fact, "government policies were, since 1899, contributing for the region to consolidate the image of Portugal's granary" (Freire, 2008, p. 31). As a result, wheat cultivation has emerged as an activity which exercised a substantial influence on soil degradation and played a significant role in the state of desertification within the region.

The scenario based approach and policy context

The scenario-based approach used in this study can be easily adapted to other national contexts and crop types, as long as country-specific data on cultivated area, production figures and climatic variables are available. By defining alternative scenarios of land allocation and productivity improvements, the same framework can simulate the evolution of production potential of other cereals such as maize, barley or oats. For example, applying this approach to maize in the southern countries of Eastern Europe is particularly relevant, as maize is one of the most important cereal crops for this region, occupying a significant share of cultivated land and playing a central role in consumption (Grčak et al., 2020).

From a political point of view, integrating scenario results with existing agricultural strategies improves decision-making at various levels of governance. In the EU, for example, scenario modelling can serve as a basis for CAP interventions and support the "Farm to Fork" strategy, which aims to make food systems fair, healthy and environmentally friendly (Wesseler, 2022). National authorities can then prioritize incentive systems, to encourage farmers to expand cultivation in environmentally sustainable ways or to rotate crops to maintain soil quality. By linking this method directly to policy instruments, future research can provide tailored recommendations that support sustainable intensification, crop diversification and resilience building ensuring that scenario-based planning becomes a relevant indicator for agricultural policymaking.

Although this study focuses mainly on consumption and production scenarios, it is important to recognize the broader economic context in which is inserted. Market dynamics, including price volatility and global imbalances between supply and demand, can have a significant impact on both domestic production incentives and the level of wheat imports. A clear example of this, as mentioned earlier, is the armed conflict on the Ukrainian territory. The disruptions in the production cycle and in the supply chain resulting from this conflict have made a significant impact on the market dynamics of wheat on the international stage (Zhang et al., 2024). Similarly, international trade policies, such as tariffs or subsidies, also play a critical role in shaping these dynamics. In the context of the EU, the CAP and the trade agreements with third parties have a profound influence on grain markets (Wieliczko, 2017). These factors collectively shape the economic environment in which agricultural decisions are made and must be considered when assessing the viability and sustainability of production strategies.

Any strategy aimed at achieving national self-sufficiency in wheat must be conceived as a long-term, carefully planned and environmentally sustainable effort. The Wheat Campaign, although it led to self-sufficiency, proved to be economically and ecologically unsustainable and cannot be repeated. Intensive cultivation led to serious erosion and degradation of soil quality due to over-exploitation, particularly in the Alentejo, reflecting a lack of planning on the part of policymakers who ignored these factors (Freire, 2008). In addition, much of the soil in Portugal is unsuitable for growing wheat, resulting in chronically low yields and high production costs due to heavy dependence on fertilizers (Faísca, 2019). Consequently, any future efforts should prioritize the expansion of wheat into the most suitable areas. To ensure that any increase in production aligns with sustainability goals, expansion must be accompanied by environmental safeguards that mitigate soil degradation, conserve water resources and preserve biodiversity. This implies the adoption of soil conservation practices and the adoption of technologies to optimize the use of production factors. Integrating these measures into national policy frameworks will be crucial to balance productivity objectives with long-term ecological resilience and to ensure that the quest for self-sufficiency adheres to the principles of sustainable agriculture.

Limitations and further research

The work carried out and described in this study has some limitations that should be acknowledged when interpreting the results. One fundamental limitation concerns the relatively weak explanatory power of the climatic variables in the model, particularly in relation to predicting productivity levels. However, this should not be interpreted as proof that climate variables are insignificant in determining agricultural results. Nevertheless, aggregating data over large temporal and spatial scales can hide more nuanced interactions between weather patterns and crop output (Srikanthan & McMahon, 2001). By relying on annual figures, the analysis fails to capture the timing and intensity of key climatic events, such as rainfall during the main growth phases or temperature extremes during sensitive periods of the crop cycle, which are known to have substantial effects on yields (Gouveia & Trigo, 2008). In this regard, the use of weekly, monthly, or even seasonal climatic data would allow for a much more precise understanding of when and how climate variables influence production (Gao et al., 2023). As such, the lack of significant explanatory power in the current model probably reflects a limitation in the availability of the data rather than the actual influence of weather on production. Future research could benefit significantly from incorporating more granular climate data, both spatially and temporally, to better understand the specific conditions under which climate variability affects agricultural productivity.

To resolve this constraint, the model was adjusted to include the year as an explanatory variable. This choice allowed MARS to capture the temporal evolution existing in our dataset, which gave it the ability to generate stable and reliable results. More importantly, this inclusion revealed that productivity trends are also significantly influenced by technological innovations, which were not previously considered. By introducing the year into the model, we were able to indirectly reflect the cumulative effect of these innovations over time, from mechanization and the use of fertilizers to the adoption of biotechnology and precision agriculture (Federico, 2010). Although this approach does not isolate specific technologies, it does incorporate their overall influence on output. The resulting models, which include year as a variable, achieved acceptable levels of explanatory power and improved predictive capacity.

CONCLUSION

In conclusion, an increase in wheat production not only depends on productivity improvement brought by innovations, but also on the increase of the cultivated area. If it remains constant, the maximum degree of self-supply that can be achieved is 8% in 2032, a figure not very different from the value of 6,1% recorded in 2021, which is very far from the 20% target. Considering the circumstances in which the periods of self-sufficiency occurred, it can be observed that an increase in production would require an extension of the cultivated area, which may become possible if incentives are created.

The scenario-based approach used not only provides policymakers with informed guidance on realistic and sustainable strategies for optimizing production efficiency but also provides a form of sensitivity analysis of the MARS method used for forecasting. While the MARS method has strengths, such as the ability to model non-linear relationships and to select the most efficient variables automatically, it also has limitations, such as sensitivity to missing data and high computational requirements for large data sets. Despite these limitations, MARS remains a valuable tool due to its ability to produce understandable models and identify influential forecasting factors. However, to ensure reliable and accurate forecasts, it is advisable to complement it with other models and validation techniques.

The use of MARS in this paper proved very efficient and it emerges as a powerful tool for modelling and predicting wheat production and consumption. It allowed us to work with a very extensive database and, by using its ability to capture nonlinear relationships and interactions among multiple predictors, it provided a robust framework for forecasting. The fact that it identifies and captures complex relationships in data, which would not be possible to unfold if we had used a linear model, was fundamental to this research.

For a strategy to be drawn up and implemented successfully in any sector of the economy, it is necessary to carry out studies and analyses of current conditions and past performance in order to establish reliable objectives. Based on historical data of variables that directly impact wheat production, our analysis was made to provide us with information on the productive capacity of the main agrarian regions. The fact that we limited ourselves to values that were previously recorded gave us the ability to state that this study is reliable and realistic, because these values have been achieved in the past. As such, this study is of great importance to researchers and policymakers to gain insights into the key factors influencing wheat production, enabling informed decision-making and resource allocation. Due to the lack of investment by the Portuguese government, which is still not paying enough attention to the problem of decreasing wheat production, it has not yet been possible to record the figures we had predicted could be achieved. As agricultural systems face increasing challenges due to climate change and fluctuating market conditions, this paper offers a valuable approach for reliable and accurate wheat production predictions, thereby aiding in the formulation of sustainable agricultural strategies. This becomes more relevant considering the current geopolitical context of the European continent, as it provides countries with information on their productive capacity so that they can design strategies to increase production and achieve self-sufficiency.

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ORCID
AS: 0000-0003-2969-4926

From subsidy to land rent: how production-linked payments shape factor remuneration in agriculture

Adrian Sadłowski

Cardinal Stefan Wyszyński University in Warsaw, Poland
E-mail: a.sadlowski@uksw.edu.pl

Abstract. The paper aims to recognize the mechanism by which production-linked payments stimulate the inputs of production factors in agriculture and the mechanism for transforming subsidies into remuneration for production factors. The study is theoretical, and the research methods used are economic modeling and marginalist analysis. It was demonstrated that production-linked payments change the allocation of resources compared to the allocation that results from the market mechanism, as well as influence the amount and structure of remuneration for production factors in agriculture. A decomposition of the remuneration of production factors was performed. This comprehensive approach to evaluating the impact of these payments, taking into account the side effects of using this instrument, represents a contribution to the literature. The proposed model can be applied to support the design of agricultural policy instruments, policymaking decisions concerning the selection of tools for achieving established objectives, and academic education in agricultural economics.

Keywords: agricultural subsidization coefficient, capitalization of direct payments, conversion rate of payments into land rent, financial support for agriculture, production-linked payments.
JEL Codes: H23, Q12, Q15.

1. INTRODUCTION

With the implementation of the 2003 reform of the Common Agricultural Policy (CAP) (the so-called Fischler reform), which envisaged the gradual decoupling of direct payments from production (Pirzio-Biroli, 2008; Swinnen, 2010), production-linked payments played an increasingly minor role. They became a kind of remnant in the structure of reformed instruments. Gradually, they were converted into so-called historical payments (Frascarelli, 2020), i.e., payments linked not to the current production volume but to the volume from a reference period earlier than the year of applying for the payment. After the transition period, they were to cease entirely, and the funds previously paid under production-linked payments were to be added to the budget for decoupled payments.

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If a broad definition of production-linked payments is adopted, their gradual disappearance was interrupted in 2010, when the so-called special support was introduced (Council of the European Union, 2009). The amount of financial assistance granted to a farmer under this instrument depended on the area of a given crop in the farm (for crop production sectors) and the number of animals of a given species (for livestock production sectors). Similarly, under the CAP reform that came into effect in 2015, European Union (EU) Member States were allowed to allocate part of the available funds to finance payments described as voluntary coupled support (Sadłowski, 2018a). The general rules for granting these payments were the same as those established for the aforementioned special support (Tangermann, 2011). Their use was optional for EU Member States and simultaneously subject to various restrictions, including a cap on funding level (Potori et al., 2013). The maximum allowable level of funding was expressed as a percentage of the so-called national ceiling, i.e., the amount allocated to a given EU Member State for direct payments (Sadłowski, 2018b). These instruments were intended to support farmers' incomes in selected agricultural production sectors. The choice of specific sectors to be supported could be driven by recognizing their particular social sensitivity, environmental importance, or susceptibility to economic crises (Anania and D'Andrea, 2015; Hristov et al., 2020). However, neither the so-called special support nor the so-called voluntary coupled support constituted production-linked payments in the strict sense, understood as payments granted to beneficiaries in amounts proportional to the volume of agricultural products sold. Similar solutions were provided for the next programming period (Sadłowski, 2019; Pilvere et al., 2022).

The issue of returning to strictly production-linked direct payments or using such instruments under extraordinary measures (financed either from the EU budget or from the national budgets of EU Member States) is raised by the agricultural self-government in discussions on subsequent CAP reforms, as well as in cases of extraordinary circumstances that have a strong negative impact on farmers' incomes. A current example of such circumstances is the increased influx of Ukrainian agricultural products, mainly cereals and oil seeds, into the EU market following the temporary liberalization of trade relations between the EU and Ukraine (Mulyk and Mulyk, 2022; Hamulczuk et al., 2023; Beluhova-Uzunova et al., 2024). However, the decision-making freedom regarding the use of production-linked payments is limited by the international commitments made by the EU under agreements concluded within the framework of the World Trade Organization (Matthews, 2018; Nedumpara et al., 2022).

This study aims to identify (i) the mechanism by which strictly production-linked payments stimulate the inputs of production factors in agriculture, and (ii) the mechanism by which subsidies granted in the form of strictly production-linked payments are transformed into remuneration for production factors.

A research gap has been identified in the existing literature, particularly in the analysis of the distribution sphere. Previous studies have primarily focused on the impact of financial support on production volume (e.g., Howley et al., 2009) or the overall efficiency of the agricultural sector (e.g., Lankoski and Thiem, 2020). The model presented in this article provides a detailed analysis of the impact of production-linked payments not only on the production sphere but also on the size and structure of remuneration for production factors (what falls within the scope of the distribution sphere (see Blaug, 1992)) while taking into account the side effect of this instrument – namely, the "capture" of support by landowners. This study therefore proposes a comprehensive approach, uniquely employing Ricardo's theory of land rent, to explain the mechanism by which payments are transformed into the remuneration of production factors. This connection of land rent theory with subsidies has not been done before in theoretical research. Furthermore, it should be noted that the existing literature predominantly adopts a macroeconomic perspective, whereas the proposed model considers the specificity of optimization decisions made at the farm level under subsidy conditions. The focus on general analyses and the scantiness of research from a microeconomic perspective may result in insufficient recognition and understanding of complex economic mechanisms, limiting the ability to draw accurate, comprehensive conclusions (compare Stiglitz, 2018). The proposed model addresses this gap in the literature and lays the foundation for more precise and multifaceted analyses of agricultural policy in response to current challenges in the sector. By proposing analytical tools for quantifying the effects of production-linked payments, this study also contributes to the standardization of terminology and the development of methodology in this field.

It should be noted that – according to the current terminology of EU regulations – so-called coupled payments are a type of financial support that is proportional to the area of a given type of crop (in the case of plant production sectors) or the number of animals of a given species (in the case of animal production sectors), and the definition commonly accepted implicitly in scientific studies is identical to the nomenclature of legal acts.

The subject of relatively numerous studies, the results of which have been reported in the scientific literature, are almost exclusively coupled payments in the sense of the current legal provisions and not production-linked payments in the strict sense of the word, which require further exploration.

The article consists of an introduction, a literature review, a methodology section, results, discussion, and conclusions. The "Results" presents a model of how production-linked payments affect land use and factor remuneration in agriculture. The "Discussion" highlights the model's advantages and limitations, followed by concluding remarks.

2. LITERATURE REVIEW

The practice of using production-linked payments under the CAP has revealed numerous shortcomings of this instrument (Beard and Swinbank, 2001). Their main disadvantage, compared to alternative forms of financial assistance to farmers, is considered to be their stimulating effect on the volume of production in the supported sectors, resulting in the creation (or widening) of a discrepancy between the volume and structure of agricultural production and the volume and structure of demand for agricultural products (Howley et al., 2009; OECD, 2020).

By rewarding production intensification, production-linked payments intensify the negative effects of agricultural activities on the natural environment (Donald et al., 2002; Henderson and Lankoski, 2019). The environmental damage indirectly caused by this form of support is particularly acute in farming systems where input use was already high at the starting point (Lankoski and Thiem, 2020).

Production-linked payments are susceptible to "capture" by next links of agribusiness or by agricultural landowners, which, however, is also a feature (albeit to varying degrees) of other forms of direct support to farmers (Góral and Kulawik, 2015; Sadłowski, 2017; Baldoni and Ciaian, 2023). In the typical conditions of agricultural markets, with greater bargaining power on the demand side, represented by processors of agricultural products (Oleszko-Kurzyna, 2007), production-linked payments can be "captured" relatively easily by the next links of agribusiness. This occurs as a result of processors lowering the purchase prices of supported agricultural products. The fewer part of production-linked payments is "captured" by subsequent links in the agribusiness chain (interactions in agricultural product markets), the greater their tendency to capitalize on agricultural land prices and their susceptibility to "capture" by landowners by raising rental rates (interactions in the agricultural land market). These phenomena reduce the effectiveness of direct payments in supporting farmers' income (Latruffe and Le Mouël, 2009).

Compared to area-based payments, while production-linked payments show less susceptibility to "capture" by agricultural landowners and greater resistance to capitalization in farmland prices, they are more susceptible to "capture" by buyers of agricultural products (Sadłowski, 2017; Ciaian et al., 2021). A critical view of the use of production-linked payments has been expressed by Tangermann (2011), according to whom a given amount of payment provides the greater economic benefit to the farmer the less it is linked to any requirement, in particular the production of a specific agricultural product. In his view, the decoupled payment is more effective than the coupled payment not only in supporting farmers' income but also in counteracting abandonment in areas with natural constraints (Tangermann, 2011).

3. METHODOLOGY

The theory explaining the mechanism by which production-linked payments influence the production sphere (the level of engagement of agricultural land) and the distribution sphere (the remuneration of production factors) was developed using economic modeling. The remuneration of land as a production factor is interpreted in the model – by Ricardo's (1996) theory of land rent – as the residual amount remaining after paying for the input of the other production factors.

The research method used is marginalist analysis, derived from the neoclassical tradition (Bartkowiak, 2008). In the model, marginal revenue (MR) is defined not as the increase in total revenue due to an increase in production (and simultaneously sale) by one unit but as the increase in total revenue (TR) resulting from an increase in land input (L) by one unit. Unlike a marginal product, which in economic theory is expressed in physical units per unit of variable production factor input (e.g., the measured in tons quantity of "additional" grain produced as a result of increasing input of a specific production factor by one unit), marginal revenue is expressed in monetary units per unit of agricultural land area (e.g., a hectare). Similarly, marginal cost (MC) is understood as the rise in total cost (TC) (inputs other than land) due to an increase in land input by one unit (Table 1).

MC, like MR, is expressed in monetary units per unit of agricultural land area, which allows the relation-

Table 1. Marginal quantities used in the model.

Variable	Definitional formula	Descriptive definition
Marginal cost	$\mathrm{MC} = \frac{\Delta \mathrm{TC}}{\Delta \mathrm{L}}$	Increase in total cost (production inputs other than land) due to an increase in land input by one unit.
Marginal revenue	$\mathrm{MR} = \frac{\Delta \mathrm{TR}}{\Delta \mathrm{L}}$	Increase in total revenue due to an increase in land input by one unit.

Source: Author's own elaboration.

ship between these two variables and an exogenous variable (land input) to be represented within a single coordinate system.

The model adopts the perspective of a farm being a "price taker" (Niezgoda, 2009) – both in the market for production factors and in the market for agricultural products. This means that the economic decisions of an individual farm, regarding the size of inputs or the scale of production, do not affect market prices (for agricultural production inputs or products). The issue of the (un)realism of the assumption regarding the independence of price from production volume, as well as the acceptability of adopting unrealistic assumptions, has been widely discussed in theoretical and methodological economic literature (see Friedman, 1953; Hardt, 2012). In the practical functioning of agricultural markets, the supply side is typically represented by numerous, fragmented producers. From their perspective, the unit price remains the same regardless of the volume of delivery (sale). The presented model focuses on this micro-level perspective.

A narrow definition of production-linked payments was adopted (the term "production support" is treated as synonymous), including only those financial support instruments for farmers where the amount of support granted is calculated in proportion to the amount of production sold. The baseline situation, in which production-linked payments are not used (the zero variant), was compared with the situation in which this form of state intervention in agriculture was applied (the alternative variant). This allowed for the determination of the economic effects of the intervention. The identification of the mechanism for converting production-linked payments into remuneration for production factors created a framework for describing and measuring the phenomenon of "capturing" the support provided to farmers by the owners of agricultural land. The essence of the model was presented using a graphical method of visualizing dependencies (charts) and its accompanying descriptive method.

The developed model is a tool for analyzing the behavior of a farm as an economic entity; thus, it is a microeconomic model. It enables the determination of the level of land resource usage in a farm that ensures the maximization of economic performance; it is, therefore, an optimization model. At the same time, it is an equilibrium model, as it indicates the functioning of an automatic mechanism that leads the farm to a state of equilibrium, in which the incentives for further changes cease.

4. RESULTS

4.1 The impact of production support on the use of agricultural land (production sphere)

The analysis is conducted in the first quadrant of the coordinate system (Figure 1), as this corresponds to the values of the examined variables that have an economic sense.

The horizontal axis represents the amount of agricultural land used (in units of area, e.g., hectares). Meanwhile, on the vertical axis, one can read – as the second coordinate of a point located on a given line – the level of MC and MR, expressed in monetary units per unit of agricultural land input, in relation to a homogeneous, unitary plot of land.

MC here means the increase in the cost of production, namely the inputs of production factors other than land (i.e. – in the classical approach – labor and capital), resulting from the increase in land input by one unit. MR is understood here as the increase in TR resulting from the increase in the level of land use by one unit.

MR_0 is the graph of the MR function under conditions where production-linked payments are not applied, thus it includes only revenue from the sale of agricultural produce. MR_1, on the other hand, refers to the situation where production-linked payments are applied. This

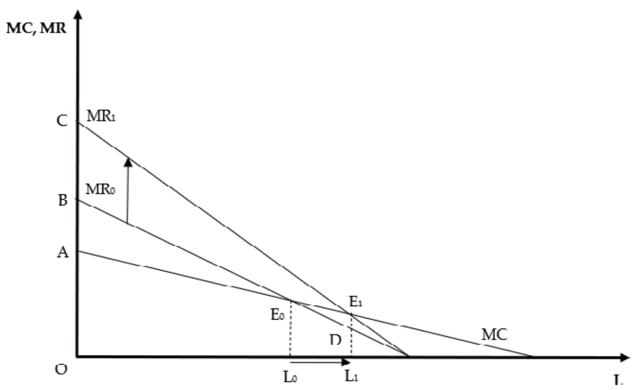

Figure 1. The impact of production-linked payments on the level of agricultural land use. Source: Author's own elaboration.

means that MR_1 includes, in addition to revenues from the sale of agricultural produce, revenues from production-linked payments.

For an agricultural parcel represented by a given point on the horizontal axis of the coordinate system, the ratio of the vertical distance between the line MR_0 and the line MR_1 to the vertical distance between the horizontal axis of the coordinate system and the line MR_0 corresponds to the relation of the amount of support granted to the value of the sale. In other words, this represents the relationship between remuneration sourced from the state and remuneration sourced from the market. Due to the assumption of the independence of the price of the supported agricultural product from the volume of production, this ratio does not change as one moves rightwards along the horizontal axis.

Sadłowski (2017) demonstrated that the application of production-linked payments leads to an increase in production intensity on land already used for agriculture (even in the absence of support) while simultaneously increasing production extensiveness by bringing previously unused land into agricultural production. In the simplified model presented in this study, the effect of a payment-induced increase in inputs (impact on the course of the MC function graph) and revenues from the sale of agricultural produce (impact on the course of the MR function graph) was omitted in relation to land on which production would be carried out even in the absence of support.

The further to the right along the horizontal axis, the less agriculturally useful the land, as the most fertile and accessible plots are used in production first. The graph of the MC function is a downward-sloping line, as the less fertile the land, the lower the amount of labor and capital required to maximize economic outcome (Sadłowski, 2017). This statement concerns the inputs of labor and capital that make up the direct costs of production and not the investment outlays (e.g., the costs of building drainage infrastructure) that make it possible to increase the agricultural suitability of the land. The graph of the MR function is also a downward-sloping line. The negative slope of this line reflects the fact that the most productive land, which generates the highest revenue from the sale of agricultural products, is engaged in production first in the pursuit of maximizing economic outcomes. As less and less fertile and increasingly peripherally located land is involved in the production process (moving to the right along the horizontal axis), the MR from each subsequent unit of land area is lower and lower. The area under the MC curve represents the TC level, while the area under the MR curve represents the TR level.

The effects of changes in factor input prices would be illustrated by a parallel shift of the MC line, while the effects of changes in the price of the supported agricultural product would be illustrated by a parallel shift of the MR line. An increase/decrease in the prices of agricultural inputs or wages would result in an upward/downward shift of the MC line, respectively. Meanwhile, an increase/decrease in the price of the supported agricultural product would be reflected in an upward/downward shift of the MR line.

The optimal level of use of available agricultural land resources when production-linked payments are not applied is determined by the first coordinate of the point where the MC curve intersects the MR_0 curve, i.e., L_0. At this level of land use, the economic outcome, understood as the surplus of TR over TC, is maximized.

However, when agricultural production is subsidized by providing farms with financial support proportional to the volume of production, the factors of production engaged in the production process are remunerated not only by the market (in the form of revenues from the sale of agricultural products) but also by the state (in the form of production-linked payments). This is illustrated by the MR function at position MR_1. In this case, the farm's equilibrium point will be point E_1, which corresponds to a higher level of land use ($L_1 > L_0$). Thus, land that was previously (i.e., in the absence of production-linked support) unused for agricultural purposes will now be engaged in production. The length of the segment $|L_0L_1|$ reflects the area of this additional land, i.e., land brought into production as a result of the introduction of production-linked payments. They can be equated with marginal lands (see Csikós and Tóth, 2023); although definitional challenges have not been fully resolved, this concept is relatively frequently used in the literature on the subject.

Therefore, production-linked support acts as an incentive for farms to increase land use, leading to an overall increase in the agricultural land area utilized in the country. However, if resource management is to be rational, there is no justification for expanding this area for reasons other than an improvement in market conditions in agriculture.

4.2 The impact of production support on the remuneration of production factors (distribution sphere)

The remuneration of land, as a resource involved in the production process, is a residual value, representing the surplus of revenues from the sale of agricultural products (in the case of application of production-linked payments, increased by revenues from these payments) over the production costs, which include inputs of production factors other than land. This definition of land remuneration is equivalent to the economic outcome.

Based on Figure 1, it can be noted that in the case without production-linked payments, the total remuneration of land at the farm's equilibrium point (E_0) is represented by the area of triangle AE_0B. The value of land rent per unit of land area (homogeneous in terms of agricultural suitability) is symbolized by the vertical distance between the MC curve and the MR_0 curve. The value of land rent decreases as we move rightwards along the horizontal axis, corresponding to the inclusion of land with progressively lower agricultural suitability into the production process. The MC curve lies below the MR_0 curve for land with a sufficient level of agricultural suitability to be profitably involved in production, given the production costs and agricultural product prices.

In the case of the use of production-linked payments, land rent consists of two components: one part financed by the market (covered by revenue from the sale of agricultural products) and another part financed by the state (covered by revenue from payments). For a unit of land area (homogeneous in terms of agricultural suitability), the value of the first component is symbolized by the vertical distance between the MC curve and the MR_0 curve, while the value of the second component is represented by the vertical distance between the MR_0 curve and the MR_1 curve. The total remuneration of land at the new equilibrium point (E_1), which, incidentally, corresponds to a greater land input than in the initial situation ($L_1 > L_0$), is illustrated by the area of the triangle AE_1C. Within this area, the market-financed component is represented by triangle AE_0B and the state-financed component by quadrilateral BE_0E_1C.

To measure the scale of the impact of production-linked payments on the distribution sphere, the following indicators can be used:

- the agricultural subsidization coefficient,
- the coefficient of land rent financing by the state, and
- the payment-to-land rent conversion coefficient.

The presented model allows for a theoretical decomposition of the remuneration of production factors into remuneration from non-land production factors and land rent. For the scenario with production-linked payments, this division can further be separated into the portion financed by the market and the portion financed by the state. The proposed coefficients are structural indicators related to the remuneration of production factors.

4.2.1 Agricultural subsidization coefficient

The agricultural subsidization coefficient is defined as the ratio of the amount of support granted to the total revenue of the farm, which includes revenue from the sale of agricultural products (sourced from the market) and revenue from various state instruments supporting agriculture financially (in the model case under analysis, state support is provided solely in the form of production-linked payments). Therefore, it indicates what portion of the total revenue is derived from state support. In other words, this coefficient shows the percentage of the remuneration of the factors of production involved in agricultural production that is financed by the state.

The agricultural subsidization coefficient (c_{AAs}) is expressed by the formula:

$$c_{AAs} = \frac{PR_V \times V}{TR_1} \times 100\% = \frac{PR_V \times V}{P \times V + PR_V \times V} \times 100\% = \frac{PR_V}{P + PR_V} \times 100\% \quad (1)$$

where:

PR_V – the production-linked payment rate (expressed in monetary units per unit of mass of the produced (and sold) agricultural product, e.g., in EUR/t);

V – the volume of supported agricultural products (expressed in units of mass, e.g., in tons);

TR_1 – the total revenue from the production of a given mass of agricultural products, including revenue from the sale of those products and revenue from production-linked payments (expressed in monetary units, e.g., in EUR);

P – the price of the agricultural product (expressed in EUR/t).

Thus, the agricultural subsidization coefficient is a dimensionless value and can take any value from the closed interval between 0 and 100%. The coefficient equals zero when the remuneration of the factors of production is entirely equivalent to the monetary value of the goods produced, which occurs only when the market is the sole source of financing for inputs. In Figure 1, this situation corresponds to the zero scenario with E_0 as the equilibrium point. However, in conditions where production-linked payments are applied, the value of this coefficient is greater than zero and, under the assumed conditions (the price of the agricultural product and the payment rate being independent of the farm's production volume), remains constant as one moves to the right along the horizontal axis of the coordinate system, accompanied by a decrease in the agricultural usefulness of the land. The insensitivity of this coefficient to land productivity is illustrated by the graph shown in Figure 2 with a dotted line.

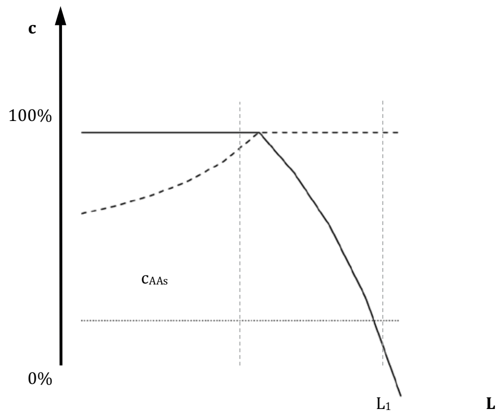

Figure 2. Values of the indicators of the impact of production-linked payments on the distribution sphere, depending on the agricultural suitability of land. Source: Author's own elaboration.

In Figure 1, the value of the agricultural subsidization coefficient for a specific homogeneous unit plot is the ratio of the vertical distance between the MR_0 line and the MR_1 line to the vertical distance between the horizontal axis and the MR_1 line. Meanwhile, the value of this coefficient for a farm at equilibrium point E_1 (i.e., using an amount of land equal to L_1) is the ratio of the area of quadrilateral BDE_1C to the area of trapezoid OL_1E_1C.

4.2.2 Coefficient of land rent financing by the state

Based on Figure 1, it can be stated that production-linked support fully contributes to land remuneration in the case of land that was already being used for agricultural purposes even without this support (up to L_0 inclusive). However, for land that was incorporated into the production process only after the introduction of production-linked payments at rate PR_V (to the right of L_0, up to and including L_1), production-linked support partially contributes to land remuneration and partially to the remuneration of other production factors. It can be observed that, as one moves along the horizontal axis of the coordinate system to the right of L_0, an increasingly smaller part of the support linked to production goes towards the remuneration of land, while the importance of this support in creating the remuneration of labor and capital is growing. This means that, as land productivity declines, the market's share in remunerating labor and capital decreases, while the state's share increases. In the extreme case of the marginal unit plot L_1, production-linked support fully increases the remuneration of labor and capital while the land rent is zero.

To measure what portion of land remuneration is financed by the state, the concept of the coefficient of land rent financing by the state (c_{LRf}) can be introduced, expressed by the formula:

$$c_{LRf} = \begin{cases} \frac{PR_V \times V}{TR_1 - TC} \times 100\% \ for\ L \in \left(0, L_0\right] \\ \frac{TR_1 - TC}{TR_1 - TC} \times 100\% = 100\% \ for\ L \in \left(L_0, L_1\right] \end{cases} \tag{2}$$

where:
PR_V – the production-linked payment rate (expressed in monetary units per unit of mass of the produced (and sold) agricultural product, e.g., in EUR/t);
V – the volume of supported agricultural products (expressed in units of mass, e.g., in tons);
TR_1 – the total revenue from the production of a given mass of agricultural products, including revenue from the sale of those products and revenue from production-linked payments (expressed in monetary units, e.g., in EUR);
TC – total cost, i.e., the inputs of production factors other than land in relation to a given area of land (expressed in monetary units, e.g., in EUR).

Like the agricultural subsidization coefficient, the coefficient of land rent financing by the state is a dimensionless value and can take any value from the closed interval between 0 and 100%. Referring to Figure 1, it can be noted that for unit land L_0 and land to the left of it, the state's share in financing land rent is expressed by the ratio of the vertical distance between the MR_0 line and the MR_1 line to the vertical distance between the MC line and the MR_1 line. This ratio remains constant as one moves to the right along the horizontal axis. For land located to the right of L_0 (up to and including L_1), the state's share in financing land rent is 100% (since, for this land, both the numerator and the denominator of the fraction expressing this share are the same number corresponding to the vertical distance between the MC line and the MR_1 line), although it does not change the fact that, in absolute terms, land rent decreases as one moves to the right along the horizontal axis of the coordinate system. The graph in the form of a dashed line in Figure 2 illustrates how the value of the coefficient of land rent financing by the state changes depending on the agricultural suitability of the land. For the entire farm at equilibrium point E_1 in Figure 1, the state's share in financing land rent is expressed by the ratio of the area of quadrilateral BE_0E_1C to the area of triangle AE_1C.

4.2.3 Payment-to-land rent conversion coefficient

The payment-to-land rent conversion coefficient (c_{LRc}) indicates what portion of the financial support provided by the state contributes to the increase in land rent. This indicator can be expressed by the following formula:

$$c_{LRc} = \frac{\Delta LR}{PR_V \times V} \times 100\% \quad (3)$$

where:
ΔLR – the increase in land rent caused by the introduction of production-linked payments (expressed in monetary units, e.g., in EUR);
PR_V – the production-linked payment rate (expressed in monetary units per unit of mass of the produced (and sold) agricultural product, e.g., in EUR/t);
V – the volume of agricultural products supported (expressed in units of mass, e.g., in tons).

Like the indicators expressed in formulas (1) and (2), the payment-to-land rent conversion coefficient is dimensionless, and its possible values range from 0% to 100%. Based on Figure 1, it can be stated that for land used agriculturally even in the absence of production-linked support (up to and including L_0), the value of this coefficient is 100% (both the increase in land rent and the amount of support paid in relation to production generated on a given unit plot are reflected by the vertical distance between the MR_0 line and the MR_1 line, so the quotient of these two values is one). For land that was incorporated into the production process only after the introduction of production-linked payments at rate PR_V (to the right of L_0, up to and including L_1), this coefficient is expressed by the ratio of the vertical distance between the MC line and the MR_1 line to the vertical distance between the MR_0 line and the MR_1 line. For land within this range, the coefficient is therefore less than 100% and decreases as one moves right along the horizontal axis of the coordinate system, reaching zero for the marginal unit of land L_1. Observing the graph in the form of a solid line in Figure 2, one can see how this coefficient changes depending on the agricultural suitability of the land. The value of the payment-to-land rent conversion coefficient for all land included in the farm at equilibrium point E_1 in Figure 1 can be calculated as the percentage ratio of the area of quadrilateral BE_0E_1C to the area of quadrilateral BDE_1C.

4.2.4 The phenomenon of "Support Capture" and its measurement

In cases where the land user is not the owner, land rent takes the form of lease rent. A consequence of production-linked payments at least partially converting into land rent is the phenomenon of support being "captured" by landowners through raising lease rent or land sale prices accordingly. In the event of a discrepancy between ownership and use of land, the measure of the degree to which production-linked payments are "captured" by landowners is the payment-to-land rent conversion coefficient (c_{LRc}).

The "capturing" of financial support granted to farmers (land users) by landowners is manifested through increased lease rent rates and higher prices for agricultural land, i.e., the capitalization of payments. This occurs when the landowner is not the same as the land user, and when the land is subject to market transactions. "Capturing" the payments involves incorporating part or all of the support into the lease rent (in the case of leasing) or the land price (in the case of sale), as a consequence of the increased discounted revenues from agricultural land due to the application of financial support instruments for agriculture.

The increase in the stream of discounted revenues from production-linked payments (ΔDIS_{VP}) can be calculated using the following formula:

$$\Delta DIS_{VP} = V \times \left(\frac{c_{LRc\,0} \times PR_{V\,0}}{(1+r)^0} + \frac{c_{LRc\,1} \times PR_{V\,1}}{(1+r)^1} + \frac{c_{LRc\,2} \times PR_{V\,2}}{(1+r)^2} + \frac{c_{LRc\,n} \times PR_{V\,n}}{(1+r)^n} \right) \quad (4)$$

where:
V – the volume of agricultural products supported (expressed in units of mass, e.g., in tons);
c_{LRc} – the payment-to-land rent conversion coefficient (a dimensionless quantity);
PR_V – the production-linked payment rate (expressed in monetary units per unit of mass of the produced (and sold) agricultural product, e.g., in EUR/t);
r – the annual interest rate;
(n+1) – the number of years of payment application.

The increase in lease rent for a given year as a result of the introduction of production-linked payments corresponds to the increase in the annual revenue stream caused by the introduction of these payments, whereas the entire increase in the future stream of discounted revenue is capitalized in the land price. Therefore, the first term on the right-hand side of equation (4) represents the theoretical increase in lease rent during the first year of payment application, while the entire sum represents the theoretical increase in land price, assuming the land was sold at the moment the payments were introduced.

The scale and intensity of the "capture" of production-linked payments by landowners depend not only on the predicted future revenue stream from this form of financial support by the potential parties to the agreement (lease or sale). Various institutional factors also play a significant role in this context. In particular, the long-term nature of lease agreements and their inflexibility result in inertia in lease rent rates (Góral and Kulawik, 2015), and legal restrictions on the sale of agricultural real estate may slow down the process of payment capitalization into land prices (Sadłowski, 2017).

5. DISCUSSION

This study aligns with the theoretical research on the economic effects of using various financial support instruments in agriculture, which includes among others the works of Chau and De Gorter (2005), Kilian and Salhofer (2008), and Graubner (2018). The issue of use of production-linked payments remains relevant and important, which stems from the need to determine the potential usefulness of this instrument in addressing current agricultural problems – especially as agriculture operates in an increasingly turbulent environment (Despoudi et al., 2020; Budzyńska and Kowalczyk, 2024). This requires recognizing and quantifying the economic effects of using production support, as well as identifying the conditions for its effectiveness and efficiency in achieving the set objectives. The economic effects of using production-linked payments relate to both the production sphere (influence on the level of engagement and directions of use of production factors in agriculture, the volume and structure of agricultural production, and relative prices of agricultural products) and the distribution sphere (influence on the amount and structure of remuneration for production factors).

The added value of this study is manifested in three dimensions: cognitive, practical, and methodological. The recognition of the mechanism by which production-linked payments stimulate the input of production factors in agriculture and the mechanism by which subsidies granted in the form of production-linked payments are transformed into the remuneration of production factors has cognitive value. The model for transforming production-linked payments into the remuneration of production factors can serve as a starting point for econometric research aimed at predicting the economic effects of regulations introduced under agricultural policy (ex-ante evaluation) and measuring the effectiveness and efficiency of agricultural policy instruments (ongoing or ex-post evaluation). The knowledge obtained from such research facilitates the design of agricultural policy tools and the adaptation of instruments to changing socio-economic conditions or revised political objectives. The study also contributes to the development of terminology concerning the economic aspects of direct payments, which promotes the development of methodology and, consequently, the acquisition of more precise and reliable knowledge.

The limitations of the research result in particular from its theoretical nature, scope and adopted assumptions. The credibility of the formulated statements results from their methodical derivation while demonstrating logical connections of consequences as part of the ongoing reasoning. However, the conclusions resulting from the model were not included in the form of hypotheses in order to be tested using statistical methods and empirical data. The study was limited to the analysis of the effects of financial incentives, while the motivations for production decisions of farms may be more complex. Assumptions about price formation and market structures may preclude the extrapolation of results to agricultural systems with significantly different market realities.

6. CONCLUSIONS

The key conclusions from the theoretical research conducted are as follows:

1. As a result of the application of the direct support system, production factors involved in agriculture generate remuneration exceeding the cash equivalent of agricultural products produced by farms.
2. Production-linked payments encourage both more intensive land use and the cultivation of less fertile or more peripherally located land.
3. The agricultural subsidization coefficient measures the relative level of support, remaining constant when payment rate and agricultural product price are independent of production volume.
4. The state's role in financing land rent grows as land productivity decreases, reaching 100% for marginal land brought into production due to these payments.
5. If payments influence rental rates, landowners "capture" the support, also reflected in land prices; this "capture" is initially limited by rigid rental agreements and legal constraints on land transactions.
6. Unlike area-based support, production-linked payments do not strongly drive rental rate increases but are more susceptible to "capture" by buyers in the supply chain.

Although production-linked payments are not currently used in the CAP, the presented model remains valuable for policymaking in the EU, as CAP revisions or trade agreement renegotiations remain possible. It enables comparisons with other support tools, helping assess their effectiveness under different conditions. Given the increasing instability in agriculture due to economic crises, wars, and rising imports (e.g., from Mercosur), the model can help predict the effects of reintroducing production-linked payments or using them as a temporary stabilization tool. It offers insights into their impact on agricultural markets and farmers' incomes. The issues addressed in the article can serve as inspiration for further multi-faceted research.

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ORCID
TM: 0009-0007-0265-965X
FP: 0000-0002-3667-7115

Expenditure allocation for Rural Development interventions: main trends and patterns in the choices of the Italian Regions under the CAP 2023-2027

Tobia Minuzzo, Francesco Pagliacci*

Department of Land, Environment, Agriculture and Forestry, Università di Padova, Italy
*Corresponding author. Email: francesco.pagliacci@unipd.it

Abstract. The introduction of the new delivery model in the 2023-2027 Common Agricultural Policy increased the decision-making and management autonomy of Member States and their regions when implementing Rural Development policies. Thus, understanding the drivers behind allocation choices for rural development funds is crucial. This study analyses the allocation of rural development funds across Italian regions, considering ex-ante share allocation for different types of Rural Development interventions. A cluster analysis is then performed. Different groups of Italian regions are characterised using the indicators developed within the common monitoring and evaluation framework, the allocation of spending in the previous programming period, and other variables. Four clusters of Italian regions are identified: cluster 1 includes rural regions with low urbanisation, prioritising supporting interventions in disadvantaged areas and "environmental" ones; cluster 2 shows large allocation for cooperation interventions; cluster 3 includes regions funding primarily agricultural investments; cluster 4 shows no distinct or unique characteristics. This study is the first one addressing expenditure allocation of the 2023-2027 Common Agricultural Policy. It confirms that expenditure patterns partially couple with geographical and historical similarities, although two main spending priorities (i.e. "environment" and "investments") persist.

Keywords: EU Rural Development Policy, political economy, cluster analysis, allocation.
JEL codes: D72, O13, Q18.

1. INTRODUCTION

Agriculture has been primarily affected by policy interventions, also in the European Union (EU), where the Common Agricultural Policy (CAP) has represented the cornerstone of the European construction, since the origin of the EU (Groupe de Bruges, 1996; Fusco, 2021). CAP objectives have profoundly changed over time to adapt to the transformations of the agricultural sector and the whole society (De Castro et al., 2020). Today, more than in the past, the main objectives of the CAP are mitigating climate change,

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protecting the environment, landscape and biodiversity, improving the quality and safety of food, social cohesion, and the socioeconomic development of rural areas (Bourget, 2021; European Commission, 2023).

For decades, the CAP has been the most significant EU policy, in terms of budget allocation (De Filippis and Henke, 2010; Matthews, 2017), although its share of the EU budget has halved, from 66% in 1980 to 35% in 2020 (DG Agriculture and Rural Development, 2023). In the current programming period (2023-2027), Italy is the third-largest beneficiary, after France and Spain, of the resources allocated to the CAP from the EU budget (Reg. 2116/2021), receiving 10.5% of the total CAP funds (about 28 billion euros). Just for the Rural Development (RD) Policy, a substantial portion of national funding is added, bringing the total funds for Italy to nearly 37 billion euros. Of this total amount, 48% is allocated to direct payments, while 43% is designated for RD policy (European Commission, 2022).

In the EU, RD Policy has been traditionally managed in a decentralised manner, granting regional autonomy in decision-making and implementations (Dwyer et al., 2007). In Italy, NUTS-2 (*Nomenclature des unités territoriales statistiques*) regions oversee its management, a role reinforced by the new delivery model. It requires Member States (MS) to develop a National Strategic Plan integrating both direct payments and RD Policy (Langlais, 2023). This shift has extended decentralisation to direct payments as well, now aligning under a need-based assessment, obtained through an in-depth regional-level analysis (Barral, 2023). RD interventions are classified into eight groups, and in Italy, 76 interventions have been selected, letting NUTS-2 regions choose implementation and fund allocation.

In this evolving governance framework, it is important to understand how funding decisions are made, in order to evaluate the effectiveness and equity of CAP distribution, helping to inform future policies that promote rural development and sustainability.

This paper investigates territorial differences in allocation of the RD funds, by analysing decision-making processes in Italy within the 2023-2027 CAP programming period. The primary objective is to understand resource allocation patterns and the key determinants of spending across the Italian regions, offering innovative and updated empirical insights compared to previous studies. While regional differences in total allocation may naturally vary due to their different sizes, it is hypothesised that the percentage distribution of funds across interventions types also differs based on regional characteristics and needs. Additionally, regional governments' development objectives and policy priorities may shape these allocation choices (Pagliacci and Zavalloni, 2024).

Stemming from this primary objective, this study also seeks to: i) identify clusters of Italian regions that allocate RD funds in a similar way; ii) examine the main drivers behind these allocation patterns, considering socioeconomic, sectoral and geographical factors.

This research contributes to the literature by explaining how decentralised governance and regional policy-making affect fund distribution, offering valuable policy recommendations for both decision-makers and farmers. Given the new governance model, these insights can enhance the efficacy and fairness of future RD policy.

The rest of the paper is structured as follows. Section 2 shows the theoretical background of this work as well as the characteristics of Italian RD Policy in the 2023-2027 programming period. Section 3 presents the datasets used and the main methods adopted. Section 4 reports the results of the analysis, while Section 5 discusses them. Section 6 concludes by highlighting possible implications and formulating hypotheses for future research.

2. THEORETICAL BACKGROUND

2.1 CAP 2023-2027

The 2023-2027 CAP was definitively approved in 2021. In the same year, the strategic context regulations of the current CAP (namely, the European *Green Deal* with its *"European climate law"* and the *"Fit for 55"* strategy, as well as the *"Farm to Fork"* strategy) were also approved.

The *Green Deal's* main objective is achieving climate neutrality by 2050 in all EU economic sectors, according to the Paris Climate Agreement (UNFCCC, 2015). In addition, it supports the transformation of the EU into a sustainable, fair and prosperous society with a modern and competitive economy, adopting a holistic and cross-sectoral perspective (Zezza, 2023). The package includes initiatives on climate, environment, energy, transport, industry, agriculture, education and research, sustainable finance, etc., all sectors deeply connected.

Among the *Green Deal* commitments with the greatest impact on agricultural policy, there are those relating to the "*From farm to fork*" (European Commission 2020a) and the "EU biodiversity strategy for 2030" (European Commission 2020b). In particular, "*From farm to fork*" was developed with the specific intention of reducing the environmental and climate footprint of the EU food system, setting some strict environmental targets that EU agriculture must achieve by 2030 (Coderoni, 2023). In doing so, it aims to strengthen EU agriculture's resilience, ensuring food security, driving the global transition towards competitive sustainability from farm to fork and exploiting new opportunities (Zezza, 2023).

The current 2023-2027 CAP started on the 1st of January 2023. Despite the traditional path dependency that had characterised CAP history (Sotte, 2023), the current programming period represents a clear break from previous ones. The new delivery model is the new governance system that makes the CAP more result-oriented, stressing the role of performance. Precisely in this perspective, increasing freedom of choice is left to local authorities (*i.e.* national governments, and regional governments), in accordance with the principle of vertical subsidiarity (Bolli et al., 2021).

The new governance model is implemented through National Strategic Plans, developed by each MS after identification of their specific needs. National Strategic Plans outline intervention strategies to achieve EU objectives according to the specific needs of each territory, selecting interventions from a comprehensive range proposed by the Commission, with specific targets and financial plans and after a negotiation phase with the Commission itself. This significantly enhances subsidiarity, allowing MSs to determine how to achieve EU objectives through the National Strategic Plans (Carey, 2019; Matthews, 2021).

The paradigm shift has simplified EU activities but has increased management complexity for MS, particularly in a country like Italy, where both the national and regional governments compete on agricultural policies. However, this shift has led to more targeted and tailored interventions.

The European Commission approved the National Strategic Plan for Italy on 2 December 2022. It establishes a uniform national strategy for the agricultural, agri-food and forestry sectors, managing resources and support from the European Agricultural Guarantee Fund and the European Agricultural Fund for Rural Development (EAFRD). The Strategic Plan provides interventions for direct payments, sectoral support and RD interventions, with a total financial allocation available to the agri-food and forestry sector and rural areas of almost 37 billion euros for the five-year period 2023-2027. The entire financial envelope must pursue the objectives of the CAP. The resources allocated to RD policy come from the EAFRD, which is increased by 55% of national co-financing.

For RD Policy, there are 76 interventions, but four of them refer to risk management and are managed at national level (as in the previous programming period). For remaining RD interventions, Italy decided to implement a management strategy that provides for national interventions with regional elements. Therefore, regional governments plan and manage RD interventions, adapting them to their economic, social and territorial specificities. These RD interventions are implemented through the definition of Regional Programming Complements for RD. They neither contrast with the National Strategic Plan nor add further choices, but detail how the general national strategy has declined at regional level, highlighting which interventions the Region will finance, fund allocation for each of them, and specific conditions relating to each intervention.

In Italy, selected RD Policy interventions belong to eight types (Table 1):

A. environmental, climate and other management commitments (Agro-climatic-environmental interventions);
B. natural or other specific territorial constraints;
C. specific territorial disadvantages resulting from certain mandatory requirements;
D. investments, including investments in irrigation;
E. setting up young farmers and new farmers and starting rural businesses;
F. risk management tools;
G. cooperation;
H. exchange of knowledge and dissemination of information.

A smaller amount of the EAFRD financial resources is also allocated to activities related to Technical Assistance.

Despite the large MS autonomy in resource allocation, the European Commission introduced some financial constraints (ring-fencing), *i.e.* minimum fund allocations that MSs must guarantee for specific types of intervention, in order to pursue the strategic objectives of the Union. The heaviest one refers to agri-environmental measures, which must represent at least 35% of expenditure for RD policy.

Among the eight RD types of intervention, as shown in Table 1, those that have recorded the largest fund allocation are: agro-climatic and environmental ones and investments, respectively accounting for 28.9% and 26.7% of total resources. Moreover, 18% is reserved for risk management measures (Table 1).

2.2 Literature review: ex-ante *and* ex-post *expenditure determinants for RD*

Previous literature mainly focused on *ex-post* investigations on the implementation of agricultural policies, aiming at understanding how government interventions have affected the agricultural sector over time (Ander-

Table 1. Types of intervention envisaged for the RD policy by the Italian National Strategic Plan and related financial allocation.

Type of intervention	EAFRD resources allocated (EUR million)	% EAFRD
A. Agro-climatic-environmental interventions	2099.42	28.92
B. Natural or other specific territorial constraints	6664.71	9.16
C. Specific territorial disadvantages resulting from certain mandatory requirements	14.30	0.20
D. Investments, including investments in irrigation	1937.72	26.69
E. Setting up young farmers and new farmers and starting rural businesses	339.97	4.68
F. Risk management tools	1287.86	17.74
G. Cooperation	591.24	8.14
H. Exchange of knowledge and dissemination of information	96.79	1.33
I. Technical support	188.14	2.59

Source: authors' elaboration on National Rural Network data (2022).

son et al., 2013). However, very little was said about what affects the allocation of funds within agricultural policies during the planning phase (Fredriksson and Svensson, 2003). For example, Fałkowski and Olper (2014) addressed the role of electoral incentives, Bellemare and Carnes (2015) focused on the personal preferences of legislators, Olper et al. (2014) addressed the pressures from interest groups and institutional contexts, while Pelucha et al. (2016), showed that RD Policy in the Czech Republic was not implemented in accordance with the socioeconomic goals of territorial cohesion.

Referring to ex-post fund allocation, Shucksmith et al. (2005) for the first time tried to assess the impact of the Rural Development Policy at territorial (i.e. regional) level, asking the question of how far CAP expenditure is compatible with objectives of territorial cohesion across the enlarged EU and consistent with the goals of the EU Spatial Development Perspective.

Later, Camaioni et al. (2016) focused on the CAP resource allocation considering NUTS-3 level regions. According to them, allocation is the joint result of top-down policy decisions and bottom-up ability of territories to attract available funds. Thanks to an *ex-post* econometric analysis on the 2007-2013 RD expenditure, they identified three major drivers for expenditure allocation, which include a "pure spatial effect" (i.e. the influence of the surrounding space on the allocation of RD expenditure) and a negative rurality effect (i.e. the less rural the region, the greater the intensity of spending).

Bonfiglio et al. (2017) analysed the main territorial models of the effective spatial (*ex-post*) allocation of CAP expenditures by considering knowledge transfer and innovation (KT&I) measures only into the 2007-2013 CAP RD. They confirm that the economy's structure plays an important role in such a spatial allocation.

Considering the same 2007-2013 programming period, Uthes et al. (2017) also compared the data of the Common Monitoring and Evaluation Framework (CMEF) and the RD policy expenditure levels at NUTS-2 territorial level across the EU. The authors highlighted four different patterns of expenditure allocation, distinguishing the EU regions into four groups: Competitiveness, Environment, Rural Viability, Equal Spending. They were established considering the percentage distribution of RD expenditure among Axes, as provided for in the 2007-2013 CAP. Among the selected groups, the largest difference was observed between regions in the *"Competitiveness group"* and those in the *"Environment group",* the latter one having a larger share of arable land and less permanent grassland, a smaller physical and economic farm size, greater workforce, less land in less favoured areas, a higher share of extensive arable land and a lower share of extensive grazing. On the contrary, the regions of the *"Environment group"* also show a higher proportion of UAA within natural areas. Uthes et al. (2017) once again demonstrate the feasibility of identifying expenditure patterns and validate the use of CMEF indicators in explaining them. Most importantly, their findings highlight a strong coherence between spending priorities, regional needs and development prospects.

Zasada et al. (2018) focused on European regions with above-average expenditures for natural capital measures within RD Policy in the 2007-2011 period. They aim to understand the drivers behind such spending priorities related to local socioeconomic and agricultural contexts. The analyses identified six different spending patterns for European regions. The results show that the adoption of natural capital-oriented spending models is only partially influenced by environmental and agricultural factors, with a higher incidence of larger farms and regions with high purchasing power and population density. However, a weak correlation exists between natural capital investments and ecologically significant areas such as Natura 2000 sites or High Nature Value farmland. This shows that these areas don't receive enough funds. Socioeconomic and agricultural indicators have limited influence, reflecting criticisms about the RD Policy's lack of attention to local needs (Copus and Dax, 2010; Piorr and Viaggi, 2015).

Lastly, Pagliacci and Zavalloni (2024) investigated the factors that influence the allocation of funds for some specific objectives of the CAP (i.e. environmental objectives), considering the European 2014-2020 RD. Compared to previous articles, which mainly analysed the *ex-post* determinants, they mostly focused on the determinants behind the decision-making process. Their results suggested that per capita GDP and population density positively correlate with higher environmental support, whereas greater decentralisation of the management of funds (i.e. at regional and not at national level) is negatively correlated with environmental support. Therefore, Pagliacci and Zavalloni (2024) suggested that maintaining central control over the financial allocation could promote greater environmental sustainability in the agricultural sector.

However, to the authors' best knowledge, no studies have yet addressed the 2023-2027 CAP.

3. DATA AND METHODS

3.1 Methods

This study applies quantitative analyses to understand the distribution of RD expenditure in Italian regions. Firstly, a cluster analysis is conducted considering 21 NUTS-2 level regions in Italy, *i.e.* 19 Italian *Regioni* and 2 *Province Autonome*[1]. A hierarchical clustering is applied to a set of input variables that refer to RD expenditure allocation (see section 3.2), and that are preliminarily standardised. For the cluster analysis, Euclidean distance and Ward's method are used to determine distance between statistical units and clusters (Ward, 1963; Murtagh and Legendre, 2014). In particular, the Ward's method aims to minimise the variance within each cluster by merging the clusters that minimise the increase in the total sum of squared distances. Despite its strengths, which make it particularly suitable when clusters show different sizes and densities, the Ward's method might be sensitive to outliers, leading to biased results if there are non-random patterns of missing data or if the underlying assumptions of normality and equal variances are violated (Ward, 1963).

Having selected a hierarchical cluster analysis, the choice of the number of clusters is defined *ex post*, under the well-known trade-off between the number of clusters considered and their homogeneity. The cluster analysis is conducted using the R software (R Core Team, 2024), and "fpc" package (Hennig, 2024).

After clustering, group description is done by submitting clustering variables to ANOVA (analysis of variance) to find significant differences among the clusters. Subsequently, a Tukey HSD (Honest Significant Differences) test is also conducted to verify which clusters differ significantly from each other (Yandell, 1997). The results of these two tests are used to support cluster labelling.

Then, a further phase of the work aims to verify whether regions belonging to the same cluster also show other similarities at structural level, *i.e.* considering other descriptive variables, such as: socioeconomic, sector-based (i.e. agriculture) and environmental variables. This analysis is accomplished by performing an ANOVA test for each variable to verify if at least one cluster behaved differently from the others, and then a Tukey HSD test to identify which one(s) differ from each other.

As a final stage of our investigation, and in order to further characterize the identified clusters and explore potential correspondences between planned expenditure and characteristics of the Italian regions, a correlation analysis is conducted. Correlation coefficients are calculated between share of funds allocated to various types of interventions and CAP context indicators (CMEF), but also allocation of public resources during the previous 2014–2022 programming period (see Section 3.2). The choice of CMEF indicators, raw data and territorial subdivision of the analysis (NUTS2) is inspired by Uthes et al. (2017), although they referred to a previous programming period.

Correlation analysis is carried out using Spearman's method, after verifying that the assumption of linearity is hardly met. All analyses are performed using R (R Core Team, 2024).

3.2 Data

3.2.1 Input Variables for cluster analysis

Cluster analysis is grounded on input data that encompass the shares allocated by each region to each type of intervention in the 2023-2027 CAP out of the

[1] According to the Italian Constitution, Article 116, second *comma*, Trentino-Alto Adige/Südtirol region is composed of the Autonomous Provinces of Trento and Bolzano. These provinces are equated to other special statute regions (*Regioni a statuto speciale*). Thus, NUTS-2 regions in Italy include both *Regioni* and *Province Autonome* and also the 2 *Province Autonome* manage RD policies separately and autonomously.

Table 2. Overview of input variables for cluster analysis of RD interventions across Italian NUTS-2 regions.

NUTS-2 Regions	Clustering variables									
	A. Agro-climatic-environmental (%)	B. Nature & territorial constraints (%)	C. Specific disadvantages (%)	D. Investments (%)	E. Young farmers (%)	G. Cooperation (%)	H. Knowledge (%)	Technical assistance (%)	Total (EUR million)	Number of interventions
ITF1-Abruzzo	36.30	12.79	0.29	27.92	7.56	9.26	2.33	3.55	343.90	33
ITF5-Basilicata	31.96	9.93	0.00	36.59	8.17	8.90	1.14	3.31	452.94	37
ITH20-Bolzano	39.36	35.86	0.00	11.16	6.62	6.49	0.18	0.33	271.87	18
ITF6-Calabria	42.29	3.84	0.00	35.69	5.12	8.85	0.90	3.31	781.29	39
ITF3-Campania	33.32	15.62	0.00	31.79	3.76	11.79	0.98	2.75	1149.61	35
ITH5-Emilia-Romagna	35.71	11.17	0.39	30.93	6.77	10.32	2.18	2.53	913.22	45
ITH4-Friuli-Venezia Giulia	33.75	11.05	0.88	37.57	5.30	7.12	1.24	3.09	226.25	29
ITI4-Lazio	33.42	8.74	1.16	27.56	10.78	13.90	1.12	3.32	602.06	31
ITC3-Liguria	17.12	5.20	0.52	54.75	8.40	8.36	2.33	3.31	207.04	48
ITC4-Lombardy	17.79	11.12	0.00	49.44	4.58	10.66	3.79	2.62	764.50	39
ITI3-Marche	34.75	11.49	0.20	34.08	3.53	10.45	3.45	2.05	390.88	38
ITF2-Molise	36.27	18.63	0.00	27.14	5.07	5.00	4.32	3.57	157.71	21
ITC1-Piedmont	34.70	5.71	0.79	35.46	5.29	12.18	2.70	3.17	756.40	50
ITF4-Puglia	35.91	1.27	0.00	41.04	4.22	12.74	1.50	3.31	1184.88	41
ITG1-Sardinia	39.88	20.26	0.00	26.24	4.88	7.64	0.49	0.62	819.49	30
ITG2-Sicily	46.54	15.78	0.00	21.56	6.81	7.09	0.52	1.70	1467.61	30
ITI1-Tuscany	37.61	7.51	0.40	33.51	6.61	11.07	2.30	0.99	748.81	54
ITH10-Trento	21.94	25.13	0.00	35.93	6.07	7.36	0.55	3.02	198.96	17
ITI2-Umbria	31.44	6.07	0.29	40.63	2.51	14.61	1.45	3.01	518.60	44
ITC2-Valle d'Aosta	35.42	33.64	2.18	17.69	1.09	8.43	0.63	0.92	91.85	27
ITH3-Veneto	25.09	10.91	0.85	38.95	8.56	9.93	3.58	2.13	824.56	44

Source: authors' elaboration on National Rural Network data (2022).

total RD expenditure. As mentioned above, RD Policy is jointly funded by the EU and the MS. For the analysis, the overall allocation of public resources is considered, according to the 8-group taxonomy already shown in Table 1. As Risk Management Tools are managed at national central level, they are not considered.

In addition to the seven types of intervention, three additional input variables are added: i) share of expenditure allocated to "technical assistance"; ii) total allocation of RD expenditure; iii) number of different activated interventions (as a proxy for heterogeneity of interventions at regional level)[2]. Table 2 shows summary statistics for input variables.

3.2.2 *Other variables: CMEF and RD expenditure in the previous programming period*

The analysis includes an additional set of variables. The CAP context indicators in the CMEF are developed by the European Commission to evaluate the results of the CAP and examine fund allocation. There are 45 main indicators, each of them with multiple sub-indices. Almost all of them are available at NUTS-2 level, hence being useful for this analysis. Twelve cross-cutting socio-economic indicators allow regions to be framed jointly (e.g., population, population density, employment rate). Moreover, there are eighteen sectoral indicators, specific to the agricultural sector, and fifteen environmental indicators, which are useful to understand environmen-

[2] Other cluster analyses have been performed, considering different input variables (e.g., including total amount allocated by each region to each type of intervention, instead of the related shares; or removing amount of total expenditure; or removing the number of different interventions). Results among different alternatives are largely comparable, and they are available upon request. However, after careful comparisons, the set of input variables described in the text has been considered. This is due to the observed dendrogram and considering the combination of input variables that demonstrate the greatest statistically significant differences among clusters.

tal conditions of regions, the strategies implemented for its protection as well as the impacts of the agricultural sector on the environment. The selected sources for these indicators are the following: EUROSTAT; Farm Accountancy Data Network (FADN); European Environmental Agency (EEA); CORINE Land Cover (CLC); DG Agriculture and Rural Development; Natura 2000 Barometer Statistics Report and Joint Research Centre (JRC Ispra). The most recent indicators available have been updated in June 2020. For those indicators that show poor updates, data from ISTAT website (https://www.istat.it/) are retrieved and used.

Given that they refer to a period which is previous to the start of the current programming period, they are not affected by spending choices, hence they can be used in this analysis.

Lastly, expenditure allocations in the previous 2014-2022 CAP programming period is also considered, breaking them down by priority of intervention and technical assistance, both in absolute and percentage terms.

This broad set of variables is used to: i) characterise and provide proper labels to the clusters of regions (e.g. in order to verify the presence of similar characteristics for the regions belonging to the same cluster); and ii) assess the existence of correlations between these additional variables and the percentage allocation of funds across RD interventions, in the Italian regions.

4. RESULTS

Figure 1 displays the results of hierarchical clustering through a dendrogram. Observing its structure, it is possible to highlight, as a best partition option, a four-cluster partition for the Italian NUTS-2 level regions.

Clusters have different size as well as different average characteristics (Table 3). The smallest group consists

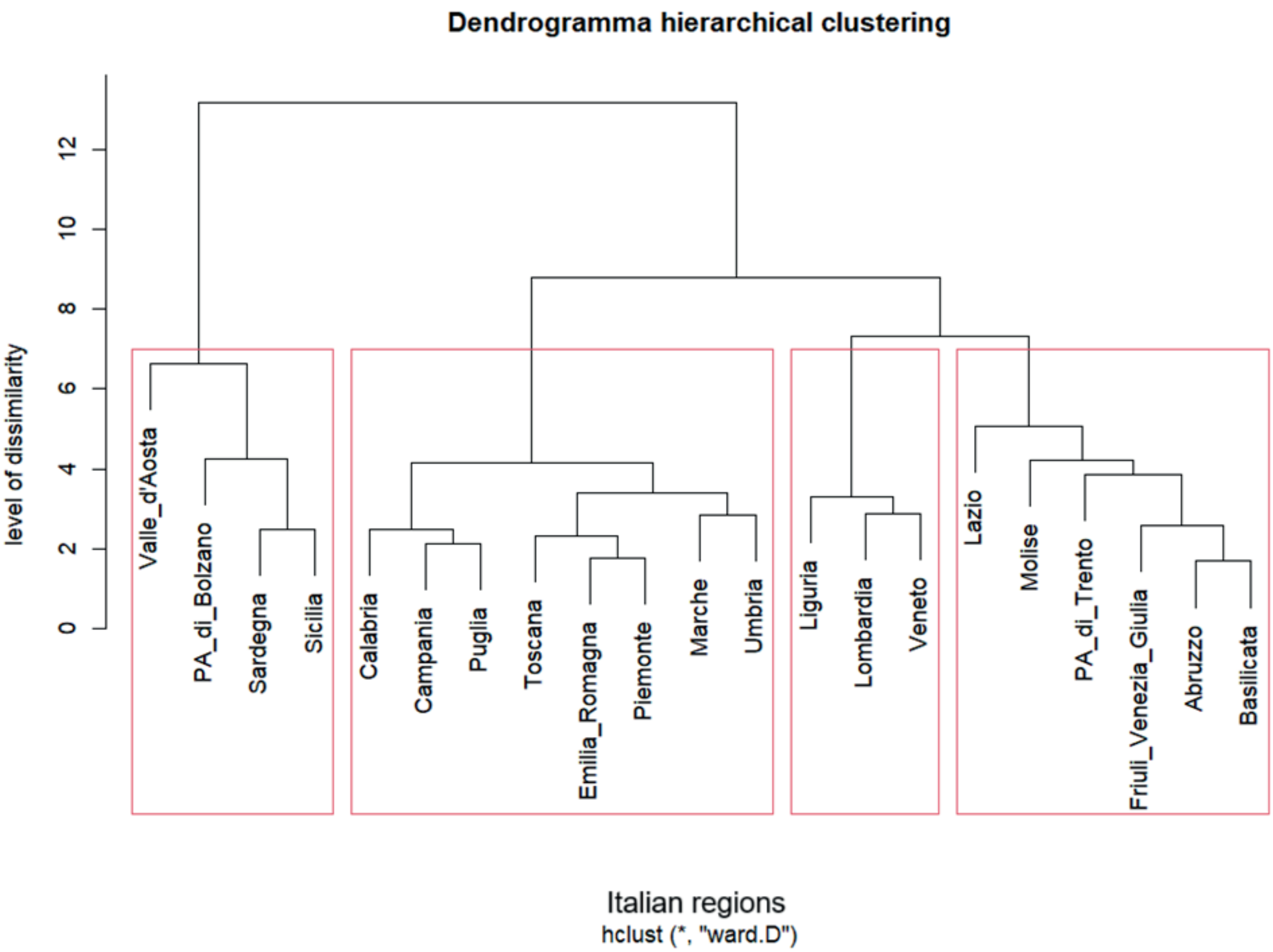

Figure 1. Dendrogram of the Italian regions, hierarchical clustering with Ward's method. Source: authors' elaboration, software R (R Core Team, 2024).

Table 3. Composition of the four clusters: regions and autonomous provinces and average values of the clustering variables.

	Cluster				
	1 Regions with disadvantages	2 Cooperation regions	3 Investment regions	4 Equal spending regions	Average value (Italy)
	PA di Bolzano Sardegna Sicilia Valle d'Aosta	Calabria Campania Emilia-Romagna Marche Piemonte Puglia Toscana Umbria	Liguria Lombardia Veneto	Abruzzo Basilicata Friuli-Venezia Giulia Lazio Molise PA di Trento	
A. Environment (%)	40.30	35.72	20.00	32.27	32.07
B. Nature & territorial constraints (%)	26.39	7.84	9.08	14.38	14.42
C. Specific disadvantages (%)	0.55	0.26	0.46	0.39	0.41
D. Investments (%)	19.16	35.39	47.71	32.12	33.60
E. Young farmers (%)	4.85	4.73	7.18	7.16	5.98
G. Cooperation (%)	7.41	11.50	9.65	8.59	9.29
H. Knowledge (%)	0.46	1.93	3.23	1.78	1.85
Technical Assistance (%)	0.89	2.64	2.69	3.31	2.38
TOT (EUR million)	662.7	805.46	598.70	330.3	599.29
Number of Interventions	26.25	43.25	43.67	28.00	35.29

of just three regions, while the largest one includes eight regions. Figure 2 maps the clusters in Italy.

Thanks to the ANOVA and Tukey HSD tests, the clustering input variables are analysed to identify those that contribute most to the identification of each cluster. It is important to note that the limited number of statistical units, in relation to the four clusters, might have reduced the ability to detect statistically significant differences between them. The results of these analyses are reported in Annex A, which displays boxplots for each of the selected input variables.

The results of the ANOVA suggest no significant differences between the four clusters regarding the percentage allocation of "Specific disadvantages" interventions, "Young farmers" interventions and the overall allocation of RD Policy funds. Thus, the analysis of the four clusters is based on the remaining seven variables.

Cluster 1 is labelled as "regions with disadvantages". It shows a significantly higher-than- average allocation for "Nature & territorial constraint" interventions (support to areas with natural disadvantages or other specific constraints), equal to 26.39%. Cluster 1 also has the highest allocation level in agro-climatic-environmental interventions, equal to 40.30%, and the lowest allocation in investment interventions.

Cluster 2 is named as "cooperation regions". It has the highest allocation for interventions related to cooperation in agriculture. On the other hand, it shows an average allocation for agro-climatic-environmental interventions, investment-related ones and those for knowledge and information exchange (AKIS). Cluster 2, together with cluster 3, is also the one that activated the largest number of interventions, about 43.

Cluster 3 is labelled as "investment regions", being characterised by a significantly higher allocation of funds to the interventions for investments. They are almost equal to 50% of the total allocation. The allocation for "exchange of knowledge and information" interventions is also higher than the average (3.23% vs. 1.85%). On the other hand, there is substantially less commitment to agro-climatic-environmental interventions, to which only 20% of resources are dedicated, half of what cluster 1 allocates and about 12% less than the average.

Cluster 4 includes "equal spending" regions, i.e. those regions not showing significant differences compared to the other three clusters. In this cluster, types of intervention show values close to the general average, with deviation usually less than one percentage point. However, it is clear that the regions of this cluster planned "smaller" budgets than the other regions, they allocate the lowest budget and also activate the fewest interventions (this can be deduced from the visual comparison of the medians in the boxplots, Tukey's HSD test did not show significant differences between the four clusters).

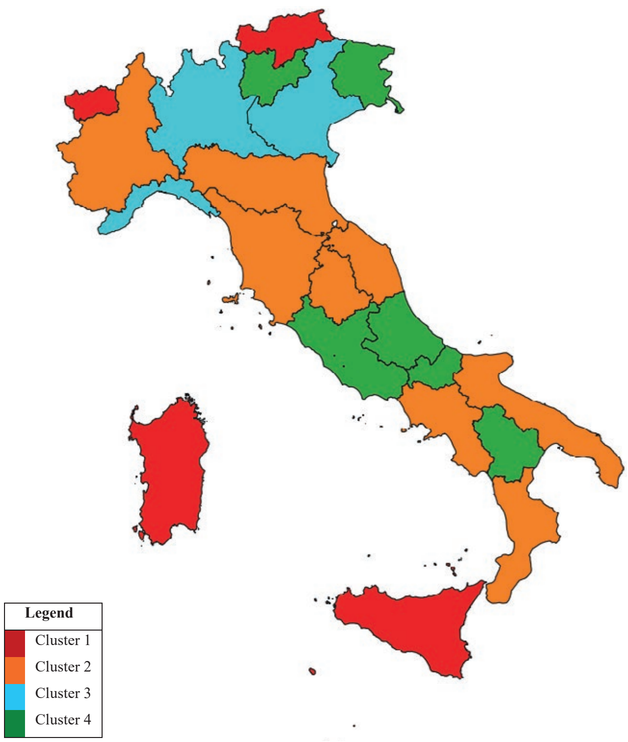

Figure 2. The four clusters of Regions and PA. Source: authors' elaboration, QGIS software (QGIS Development Team, 2024).

To further expand cluster classification, it is possible to identify the statistically significant differences among clusters and the additional CAP context indicators. Of the large set of variables, 20 of them have proven to be helpful for characterization (see Annex B for some boxplots of the variables that show significant differences between the clusters). In what follows, there is a brief description of each cluster, under these additional covariates.

The regions included in cluster 1 are characterised by an extremely higher endowment of semi-natural areas (31.05% on average, but with a large standard deviation, equal to 13.79%) than the other clusters. Consequently, it is also the group with the lowest share of urbanised areas (only 2.79%, compared to an average of 4.91) (Annex B). This is coherent with low population density (95 inhabitants/km^2), significantly lower than the general average (196 inhabitants/km^2). Cluster 1 also has a very high share of employment in the tourism sector (9.89% ± 2.28%), which is higher than the Italian average (7.10%). Finally, the regions belonging to cluster 1 appear to be those with the greatest involvement of young farmers in the management of farms. Indeed, 12.19% of companies are led by farmers under 40, while the average value is 8.70%. This is also confirmed by the consequent lower number of farm managers over 55, who represent only 55.49% of the total (but with a large standard deviation, 7,40%).

Cluster 2 does not show specific elements of difference. One item, however, appears worthy of interest: female employment in agriculture. The total and male non-family workforce does not show differences compared to the other clusters. In contrast, for the female workforce the difference is great both in absolute (Annual Work Units – AWUs) and relative terms. In cluster 2, 19.42% of the total workforce are women (although its standard deviation is 13.48%), while the Italian average is just 9.39%.

Cluster 3 has the highest population density: 338 inhabitants/km^2 (compared to an average of 196 inhabitants/km^2 in Italy). This value is significantly higher than the one observed in clusters 1 and 4 (for this variable, the Tukey HSD output is statistically significant). Cluster 3 is also the group with the most urbanized regions, with 8.81% of its area characterised by urban surface, compared to only 6.21% of the area covered by semi-natural areas, below the average of around 10.37%. The presence of manufacturing companies is therefore large, and this is confirmed by the number of employees in the secondary sector, twice as high as the Italian average, and by all the other economic indices. The agricultural sector follows a similar trend. Cluster 3 shows the largest share for irrigated/irrigable area (56.70% of the total, but with standard deviation of 17.52%), amount of fertilisers distributed and also livestock units. All these are indicators of the high level of specialisation and productivity of farms in these regions. In this way, the percentage of farms of large economic size is significant. Companies between 250,000 and 499,999 EUR in turnover represent 4.17% of the total, the Italian average does not reach 1.80%.

For cluster 4, as observed in the cluster labelling phase, no distinctive features emerge compared to the general average of the Italian regions. The average population density is 142 inhabitants/km^2, the regional territory is covered by 7.29% of semi-natural areas (but with large standard deviation, equal to 6.23%) and 4.02% of artificial areas. 5.24% of the population is employed in the primary sector, 22.08% in the secondary sector and 72.68% in the tertiary sector.

As a conclusive test, the analysis of correlation coefficients suggests that demographic variables, economic variables, characteristics of the agricultural sector, and the allocation of funds in the past programming period correlate with current RD expenditure allocation.

On the contrary, total expenditure is positively correlated with total population and population density, as expected. Moreover, more populous regions allocate more funds to investments but less funds to address natural constraints. At the same time, there is a negative correlation between "Natural or other specific territorial constraints" interventions and urbanisation rate. Conversely, larger shares for semi-natural or protected areas couple with larger shares of funds, for interventions for Natural or other specific territorial constraints.

Referring to the economic variables, there is a positive correlation between per capita GDP and the total allocations of funds. Total labour productivity is negatively associated with Agro-climatic-environmental interventions, while it is positively correlated with the funds for natural disadvantages. Regions with larger farms allocate more funds for investment but less for environmental interventions. A more detailed overview of the correlation analysis is reported in Table 4.

Lastly, the distribution of funds between the 2014-2022 and 2023-2027 programming periods shows continuity in priorities, with a focus on farm competitiveness and over environmental measures (Table 4).

5. DISCUSSION

The analysis of the allocation of RD Policy expenditure in Italy, in the 2023-2027 programming period, seems to confirm the results of previous studies on similar topics. The territorial imbalances produced by the CAP and its – at least partial – inconsistency with the EU's cohesion and convergence objectives have already been debated (see for example Esposti, 2007; 2011). Moreover, many studies have investigated how little "rural" the allocation of RD Policy spending is, in fact supporting less rural regions compared to what is stated in its political intentions (Camaioni et al., 2013; Shucksmith et al., 2005; Crescenzi et al., 2011). Similarly, such a trend also seems to be confirmed by this study, as shown by the correlation analyses conducted. If it is reasonable to expect a positive correlation between total expenditure allocation and the total amount of people living in each region, or their regional area, since larger regions can correspond RD Policy with higher budget, it is much more complex to justify the existence of a positive correlation between total expenditure and three major indicators of the presence of a larger urban population: population density (inhabitant/km^2), population in urban areas (% total) and the share of urban territory (% total). It can be deduced that, also in the 2023-2027 programming period, urban regions, also due to their likely better administrative capacity (Charron et al., 2021), were more successful in attracting RDP funds, thus feeding a counter-selection mechanism that has already been verified in the past.

However, when dealing with the allocation of RD Policy budget across regions, and in order to identify which Italian regions share similar spending behaviours, the results of the hierarchical cluster analysis seem inconsistent from a geographical point of view, with neighbouring regions showing different patterns. Nevertheless, if one looks at the structure of the dendrogram at a deeper level, some geographical coherences can be found. It is possible to identify micro-clusters of regions that spend in a similar way and are also neighbours. For example, the cluster 2 "cooperation regions" can be divided into two further sub-groups of neighbouring regions: on the one hand, Piedmont, Emilia-Romagna, Tuscany, Umbria and Marche; on the other, Puglia, Campania and Calabria. This further segregation of the dendrogram turns into greater similarity in expenditure allocation within the two subgroups. Also, within cluster 1 it is possible to identify a sub-cluster composed of the two Italian islands: Sicily and Sardinia. The same applies to clusters 3 and 4 even if the phenomenon is less clear.

This could eventually suggest the existence of something similar to a "local agglomeration effect" (already identified by Camaioni et al., 2016) even at NUTS 2 level for Italy. According to this, neighbouring regions with high RD Policy support also tend to induce more support in the region in question and *vice versa*. The phenomenon had been studied at a more detailed level of disaggregation (NUTS 3, compared to NUTS 2 in this study) and over a more extended programming period in past studies, e.g., the one by Camaioni et al. (2016) and by Crescenzi et al. (2011). Nevertheless, it is important to highlight the added value of the current study. Indeed, it confirms similar results, also when considering ex-ante fund allocation and even under the current 2023-2027 programming period. This is true even though the current programming period is characterised by a new governance system, i.e. the new delivery model.

Moreover, when identifying the determinants of the expenditure behind clusters, it is possible to understand the regional structural characteristics that led to those specific allocation choices.

Similar analyses have been conducted in the past, referring to previous programming periods. The clustering made by Uthes et al. (2017) has many similarities with this one, even though more than ten years and two programming periods have passed. They traced all Italian regions into two groups: Veneto, Liguria and Friuli Venezia-Giulia to the "Competitiveness" group while all the others to the "Environment" group. It is interesting to see that Veneto and Liguria were assigned to the group of "Competitiveness" regions, as it is the case in the present study. However, in this study, given the

Table 4. Spearman's correlation coefficients between 2023-2027 RD interventions allocation and CMEF indicators and past funds allocations (p-values in parentheses).

	Descriptive variables	Unit	RD interventions 2023-2027									
			A. Agro-climatic-environmental (%)	B. Nature & territorial constraints (%)	C. Specific disadvantages (%)	D. Investments (%)	E. Young farmers (%)	G. Cooperation (%)	H. Knowledge (%)	Technical Assistance	TOT	Number of Interventions
Demographic variables	Regional surface	ha	-	-	-	-	-	0.387 (0.084)	-	-	0.847 (0.000)	0.456 (0.038)
	Total population	1000 inhab.	-	-0.371 (0.098)	-	-	-	0.526 (0.016)	-	-	0.804 (0.000)	0.486 (0.026)
	Population density	Inhab/km²	-	-0.443 (0.046)	-	0.408 (0.068)	-	0.494 (0.024)	0.385 (0.085)	-	0.547 (0.011)	0.499 (0.021)
	Urban area	% total	-	-0.454 (0.039)	-	-	-	-	-	-	0.482 (0.027)	0.439 (0.047)
	Population Urban area	% total	-	-0.482 (0.027)	-	-	-	0.408 (0.067)	-	-	0.457 (0.037)	0.426 (0.054)
Economic variables	Regional protected area	% total	-		0.443 (0.044)	0.425 (0.055)	-0.382 (0.087)	-	-	-	-0.402 (0.07)	-0.397 (0.075)
	GDP per capita	EUR/inhab	-	-0.386 (0.085)	-	-	-	0.519 (0.017)	-	-	0.651 (0.002)	0.563 (0.008)
	Primary sector GVA	% total	0.568 (0.008)	-	-0.729 (0)	-	-	-0.404 (0.071)	-	-	-	-
	Secondary sector GVA	% total	-0.416 (0.062)	-	-	-	-		0.561 (0.008)	-	-	-
	Total employment	1000 persons	-	-0.416 (0.062)	-	-	-	0.558 (0.01)		-	0.691 (0.001)	0.59 (0.005)
	Employed in primary sector	1000 persons	-	-	-	-	-	0.449 (0.042)		-	0.936 (0)	0.382 (0.087)
	Employees in the secondary sector	1000 persons	-	-0.391 (0.081)	-	-	-	0.596 (0.005)	0.45 (0.041)	-	0.645 (0.002)	0.622 (0.003)
	Employed in tourism	% total	-	0.449 (0.042)	-	-	-	-	-0.531 (0.013)	-0.47 (0.032)	-	-
	Unemployment rate 15- 74 years old	% total	-	0.374 (0.096)	-	-	-	-	-	-	0.391 (0.08)	0.388 (0.083)
	Annual working unit	AWU	-	-	-	-	-	0.427 (0.055)	-	-	0.947 (0.000)	0.39 (0.081)
	Total Labour Productivity	EUR/person	-0.422 (0.058)	-	0.433 (0.05)	-	-	-	-	-	-0.447 (0.044)	-
	Labour Productivity in Primary sector	-	-0.381 (0.09)	-	-	-	-	-	-	-	-	-
	Labour Productivity in Secondary sector	-	-0.488 (0.026)	-	-	-	-	-	-	-	-0.438 (0.049)	-
	Large companies (EUR 250,000-499,000)	% of total	-0.423 (0.057)	-0.374 (0.096)	0.397 (0.074)	0.448 (0.043)	-	-	0.421 (0.057)	-	-	0.571 (0.007)
Sectoral variables	Agricultural holding	N.	-	-0.399 (0.074)	-	-	-	0.427 (0.055)	-	-	0.918 (0.000)	0.382 (0.087)
	SAT	ha	-	-	-	-	-	0.37 (0.099)	-	-	0.890 (0.000)	0.393 (0.078)
	UAA	ha	-	-	-	-	-	0.408 (0.068)	-	-	0.912 (0.000)	0.389 (0.081)
	Organic area	% total UAA	0.486 (0.027)	-	-	-	-	-	-	-	0.486 (0.027)	-
	Irrigated and irrigable areas	% total UAA	-0.371 (0.098)	-	-	-	-	-	-	-	-	-
	Arable land	% of total UAA	-	-	-	0.403 (0.071)	-	0.451 (0.042)	0.676 (0.001)	-	-	0.514 (0.017)
	Permanent grassland and meadow	% of total UAA	-	0.439 (0.048)	-	-0.41 (0.066)	-	-0.486 (0.027)	-0.529 (0.014)	-	-0.566 (0.008)	-0.597 (0.004)
	Permanent crops	% of total UAA	-	-0.487 (0.027)	-	-	-	-	-	0.433 (0.05)	-	-
	Companies with a young and graduate leader	% total	-	-0.47 (0.031)	-	0.387 (0.083)		0.452 (0.04)	0.511 (0.018)	-	-	0.517 (0.016)

(Continued)

Table 4. (Continued).

	Descriptive variables	Unit	RD interventions 2023-2027									
			A. Agro-climatic-environmental (%)	B. Nature & territorial constraints (%)	C. Specific disadvantages (%)	D. Investments (%)	E. Young farmers (%)	G. Cooperation (%)	H. Knowledge (%)	Technical Assistance	TOT	Number of Interventions
Past funds	Priority 1 - Fostering knowledge transfer and innovation in agriculture, forestry and rural areas	-	-	-	-	-	-	-	-	-	-	-
	Priority 2 - Enhancing the viability and competitiveness of all types of agriculture, and promoting innovative farm technologies and sustainable forest	-	-0.409 (0.067)	-	-	0.606 (0.004)	-	-	0.416 (0.06)	-	-	-
	Priority 3 - Promoting food chain organisation, including processing and marketing of agricultural products, animal welfare and risk management in agriculture	-	-	-	-	-	-	0.499 (0.023)	-	-	0.431 (0.052)	0.38 (0.089)
	Priority 4 - Restoring, preserving and enhancing ecosystems related to agriculture and forestry	-	0.522 (0.016)	0.564 (0.009)	-	-0.644 (0.002)	-	-0.526 (0.016)	-0.557 (0.009)	-	-	-0.524 (0.015)
	Priority 5 - Promoting resource efficiency and supporting the shift towards a low carbon and climate resilient economy in agriculture, food and forestry sectors	-	-	-0.487 (0.027)	-	0.506 (0.02)	-	-	-	-	-	0.402 (0.071)
	Priority 6 - Promoting social inclusion, poverty reduction and economic development in rural areas	-	-0.408 (0.068)	-	-	-	-	-	0.461 (0.035)	0.436 (0.048)	-0.378 (0.092)	-
	Total public expenditure	-	-	-	-	-	-	0.425 (0.056)	-	-	0.983 (0)	0.391 (0.08)

Note: Only correlation coefficients, with p-values <10% are reported. Source: our elaboration on ISTAT (http://dati.istat.it/) and EU Commission data (https://agridata.ec.europa.eu/extensions/DataPortal/cmef_indicators.html).

change in name of the interventions in the new programming period, this group has been labelled "Investment Group". However, the expenditure targets are similar, as demonstrated by the correlation analyses conducted between investment interventions of the 2023-2027 programming period and the allocation for Priority 2 – Competitiveness and profitability of farms – of the 2014-2020 CAP.

Also, the characterization made by Uthes et al. (2017) about the "Competitiveness" and the "Environment" groups shows clear similarities with our description respectively of "Investment" group and "Disadvantaged" regions.

The identification of similarities, based on spending behaviour in the 2007-2013 and 2023-2027 programming periods, as well as the clear correlation between the expenditure allocation for related objectives between the 2014-2020 and 2023-2027 programming periods, eventually suggests the existence of a sort of resistance to change, which has characterised the CAP since its establishment (Moyer and Josling, 2002; Greer, 2013; von Cramon-Taubadel, 2017). It can be explained by the concept of path dependency (Iagatti and Sorrentino, 2007). It is clear at this point that despite the clear intention of a greener and more sustainable CAP, carried out especially in the last two decades, the paradigm has not changed substantially. The decision-making process is still strongly affected by stakeholders and agricultural lobbies, who enforce immobility to maintain their status quo, as still envisaged in the design phase of the current CAP by Rac et al. (2020).

Given the increasing importance which has been given to environmental aspects in the current programming period of the CAP, because of the Green Deal, Farm to Fork, and the New Green Architecture (Fusco, 2021; Zezza, 2023; Coderoni, 2023), it is crucial to elaborate a bit more on the allocation of funds for environmental interventions by the Italian regions. In fact, this analysis does not show significant differences among clusters. Instead, there is expenditure similarity in relative terms. This is probably the result of the ring-fencing itself, as imposed by the European Commission, requiring that a minimum share equal to 35% of the total plafond is devoted to environmental interventions. In Italy, all the regions have allocated resources for these interventions in line with this minimum threshold or slightly higher than it. Actually, the European Commission itself asked Italian regions to raise their allocation during the approval phase of the National Strategic Plan. This sort of financial constraints, set by the EU, seems to be one of the latest top-down initiatives inherited from the past centralised governance system of the CAP, in stark contrast to the new delivery model. Despite this, ring-fencing seems to be an essential tool to pursue strategic and far-sighted policies or objectives such as the environmental one, considered essential by the Commission but too much relegated to a secondary level compared to others considered more tangible in the short term by local politics.

Despite returning insightful results, the current analysis might suffer from some limitations, e.g. a focus on Italian regions only. Moreover, an analysis adopting the same methodologies (e.g. cluster analysis and correlation coefficient analysis) might be replicated over previous programming periods. Despite the main limitations of the adopted methodological approach (e.g. sensitivity to the choice of clustering algorithm, number of clusters to be selected, and input variables), this could verify whether groups of regions are maintained over time. Any changes in the placement of the individual regions could then be explained by analysing the determinants to verify whether changes in regions' characteristics may have also led to a change in the regions' placement among the groups. If this were confirmed, it would validate specific indices that *ex-ante* would show the putative allocation of the region for each type of intervention.

6. CONCLUSION

This work aims to understand the main RD Policy expenditure characteristics in the 2023-2027 CAP across Italian regions. It aims to verify the existence of similarities among regions when considering expenditure allocation and then to identify the major determinants behind this allocation. To achieve this goal, a cluster analysis is firstly conducted followed by correlation analyses. In particular, to the authors' best knowledge, this analysis represents the first effort to study expenditure allocation of the 2023-2027 CAP, thus providing new and interesting insights into this topic, thanks to a quantitative technique which also allows for direct comparisons across different observations. However, as an additional added value of the work, the current study also confirms the findings from previous analyses, conducted under different programming periods and governance systems.

In the current analysis, four clusters of regions are identified by analysing the percentage distribution of expenditure allocated to each type of RD intervention. The results show that some regions, despite major geographical and historical differences, have similar spending behaviours and this could be linked to some other common characteristics.

This finding could lead to some key policy implications, in particular enhancing improvements in the effectiveness of spending. At the end of the programming cycle or at the mid-term review stage, comparing the results achieved by different regions that improve the same expenditure mix would make it possible to determine which of them has achieved the best results. Therefore, greater coordination across regions could improve the overall effectiveness of spending.

From this perspective, the new delivery model might play a strategic role. It might open new opportunities for regions to adapt current spending to their specific needs, as well as increase coordination with those territories that share similar characteristics. At the same time, however, it could have the opposite effect. Greater decision-making and management power could increase the gaps between lagging-behind and other regions, with the former group being disadvantaged with this new governance system.

The implementation of the new delivery model, which further emphasizes the principle of subsidiarity, might suggest that in this programming period, expenditures of each MS are even more distinct from one another than before, potentially making comparison between them less meaningful. However, this work has confirmed that there are two main spending guidelines ("environment"-oriented and "investments"-oriented), which have survived, under different names, to the changes in the CAP and its governance system, with the attention to the environmental aspects being reinforced under the current Green Deal context. It is for these reasons that it could be useful, in the future, to extend the same analysis to all EU regions. Submit the expenditure mix of each European RD Policy to cluster analysis and then research if the determinants of that expenditure could reveal whether the type of clusters identified in Italy also holds at the EU level.

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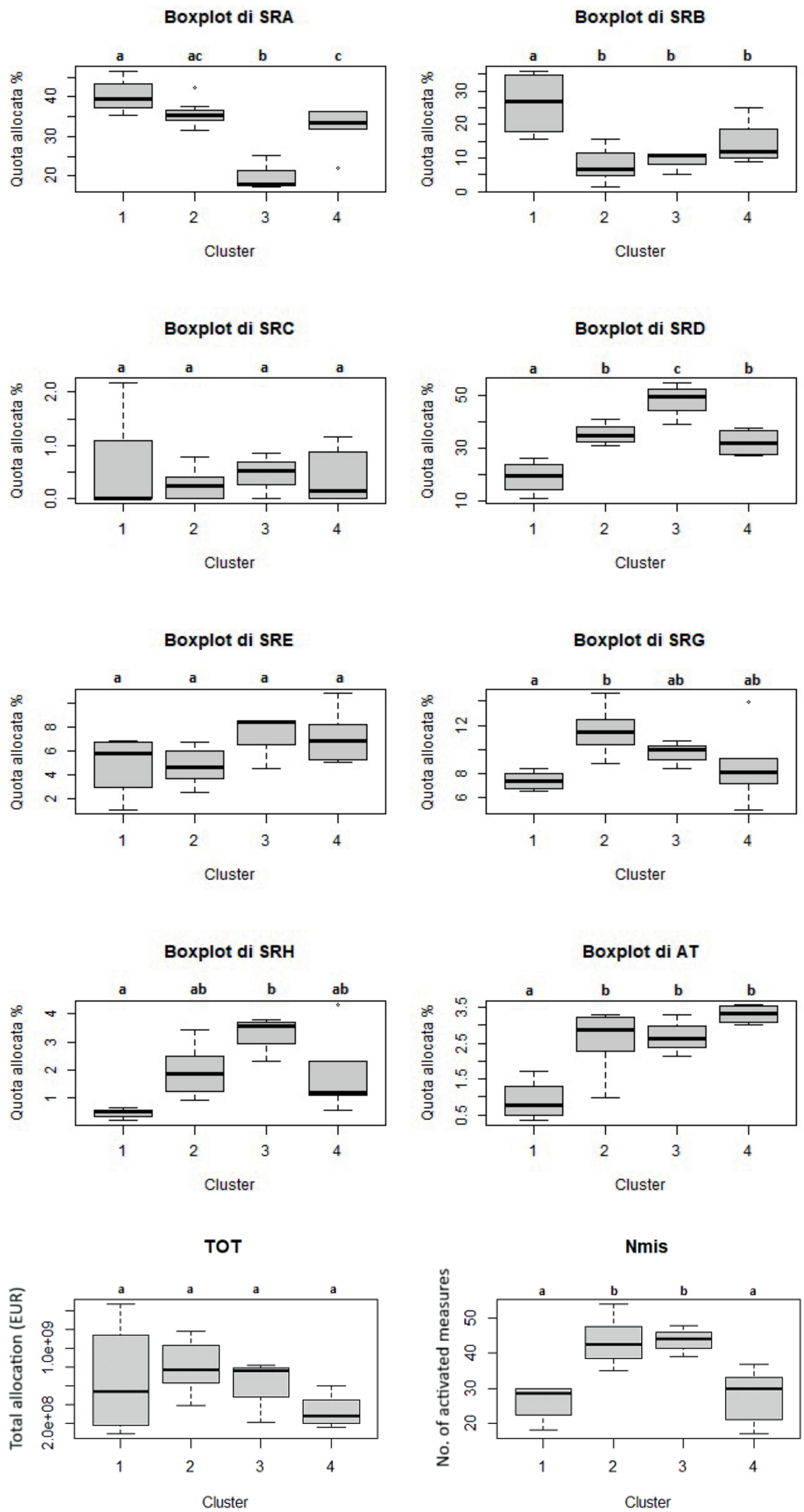
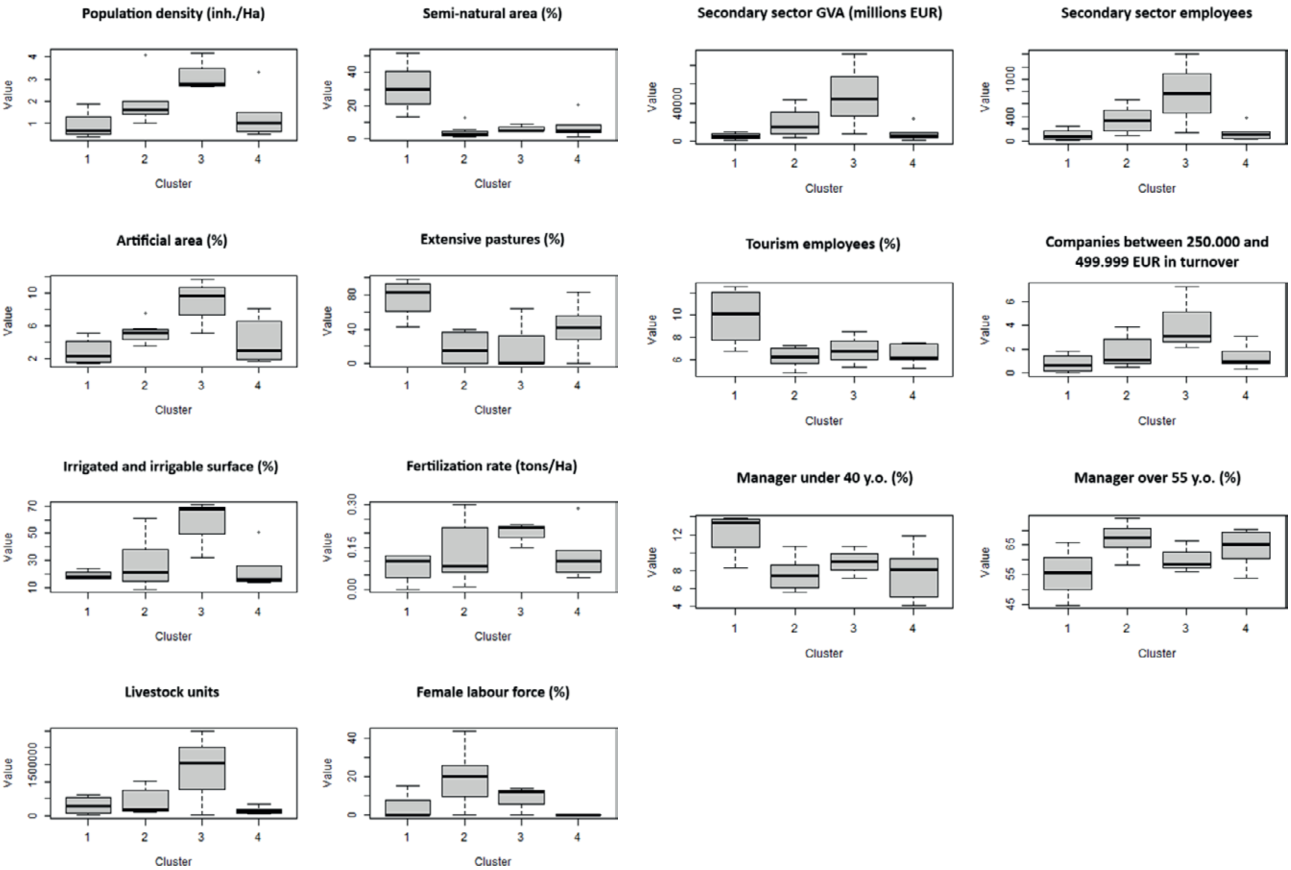
ANNEX

Annex A. Box-plot of the resource allocation for the seven types of RD interventions, of the total resource allocation and of the number of interventions activated, for each cluster of regions. Source: our own elaboration, R Core Team (2024).



Annex B. Box-plot of descriptive variables that have significant differences among the four clusters. Source: our own elaboration. R Core Team (2024).



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