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Editorial

Taking stock to look ahead

Around 2017, CREA and SIDEA embarked on the relaunch of REA, redefining its place within the context of Italian academic publishing while simultaneously strengthening its international profile. From the outset, both the objectives and the strategic direction of this process were clearly defined. A primary goal was to secure a distinctive position among the many journals, both established and newly founded, that had chosen to align themselves fully with the standards and practices of contemporary international scientific publishing. While firmly situated within this broader scholarly framework – also thanks to the composition of its successive Editorial Boards and International Scientific Committees – the journal has consistently preserved a dedicated space for an informed national debate on the implementation of European, national, and local policies, always grounded in rigorous scientific standards.

The expansion of the International Scientific Committee to include scholars from new countries and disciplines in dialogue with agricultural economics and policy analysis has further strengthened the journal's international standing. Such development has enabled a younger generation of researchers, trained in diverse academic and geographical contexts, to engage with a publication capable of ensuring both high scientific quality and broad dissemination of research findings. At the same time, the journal has deliberately sought to provide increasing visibility to the work of early-career scholars, encouraging the circulation of new ideas, methodological innovations, and emerging research perspectives within our academic community.

Thanks also to the fruitful collaboration with SIDEA working groups and the wide range of research activities promoted by CREA, the journal has progressively embraced new themes and interdisciplinary approaches. Its scope has expanded to include food systems and food policies, territorial and local development policies, environmental sustainability and climate change, as well as the evolving relationships among agri-food systems, food production and consumption, urban contexts, and rural areas. These are only a few examples of the issues that have broadened the journal's scope and that reflect the growing complexity of the challenges facing agricultural economics and the analysis of agricultural and rural policies today.

Above all, REA has become a meeting point between agricultural economics and the neighbouring fields of knowledge that broaden its horizons and enrich its analytical perspectives. Equally important, and increasingly distinctive of the journal's identity, has been the central role assigned to the involvement of stakeholders within the Italian and European agri-food systems. The journal has consistently promoted open and constructive dialogue with practitioners, institutions, and interest groups. This dimension is essential for a journal that seeks to make policy analysis, and the territorial impacts of policy, one of the defining features of its scientific identity.

All these ambitions are reflected in the journal's current title, the *Italian Review of Agricultural Economics* (REA), which preserves a connection with its distinguished history – dating back to 1945 – while projecting it toward a new phase characterised by openness to emerging and highly relevant issues, with particular attention to the national academic and public debate. It is along this deeply rooted and strongly identity-driven path that the outgoing Editorial Board has worked, and to its members we extend our sincere gratitude for the commitment, expertise, and sense of responsibility they have shown in serving both the journal and its wider scientific and professional community.

With this issue, the new Editorial Board inherits not merely the legacy of the past, but also a vivid responsibility toward the future of the journal. This awareness inspires a renewed commitment to exploring new topics, perspectives, interlocutors, and scientific collaborations capable of further enriching the journal's outlook and its role within an ever-evolving contemporary debate. Building upon the quality standards already achieved, we also hope to secure the journal's inclusion in the Web of Science, thereby strengthening REA's position among the leading journals in agricultural economics and agri-

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cultural policy, while at the same time fostering dialogue with other disciplinary fields with which engagement is both necessary and desirable.

We hope that the journal will continue to serve as a meeting place for the national and international scientific community, hosting contributions developed within robust scholarly contexts: European research projects, SIDEA working groups and other relevant scientific associations, as well as the many scientific and institutional initiatives promoted by CREA. This ongoing endeavour is made possible by the support of CREA and SIDEA, by the commitment and continued closeness of our publisher and support staff, and by the contributions of researchers, institutions, professionals, and stakeholders to whom the journal is addressed and upon whom the Editorial Board relies in pursuing its mission with rigour and dedication: to disseminate knowledge, foster critical debate, and preserve while renewing a scientific tradition placed at the service of society.

The Editorial Board
Mario Cozzi, Federica Demaria, Roberto Henke,
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Keynote article

Policies and prospects for UK agriculture and rural areas after Brexit – navigating turbulent times at home and abroad

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Abstract. This paper reflects on the Brexit process, impacts and influence upon UK agri-rural businesses, communities and policies. Tracing a timeline, we cover the stages of Brexit debate, development and implementation and note the complexity of identifying impacts against a turbulent external context. Impacts from new trade policy have been modest but negative, particularly for smaller agri-food and rural businesses, whilst impacts from changing agri-rural policies have diverged across the four nations of the UK, with the most dramatic changes in England. Significant uncertainty remains around the future evolution of UK agri-rural policies and trading relations with Europe. We see a risk of reduced political attention towards farming, food production and rural development, notably in England but also in the UK policies led from London which affect farming and rural areas including trade, taxation and migration. At the same time, interest in agri-rural policies across Wales, Scotland and Northern Ireland seems likely to remain strong. We suggest this imbalance is unwise for a country which is strongly committed to a successful climate transition, where careful management of UK land and agri-rural resources will become ever more critical, in the years ahead.

Keywords: Brexit, agri-rural policy, policy design and implementation, future prospects.
JEL codes: H50, Q18.

HIGHLIGHTS

- Brexit impacts on UK agri-rural policy and issues are complex, compounded by both external global, and internal policy turbulence, post-2020
- Post-Brexit agri-rural policies are markedly divergent across the UK's nations with the most dramatic changes in England, increasing sector uncertainties
- Impacts from new trade policies are modest but negative for agri-food and rural businesses
- UK government should increase its focus on rural resource management and enhance policy design and implementation to reach its climate and SDG targets

1. INTRODUCTION – SETTING THE AGENDA AND DESCRIBING THE TIMELINE

It is almost ten years since the results of the UK Brexit referendum were made public, and more than five since the UK ceased to be a member of the European Union. This might be regarded as a sufficient period in which to analyse its impacts. Nevertheless, these years have been marked by major unanticipated global 'shocks' – external effects which have also affected UK policies. In turn, those policies have undergone significant change with increased divergence among the UK's four nations in internal policy development, its drivers and consequences. Therefore, it is essential to build contextual understanding when examining the empirical evidence, and to consider the policy process, as well as counterfactual hypotheses and reasoning, to achieve a useful understanding of causes, lessons and likely implications. This paper adopts a largely qualitative approach combining policy narrative, evidence review, expert interpretation and forward-looking reflections to respond to its chosen topic. As authors, we first address the question of 'What did Brexit mean in practice?' before moving on to 'What have been the impacts and implications, for markets and policies?', and conclude with suggestions about future remaining challenges and possible developments. Our aim is to synthesise, interpret and compare UK post-Brexit agri-rural policy trajectories as a 'real-time experiment' in post-CAP policy, and assess their implications for meeting future needs.

This paper is organised as follows: section 2 provides a narrative of the Brexit process; section 3 examines Brexit impacts on trade and its implications for agri-rural sectors; sections 4 and 5 detail the UK's specific agri-rural policy changes since Brexit and section 6 analyses specific features of the process in England, the UK's largest agri-rural region. Section 7 discusses and analyses overall impacts of the post-Brexit changes and prospects for the future. Section 8 summarises the current situation, identifies shortfalls and offers concluding reflections.

2. TIMELINE AND PROCESS – A BRIEF NARRATIVE

The summer 2016 UK Brexit referendum resulted in a small margin in favour of leaving the European Union (48% voted to remain, 52% to leave, with a turnout of 72% of the registered electorate). Among UK nations, England and Wales voted to leave while Scotland and Northern Ireland voted to remain (UK Parliament, 2016). The result set in train a process for departure, initiated following Prime Minister David Cameron's resignation as he had campaigned strongly on the 'remain' side. His replacement Theresa May, from his same centre-right party, committed to secure the UK's exit from the EU.

However, a long period of negotiation followed over the 'type' of Brexit to be implemented, due at least in part to the lack of political consensus on this point before the vote. Early decisions by party leaders to allow MPs a 'free vote' in the referendum led to prominent 'leavers' and 'remainers' in each of the two main parties (centre -left and -right), although the smaller parties took clear positions. Thus, the voting public had no clear idea of exactly what leaving the EU meant, as both referendum campaign groups included people from different parties, with very different policy ideas about this.

It could also be argued that prior to 2016, there was insufficient detailed preparation for the possibility and consequences of a leave vote within the government administration. The period was marked by a strong 'austerity' agenda applied to help the UK recover from the impact of the 2008 global financial crisis. Implemented under a centre-right coalition, this drove deep, sustained and cumulative cuts in public spending (in real terms), and in public sector employment. Ministries and government agencies increasingly had to concentrate on maintaining only their essential roles, so capacity to explore future scenarios was limited. A government exercise to examine the impacts of EU membership ('Review of the balance of competences') across national Ministries and Departments in 2014 had concluded that its benefits significantly exceeded costs, but little work was devoted to designing feasible or desirable Brexit processes before 2016. Interestingly, a very different position was taken by the Irish government: officials in Dublin already had clear understanding about the implications of different types of Brexit by early 2016, publishing a framework immediately following the UK's announcement of the referendum result (Rte, 2016).

During 2017-2018 the UK underwent a gradual shift of focus from a 'soft' Brexit, partially negotiated but not agreed under Theresa May, to a 'hard' one supported by others in her party who unseated and succeeded her. Key elements affirmed 1) leaving the single market, and 2) leaving the customs union, plus statements about tightening UK border controls and shifting public funds away from agriculture and Europe towards the core UK institutions of the National Health Service and state education. Brexit lobby groups effectively orchestrated this shift, using strong rhetoric criticising open borders and high levels of immigration, inaccurately portrayed as linked mainly to EU obligations.

In this same period, the negotiation changed from a detailed and carefully discussed process with stepwise clarification and deliberation, to something appearing increasingly desperate as time passed and no firm agreement emerged. Mainstream media increasingly voiced frustration over the timetable but offered little deep analysis of choices and their implications. In 2019, new elections gave Boris Johnson a strong mandate for a 'Get Brexit Done' agenda, echoing media sentiment, and his Conservative administration adopted unorthodox (later judged illegal) methods to accelerate decision-making. The departure agreement was signed as Johnson had promised on 31 January 2020, but the deadline was achieved only by leaving many detailed issues unresolved.

2020-2023 then saw enormous turbulence in the agri-food and rural arena caused by external shocks and crises: the Covid 19 epidemic, then the invasion of Ukraine by Russia which markedly disrupted key food production, global food markets and trade patterns. In this difficult period the UK was setting up new systems and approaches to agri-rural support, which had previously been strongly shaped within the EU's Common Agricultural Policy. And partly influenced by the Brexit sentiment, internal UK agri-rural policy became increasingly divergent and contested, with impacts on farm structures, sectors, and morale.

In the 2024 election, the UK's main political parties had only slightly different "manifesto" visions for the agricultural sector: the centre-right conservatives adopting a laissez-faire liberal approach noting sector inefficiencies to remedy, whilst recognising a need to pay for the environmental public goods provided by farmers; while centre-left labour expressed a less clear political view on farming but consistent support for the environment, and some interest in reducing inequalities in rural areas. A Labour government was elected with a significant majority, and a partial 'reset' of the UK's relationship with the EU has since developed, accentuated by global and security concerns arising from the re-election of Donald Trump to the US White house, and the wars in Ukraine and the middle east.

3. POST-BREXIT TRADE POLICY AND ITS IMPACTS

Brexit was widely presented as an opportunity for the UK to seek access to other markets by concluding more, and more ambitious trade deals independently of the EU; but the EU was the UK's biggest trade partner when Brexit started (Hix *et al.,* 2022) and it remains so.

A Free Trade Agreement with the EU was signed in December 2020 and applied from May 2021 but required significant further change to resolve implementation details (Freeman *et al*., 2022; Du *et al.,* 2023). The UK wanted to be able to diverge in terms of its regulatory environment, to be more competitive in global markets (the term 'Singapore under-Thames' was coined to describe the government's favoured future trading environment; Erkkila *et al.,* 2025). The government also made a political commitment to seek other trading opportunities beyond Europe, mostly via 'rollover' of pre-existing agreements that had applied to the UK within the EU (Erkkila *et al.,* 2025). In addition, the UK was integrated into the Pacific CPTPP, promoting freer trade with American and Asian nations.

UK trade was also strongly affected by complicating factors – Covid lock downs, wheat production collapse and export blockades in Ukraine, gulf 'blockades' by Yemeni groups, energy price volatility, and then Trump's tariffs. Compounding these sources of political and market turmoil, markets reacted to the negative production consequences of extreme weather conditions – with devastating winter rains / floods in 2023, followed by drought / extreme heat in the summers of 2022 and 2025 (Jelliffe and Gerval, 2025).

When considered net of the counterfactual, the trade impact of the UK's departure from the EU on the UK is challenging to clarify but has clearly been more negative than positive. However, major external factors and shocks provided a 'smokescreen' for Brexiteers and mainstream politicians to hide these negative impacts, avoiding discussion and open debate. Following the highly aggressive and divisive rhetoric of the referendum, Brexit consequences were a 'toxic topic' that neither the people nor the press wanted to discuss, because views had become so divisive and corrosive, and both main political parties refused to challenge the decision to leave the EU. It has only been since 2024, as the labour government has sought to explain its difficult economic circumstances and respond to current international developments, that more critical analysis of Brexit impacts has accumulated.

UK exports or imports to the EU required traders to be registered, with a compliance certificate (covering health, veterinary status, composition and other details). Businesses needed to specifically notify some items (e.g. perishable goods), to apply information on warranties, rules of origin, and VAT status. The paperwork confirming each element had to be completed on both sides of the border during the process. Packaging and transport conditions also applied to movement of goods across borders (e.g. type of pallets used: HMG 2021a).

The UK government repeatedly postponed implementation of certain import controls, partly in response to the disruption caused by the COVID-19 pandemic and concerns regarding supply chain readiness (HMG, 2021b). Although some additional procedures related to Sanitary and Phytosanitary (SPS) requirements became applicable from 2021, comprehensive SPS controls on EU to UK imports were delayed several times and not fully introduced until 2023-2024. By contrast, EU members began applying full border controls on goods arriving from the UK in 2021, including documentary and physical SPS checks. As a result, some perishable shipments were temporarily withheld at EU borders due to incomplete documentation or SPS non-compliance (EC, 2021). Also, formal verification of rules of origin were more fully enforced from 2022, increasing administrative costs for exporters (UK Trade Policy Observatory, 2022). This created additional transaction costs and border friction for EU-bound shipments that negatively impacted UK meat, dairy and seafood exports (House of Commons, 2021).

Northern Ireland (NI) has special 'hybrid' status, depending on the final consumer of the goods moved into or through its territory. Goods imported for consumption within NI do not suffer new controls, but goods imported from UK to NI and thence on to Ireland, or *vice versa*, have new controls applied. Improvements have gradually been achieved, reducing frictions in NI.

Today, the UK is resetting its relationship with the EU after the change in government to Labour (NFU, 2025), and especially since the new US Trump administration and international conflict have increased anxieties about Europe's defence and US trading relations. There has been a new commitment to negotiate a SPS agreement leading to reduced controls once agreed; and more general "dynamic regulatory alignment" (Berg, 2024) is being pursued.

Overall, 'relative to trade with the rest of the world, rates of agri-food trade growth in the European Union and the United Kingdom suggest that both regions are diversifying to other trading partners, despite observed increases in bilateral trade.' (Jelliffe *et al*., 2025, p. i). The biggest negative net impact of Brexit has been on UK exports to the EU, largely due to the introduction of non-tariff measures such as customs declarations, rules-of-origin documentation and sanitary and phytosanitary checks (Food and Drink Federation, 2025). These requirements have disproportionately affected smaller producers, many of whom face higher administrative costs and limited capacity to comply with complex export procedures (British Chambers of Commerce, 2023). Empirical estimates suggest the Trade and Cooperation Agreement (TCA) reduced UK goods exports by around 6.4% (approximately £27 billion) in 2022,

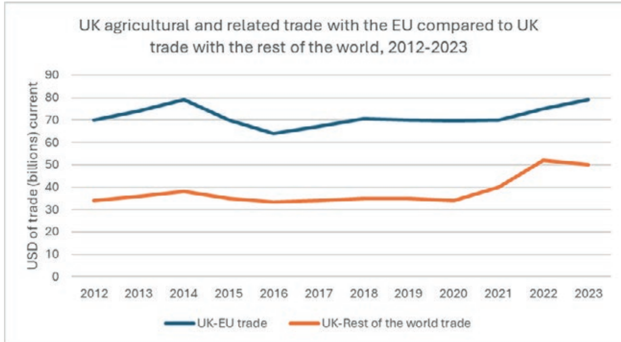

Figure 1. UK agri-food trade before and after Brexit. *Source*: adapted from Jeliffe *et al.,* 2025.

driven primarily by a 13.2% decline in exports to the EU, with the smallest firms experiencing export reductions of 30% on average (Jelliffe *et al*., 2025; LSE CEP, 2024). Around 14% of firms that previously exported to the EU ceased exporting after the TCA came into force, highlighting disproportionate impact on SMEs. Accompanying adjustments in trade and labour supply patterns now give some evidence of growing trade with non-EU partners – including Commonwealth partners, as firms respond to weakening EU-UK integration (Food and Drink Federation, 2025) – although the EU also shows growth in a similar direction.

In sum, Brexit is likely to have had a net negative impact on UK agri-food exports and imports. Fewer imports now come from the EU and more from the rest of the world, indicating that the UK has not prioritised its agricultural sector when pursuing trade negotiations and new deals, removing some tariffs and quota barriers to imports from nations that compete directly with its distinctive agri-food products (e.g. in meat and dairy). Nevertheless, since similar patterns are seen in EU agri-food trade post-Brexit, the counterfactual might also have been more UK trade beyond the EU.

If the net impact of changes in external trading balance has been modest but negative for the post-Brexit UK agri-rural economy, what could be said of changes in the internal policy mix?

4. BREXIT IMPACTS ON UK AGRI-RURAL POLICIES – CONSIDERING THE CONTEXT

Shortly after the 2016 referendum, the government confirmed that post-Brexit, UK agricultural policy would continue to be devolved, in line with the pattern that applied under the CAP since 2014, for both pillars of the policy (UK Parliament, 2017).

Across the nations of the UK, post-Brexit agricultural policy has diverged with each administration moving away from the previous CAP support model to different extents (OECD, 2025). England has gone the furthest in signalling major changes to policy objectives and instruments. Wales follows with more conservative policy objectives but a greater novelty in its policy approach. By contrast, Scotland and Northern Ireland have largely retained pre-Brexit policy goals and the instruments associated with the CAP, although both have introduced targeted innovations to better align with their respective national priorities.

These differing tactics and models reflect the relative importance of the Pillar 1 and Pillar 2 CAP agendas in each case, as well as the balance of Brexit sentiment and political 'character' of each country. England has traditionally had more liberal market-oriented goals and delivery approaches in agri-rural policy, compared to either Wales, or Scotland and Northern Ireland (Lenormand, 2023). These three nations have significantly higher shares of agriculture and rural business in their economies and total employment. They also have much larger shares of rural land and rural communities than England (DEFRA *et al.*, 2022).

Policy change and impact should always be set in context. The UK's rural areas exhibit a gradient across its four countries, from very accessible areas in the south and east, to its most remote territories particularly in the extreme west and far north, and on higher ground. The total rural population of the UK is relatively high, and growing or stable in many areas, but decline affects its remote uplands and other inaccessible rural locations, also rural former industrial areas (ex-mining, or adjacent to major ship-building or steel production industries, etc.), where the territory and community was dominated by part-time farming alongside employment in these sectors, which has now ended (Defra, 2022). Rural economic structure, as expressed in standard statistics, is similar to the urban economy in England, but more differentiated in Wales, Scotland, and Northern Ireland (Welsh Government, 2026). This gradient of rural characteristics and importance has clear consequences for policy priorities.

UK-wide, rural services are generally less well-supported than urban; so rural living is more costly when households with similar incomes are compared. Similar types of need and issues in rural areas are noted including: poor public transport; comparatively high land and property prices compared to urban; declining provision of key facilities (pubs, shops, doctors); labour shortages; and high reliance on non-UK workers for many typical rural jobs (tourism / leisure, social care, vets, farm work, food processing). Rural territories mostly have weaker than urban digital access and broadband speeds, but these are improving (e.g. see NICRE, 2021 and 2023). Finally, NGOs and devolved governments voice concerns about the 'invisibility' of rural issues and understanding in central UK government, where largely urban agendas dominate policy (e.g. RSN, 2024).

5. IMPLEMENTATION PATHWAYS FOR POST-BREXIT AGRI-RURAL POLICY

In brief, England chose to completely phase out support for farm incomes under the former Pillar 1 of CAP, reducing them gradually over seven years from 2020, aiming to achieve a smooth transition to new schemes, which were to be launched in parallel over the same period (Defra, 2019; AHDB, 2022). Other nations adopted a more cautious approach, retaining Pillar 1 funding in full whilst their new schemes were developed, tested and incrementally implemented. Figure 2 shows how the funding allocation pattern shifted, in England: in reality, this shift has been more dramatic than the original plans announced in 2022.

The total budget for UK agricultural support is relatively unchanged, but there have been some cuts in England and Wales which have arisen due to shifting domestic priorities since leaving the EU (Defra blog, 2025). Nevertheless, specific rural development policies have almost disappeared in England in favour of more general 'recovery' funds targeting growth and economic regeneration through undifferentiated competitive calls, while dedicated rural policies have stronger focus in Scotland, Wales and Northern Ireland (Welsh Parliament, 2025).

England has undertaken the most radical departure from the CAP model. Its Environmental Land Management Schemes (ELMs) replace direct payments with a tiered system of contracts for environmental delivery, reflecting the principle of "public money for public goods." (Kam *et al.*, 2023). The three tiers of: Sustainable Farming Incentive (SFI); Local Nature Recovery (LNR); and Landscape Recovery (LR) schemes; were designed to collectively shift policy entirely away from income stabilisation and into environmental outcomes, climate mitigation and ecosystem restoration. From 2020 to 2026 all funding previously allocated to Pillar 1 income support has been transferred to this ELMs 'package'. The three new schemes as announced aimed to offer a hierarchy in environmental delivery ambitions, going from "simple actions ('standards') at farm level" for the SFI, to long term (20-year) landscape scale agreements in the LRs. But effectively, due to time constraints on the need to redirect and absorb the former

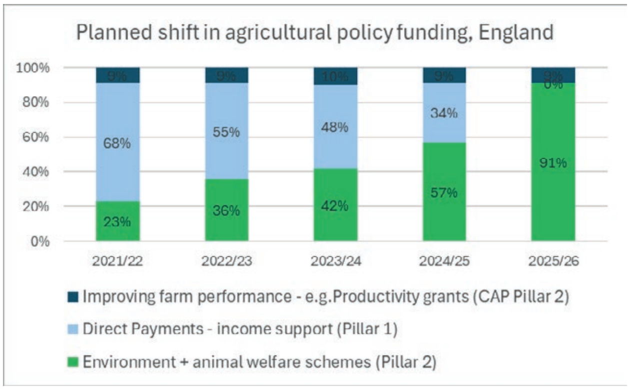

Figure 2. Changes in Agricultural support in England, 2021-2026. *Source*: the authors, adapted from Defra, 2020.

pillar 1 funding, England's pre-existing 'Countryside Stewardship' (CS) agri-environment-climate measure, based on management prescriptions, was amended so that it could replace the planned new LNR in the package, becoming its middle tier which is now denoted as 'CS+'. This reduced the need for a new middle tier to be designed and launched. However, the new SFI 'base tier' also drew some elements from the CS approach, with some options overlapping with those in the middle tier. Most CS+ agreements offer 5-year contracts, as similar schemes previously did under the CAP, while SFI agreements are only for 3 years.

Across the planned new schemes for England, delivery dates were gradually pushed back, highlighting design and administrative difficulties in launching a complex and ambitious new programme within so few years. In particular, the highest tier LR component is progressing very slowly as these territorially-based agreements are based around local partnerships but build on common national procedures, with plans for 20-year contracts and some desire to attract new funding from private finance, in a 'Natural capital blended funding' approach to delivery. Overall, this shift aligned with critiques of the CAP that highlighted the limited additionality of its decoupled payments and called for more targeted, outcome-oriented environmental schemes. However, England's decision to rely on the WTO-prescribed 'income foregone' formula for payment calculations in its new schemes has the effect of under-rewarding less productive regions of high nature value, whilst paying higher rates on land of relatively low existing environmental value and thereby potentially exacerbating structural inequalities across the territory.

England also offers productivity-enhancing investment aids to farms and food processors (targeted to address a statistically identified trend of 'flatlining' in UK agricultural productivity, over the past 20 years). At the policy-NGO interface, a focus on 'the Food System' is gaining attention – embracing issues of diet / health / climate links, connecting the national obesity epidemic with interest in improving people's access to fresh and more diverse, affordable and healthy food and discouraging consumption of high proportions of ultra-processed products of low nutritional value. However, to date these aims are not translated into concrete funding initiatives.

Wales has also moved decisively away from the CAP, but through a more integrated, socially-oriented model. The Sustainable Farming Scheme (SFS) adopts a whole-farm approach seeking to balance food production, climate action, and nature recovery. Wales has developed a "holistic Sustainable Farming Scheme... to integrate food production, nature recovery and climate action," with a two-tier structure and a "social element" in the base payment reflecting the previous income support mechanisms of the CAP.

The goals (or desired 'outcomes') reflect this more holistic approach compared to that in England (Figure 3): and the tools (precise measures) differ also, although they remain based on a menu of options where a farmer opts-in for a 5-year contract.

The Welsh scheme has a 'universal' base layer with minimal requirements to enter and some obligatory actions, including a self-assessment-led whole farm plan wherein the applicant must set out further actions, selecting from a mix of options to achieve the different goals of the scheme. Further, for each main option, different levels of 'ambition' are available to be chosen. In total, the scheme offers a base payment for achieving the actions in the "universal layer" of the scheme, plus specific top-up payments for each of the environmental actions that are chosen from among the various options, with generally higher payments if the applicant chooses higher levels of 'ambition' (Table 2).

Compared with England's redesigned system, the Welsh model retains a stronger emphasis on farm viability, community well-being and multifunctionality, echoing strands of the literature that argue for agricultural policy to support broader rural socio-ecological systems and goals. It also includes integral advisory provision, in contrast to the English SFI scheme, and all elements launched simultaneously as one package (before any significant reductions in farm income support were made), again in contrast to England.

However, the transition has been politically contentious, particularly the SFS' proposed land-use requirements which have undergone significant change during the development process. After a widely criticised first set of proposals were published in 2023, a participatory

Outcomes of the Welsh Government agricultural policy

- Resilient and productive farms
- Reduce, reuse and recycle inputs, nutrients and waste
- Reduce on-farm emissions and increase carbon sequestration
- Protect and improve the farm ecosystem
- Benefit people, animals and places

Figure 3. Wales' new agricultural policy goals. *Source:* Welsh Government, 2025.

and deliberative process enabled a revised version of the scheme to be finalised and launched in 2025. This has been well-received by farmers and other stakeholders across Wales, offering 5-year contracts and attracting a good level of applications.

The policy transition has also been less drastic than in England: Wales planned only a 20 to 40% reduction in direct payments in 2026 (Welsh Government, 2025), whilst the SFS was designed, revised and finally launched before this date. Among farmers, fears remain about the potential administrative burden and negative impact on the industry of this broad policy shift (NFU Cymru, 2025).

Scotland has chosen a more evolutionary path than England or Wales, retaining the core structure of the policy as it was under the CAP, while strengthening environmental conditionality. Direct payments remain central, including the continued use of coupled support for sectors such as suckler beef and upland sheep. Scotland is introducing a suite of Whole Farm Plans – including carbon audits, biodiversity assessments, soil analysis, and animal welfare plans – that significantly increase the environmental and managerial requirements attached to farm income support.

There is also a greater emphasis in Scotland's post-Brexit approach, compared to other UK nations, on combined objectives of climate resilience, biodiversity pro-

Table 1. Basic structure of England's new ELMs support schemes.

Scheme	Principal role	Content	Key Outcomes
Sustainable Farming Incentive (SFI)	Broad, entry-level scheme for most farms – contracts for 3 years	Simple actions ('standards') at farm level for general environmental benefits. Relatively popular / flexibility. Actions that can be delivered across the whole farmed landscape.	Soil health, nutrient management, hedgerows, integrated pest management, water quality, carbon sequestration, biodiversity. (GOV.UK)
Countryside Stewardship (CS) *(a transition from the CAP legacy scheme)*	More targeted agri-environment support – 5 years at least, depending on the options chosen	Locally targeted environmental benefits, particularly habitats, watercourses and species recovery. Different tiers reflecting different ambition.	Habitat creation, species recovery, water management, historic features, boundary management. (GOV.UK)
Landscape Recovery (LR) schemes – bespoke for each location	Highest ambition / transformational tier – Long-term (typically 20 years)	Long-term and landscape-scale change – restoration of landscapes and ecosystems. Complex, binding agreements often requiring blended public/private finance.	Rewilding, woodland creation, peatland restoration, river catchments, saltmarsh, ecosystem recovery. (GOV.UK)

Source: the authors, adapted from UK Government publications.

Table 2. Basic structure of Wales' Sustainable Farming Scheme (SFS).

Tier	Principal role	Content	Typical Examples
Universal Actions	Baseline actions expected from most farms	Mandatory / entry level actions to secure baseline payment	Soil testing, nutrient planning, habitat maintenance, hedgerow management, animal health planning
Optional Actions	Additional actions for higher environmental delivery	Menu of actions with different levels of expectation – not everyone can do all actions	Tree planting, pond creation, precision nutrient use, habitat enhancement
Collaborative Actions	Joined-up delivery across multiple farms or landscapes	Collective solutions for bigger challenges	River catchments, commons management, peatland restoration, flood management
Advisory / Capacity Support	Help farmers transition and comply	Whole-farm approach with guidance and planning support	Business advice, carbon baselining, habitat mapping

Source: the authors, based on information from the Welsh Government, 2025.

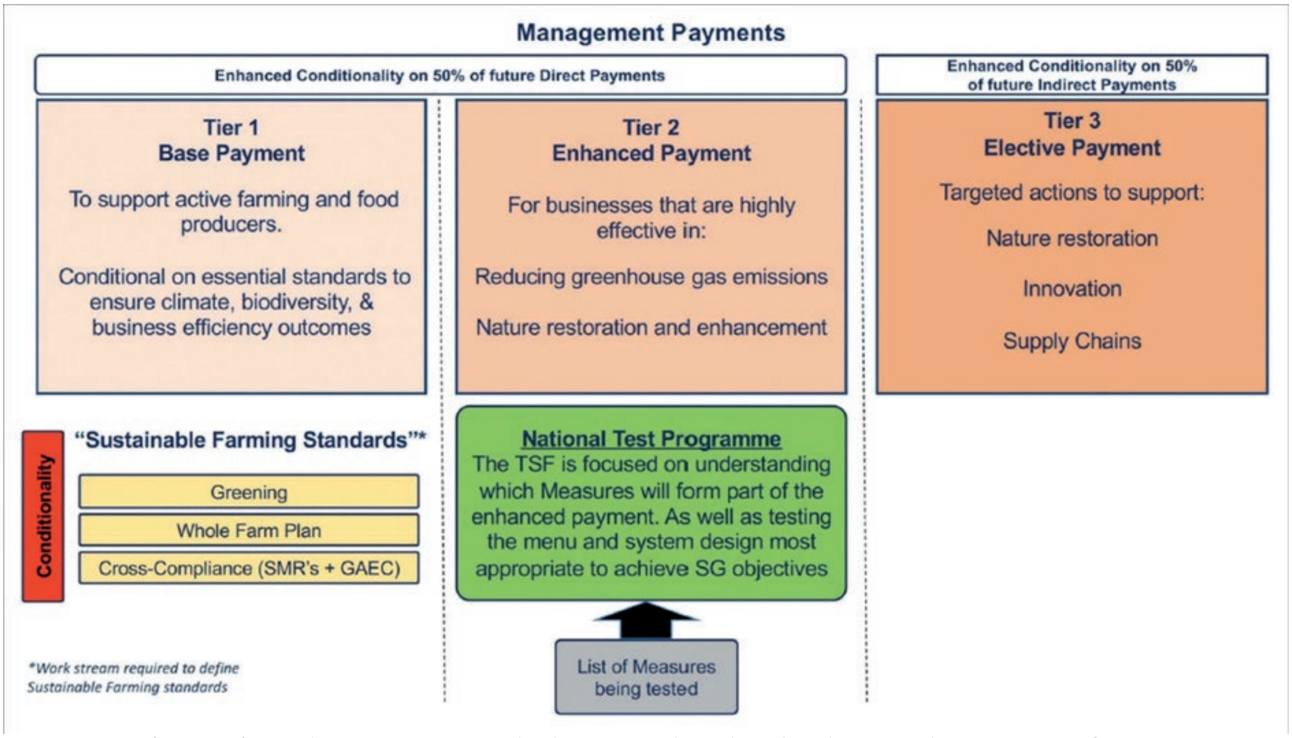

Figure 4. Main features of Scottish post-Brexit agri-rural policy. *Source:* the authors, based on Scottish Government information, 2026.

tection and thriving rural communities. This approach mirrors the direction of travel of the post-2023 EU CAP reforms, which also emphasised enhanced conditionality and eco-schemes. Scottish agri-environment scheme coverage declined from 2020 to 2024, suggesting a period of consolidation rather than expansion. Scotland's model thus represents a reformed CAP framework, rather than a complete replacement (Figure 4).

Northern Ireland's agri-rural policy remains closest to the pre-2020 CAP architecture among the four nations of the UK, reflecting political preferences and a wish to retain policy alignment with the Republic of Ireland. Direct payments for farm income support continue with some increased environmental conditionality, and accompanying agri-environment schemes remain relatively modest in scale. However, Northern Ireland has introduced some innovative environmental tools within the conditionality element, including LiDAR-based land assessment, whole-farm soil testing and nutrient management planning. These sit alongside the "Farming for Nature" agri-environment package. The approach reflects a technocratic, data-driven enhancement of the CAP model to prioritise soil health, nutrient efficiency, and carbon reduction while maintaining basic income support. It aligns with literature from the administration emphasising the importance of precision management for agriculture, but it avoids the scale and complexity of structural re-designs that have been seen in England and Wales (Figure 5).

Taken together, across the four nations the post-Brexit landscape is characterised by divergent policy instruments and rationales for environmental ambition and the scale and relative role of farm income support, despite a broadly stable overall agri-budget. England and Wales have replaced the CAP with new systems grounded in environmental public goods delivery and whole-farm sustainability, respectively. Scotland and Northern Ireland have retained the CAP's foundational architecture but strengthened environmental conditionality and measures, and associated planning requirements. This within-UK divergence reflects broader debates in the scientific literature about the future of agricultural policy in high-income countries: whether it should prioritise environmental public goods, multifunctional rural landscapes or stability and security in primary production. The UK now provides a real-time experiment that is testing these competing visions, through its variety of approaches.

Considering the counterfactual, we should note that even under the CAP, divergence between the four nations' agri-rural policy approaches was to be expected and a modest decline in resources would also have likely occurred, as it has for the EU. However, all four nations would have been bound by the regulations to retain a significant ele-

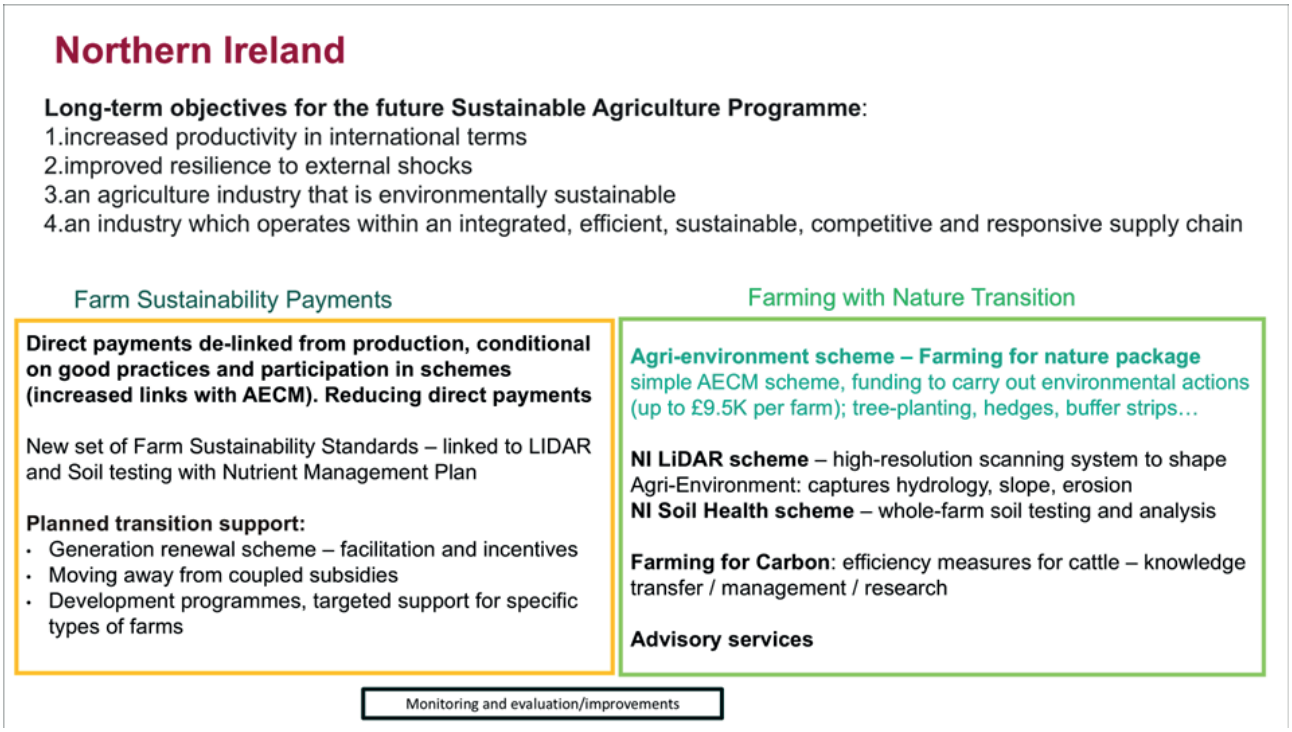

Figure 5. Main features of Northern Ireland's post-brexit agri-rural policy. *Source:* the authors based on DAERA published information, 2026.

ment of income support and respond to a common set of priorities through a common preparation and justification process, in dialogue with the European Commission. One might anticipate therefore that direct and significant negative financial impacts on farms and rural communities in England, at least, would have been reduced.

6. POLICY LEARNINGS: REFLECTIONS ON PROCESS MANAGEMENT

The UK's post-Brexit experience offers important learning on change management, in this contested policy domain.

Farmers and environmental NGOs have criticised an evolving 'disaster' in respect of the design and implementation of the new policies in England. Despite an initial assurance that funding levels to farmers would be maintained, Defra applied BPS reductions steadily but failed to roll out its new schemes at an equal pace; then made a more rapid phase-out of the farm income support payments than was previously indicated. This occurred alongside shrinking production in certain sectors – particularly beef - and triggered significant financial and production crises in both arable and marginal upland areas. The Defra Ministerial team changed more than once in 2025, as government reshuffled roles in response to other, wider political challenges.

Among farming communities, the inconsistent pathway of England's agricultural transition has undermined farmers' trust in government and its officials, on grounds that commitments have not been honoured, and with fears that the government is uninterested in domestic food production, increasing imports from other countries while land leaves agriculture for competing uses including energy, housing and large-scale 'rewilding' projects focused on nature recovery.

The land-based sector also reacted strongly to the Government's decision in 2025 to remove a 20-year exemption for farmland from liability for inheritance taxes. Many farmers and landowners in the UK are classically asset-rich but income-poor, so an inheritance taxation crisis arose following a decision to increase the liability for taxation on farmland at the point of transfer between generations, on the death of the owner. This triggered rapid casting of the Labour government as 'killing the family farm', with protests and blockades staged in many cities, over a sustained period. The change has now been modified to reduce its scope of impact.

An averted disaster was seen in Wales in respect of the new Sustainable Farming Scheme's initial design, which proposed significant requirements for new woodland and other controversial conditions. There were tensions between the Welsh government reassuring farmers about its commitment to ongoing support and yet aiming to generate concrete evidence of environmental or climate-positive rural change, compounded by poor communication (e.g. raising fears of large forestry plantations and solar panels replacing farms and displacing communities). Nevertheless, co-design and effective political pressure from agri-rural stakeholders appears to have paid off for Welsh farmers, and the new SFS is now attracting a strong level of applications and uptake.

The more gradual and strategic 'upgrading' of existing policies applied in Northern Ireland and Scotland appears to have caused fewer concerns for farming and rural communities, so far.

With hindsight, we can draw lessons from the negative experience in England. There was clearly a degree of inexperience among the civil servants tasked with designing and implementing the new schemes and overseeing the funding shift. As noted, it was planned to maintain a level budget, so BPS would decline steadily as the new schemes grew. But this plan ignored some key factors which would affect the feasibility of this plan.

Firstly, the classic 'adoption curve' for new initiatives and schemes among businesses is non-linear, with small numbers adopting initially and then slowly this builds until a critical mass is reached and the curve becomes much steeper as the majority of adopters join, after which additional adopters represent a more conservative or resistant group, entering the new scheme in much smaller numbers over a longer period of time. With this classic pattern, it is clear that the earliest adopters are different from those who join later – they will be those with more ability to move quickly to make changes and more confidence in their ability to benefit from the scheme. Often, these will be farms in a relatively strong business position, followed by those who can see ways to easily fit the scheme options alongside their existing systems (i.e. offering relatively low additionality).

Secondly, the external circumstances for producers were very unpredictable in the first years of the agricultural transition, with weather extremes and major global conflicts, destabilizing market prices on inputs and products and therefore returns to farms. This is likely to have made farm businesses more wary of making multiannual commitments with a suite of new and relatively untested government schemes.

Furthermore, the new 3-tier approach to support, with the SFI as a basic scheme and then a middle-tier resembling previous schemes plus a top tier promising much more ambitious and long-term support, represented a significant design challenge for Defra. It was clearly future-focused; launched gradually over several years as the various elements were put together, but with no clear transition pathways and little explanation of what the future vision for farming in England was.

- The SFI implemented a new philosophy of judging farm environmental performance against national 'standards', which was intended as more outcome-focused than previous schemes. However, this could also be seen as transferring more delivery risk to the farmer than previous schemes that had been focused on detailed management prescriptions. This might explain a degree of initial hesitation among farmers, in coming forward with applications.
- An early design decision to require all the new schemes to use the WTO-compliant payment formula of 'compensation for income forgone plus management costs' was applied, but with a relative under-estimation of the relevant costs during a period of rapidly rising input prices. This offer failed to attract sufficient applications for the available budget in the first two years of the new schemes, leaving Defra with an underspend and many farms holding back and relying on BPS while it remained relatively intact. Thus the approach to payment had to be recalculated upwards in year three, to provide a greater incentive to adopt.
- The uplift in payments coincided with more dramatic cuts to BPS in that year, which finally triggered a much more substantial wave of applications. The shift was so dramatic that it rapidly eradicated and overshot the scheme underspend, which then forced Defra to close the SFI scheme to new applicants, as there was no more money to spend.

In addition, it proved difficult for Defra to identify appropriate 'national standards' for more complex / variable types of agricultural land. Thus, the chosen pattern of SFI roll-out was to define and offer the easy standards first, before completing the more complex ones. This created a pattern of very uneven access to the SFI across different farm sectors, over time. Farms in the uplands waited five years for their SFI offer while those farming the best and most versatile crop land were given SFI standards from the first year. Particularly challenging has been to identify an element that is fully applicable on common land (much of which has high nature value), meaning that this is still unavailable, in 2026.

There was no targeting of the SFI budget, and contracts were agreed on a first-come-first-served basis, with a pattern of uptake characterised by delays and lagged adoption up to the end of 2022, followed by the payment revisions and a rush to commit the funding in the 2023-2024 period. After this, with no more funds for new agreements, the scheme was closed for a year while Defra considered, with hindsight the undesirable and unforeseen consequences of its first years: having been very critical of the BPS as paying the largest sums to big farms in the most productive parts of England, the SFI uptake actually shifted an even greater share of scheme funds to larger and more productive farm businesses, and away from the uplands and other marginal farming contexts. The scheme's closure also created considerable negative reputational impact, among farmers and other stakeholders who had been working hard to promote the new approach across the country.

The novel process of 'co-design' that had been promoted and pursued in the early years of new scheme development was also reportedly hamstrung by a broader 'defensive culture' in Defra and its agencies, and apparent lack of farming expertise or relevant knowledge among new staff recruited to support the new policy framework. Stakeholders stated that they frequently felt manipulated in the schemes' 'co-design' meetings, and trust between the various parties was arguably eroded, rather than strengthened as would normally be anticipated from co-design working, through this process.

With further hindsight, this record of poor implementation could have been predicted and avoided. Defra could have made more effort to capture, listen and learn from past experience and accumulated knowledge and expertise among the wider agri-environmental stakeholder community, which would have enabled them to plan for the anticipated adoption curve pattern and adapt budgetary management to shifting external conditions. But instead, the many new recruits to the Department appear to have been keen to 'start from scratch' in how they designed the schemes framework, thereby making many classic mistakes in policy design and delivery.

7. OVERVIEW OF BREXIT IMPACTS AND FUTURE PROSPECTS

The consequences of Brexit for UK farm sectors have been varied. In livestock products, global pressures have limited the scale of impacts: there has been continued increase in demand worldwide for meat and dairy products. A reduction in the EU dairy herd, and in the UK herd before Brexit, continues, fostering buoyant prices for farms across these key livestock commodities. A more challenging context has evolved for cereals, year on year (linked to market trends and harvest volatility) and thus smaller operators have been financially squeezed or shocked, in turn.

Brexit has seen a reduction in the total number of fulltime farm holdings across the UK and greater concentration of production into fewer, larger businesses (especially in England – Figure 6). There have also been some moves toward regulatory strengthening on specific topics of particular concern (e.g. water quality, which has been declining in recent years). This has contributed to some farmer protests, but these trends were also occurring prior to Brexit.

More broadly, the UK business environment is challenging for farmers. Currently, they are affected by subsidy cuts, high costs of production due to inflationary pressures, and significant workforce gaps and needs arising partly from an exodus of former farm workers from Europe, who have been replaced, where feasible, with workers from much further afield (e.g. dairy workers from the Indian Punjab and Pakistan). Challenges have persisted from a continuation of extreme weather events (e.g. floods in 2024, followed by an extremely long spring and summer drought in 2025), probably linked to wider anthropogenic climate change. Against this backdrop, it is the farms in those UK nations that have continued to receive CAP-style income support, that have been less negatively impacted by Brexit, as well as the early adopters of SFI in England for whom the new scheme offered the best financial returns – i.e. larger farms, in the most productive areas of the country.

Marginal farms in England face particular significant concerns. Many are 'trapped' in former (pre-Brexit) agri-environment scheme agreements for which they are negotiating short-term annual 'rollover' extensions, due to the much less feasible and/or less financially generous options available to them from the still-incomplete new schemes. The almost complete removal of Pillar 1-style support in 2026 has had severe income impacts on these farms, because their level of dependence on subsidy was historically high. However, a significant uplift in livestock prices since 2024, especially for beef cattle, has provided

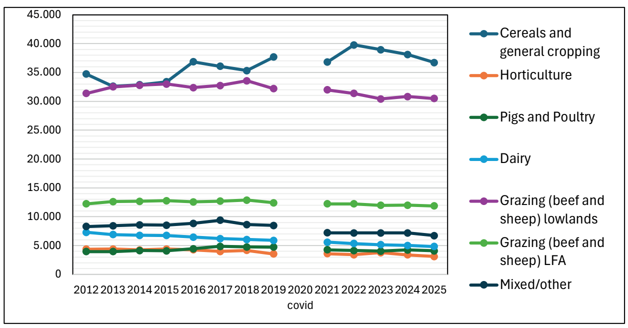

Figure 6. Number of commercial farm holdings by type, England, trends 2012-2025. *Source:* data from Defra, 2025.

one element of positive impact to cushion the negative impacts of an inadequate policy transition package.

Across the UK, farm businesses are increasingly exposed to new demands for land related to other elements of post-Brexit transition, including the development of carbon markets and major investment in renewable energy infrastructure, as well as new housing and transport infrastructure keeping land values high and increasing the gap between farm wages / incomes and the cost of living in rural areas. These trends have been accompanied by reduced UK policy focus on the particular challenges and specificities of rural communities and quality of life, as London-based policy makers have chosen not to retain dedicated 'rural development' support within the agri-linked portfolio. But currently (May 2026), we understand that Wales, Scotland and Northern Ireland are each considering creating new rural development programmes, enabling the continued offer of measures and approaches previously available in CAP pillar 2 (e.g Community-Led Local Development, farm and rural diversification aids, etc.).

8. FUTURE PROSPECTS – NO AGRI-RURAL REPRIEVE?

Following the most recent change of government in 2024, there is now much talk about negative Brexit impacts on the UK economy. Illegal immigration across the English Channel has continued in significant numbers; and polls suggest a reversal of the public's view registered in 2016 – if held tomorrow, a referendum would apparently produce a majority vote in favour of rejoining the EU. Stimulated particularly by political change in the USA and global defence considerations, the UK government is now actively embarking on securing closer ties with the EU, beginning with discussions on achieving alignment in standards and processes.

Considering other contemporary factors, we suggest that farming will remain a low priority for the UK government, within its strong 'growth' focused agenda. However, food policies may have a strengthening profile linked to human health and social inclusion agendas, and the environment will stay (comparatively) strong, among UK policy priorities. Thus, key questions for agri-rural futures could include the following: will we move beyond simple enthusiasm for 'rewilding' which ignores cultural and historic farming-nature interdependence and co-evolution, in the environmental land management arena? What price are UK citizens willing to pay, and at what pace, for better water protection and carbon neutrality? Where does the UK's appetite for food security currently stand, having been comparatively weak in recent decades? And will the UK's obesity and dietary health concerns lead to a new focus on its horticultural production, as several influential NGOs are now proposing? All of these questions are under discussion, among core agri-rural stakeholder communities in the UK nations.

In agri-rural policy, we foresee more scheme-related and policy 'churn' linked to the various policy resets (most notable in Wales and England), plus further roll-out of new elements (perhaps more will now occur in Scotland and Northern Ireland), and a continuing struggle to achieve effective re-design in the face of multiple challenges (especially in England). Whilst the current picture is predominantly of 'top-down' post-Brexit designs, it is possible that in this process of ongoing adaptation, more bottom-up, locally-delivered policies could emerge, building on accumulating research findings in the UK (e.g. Defra, 2022) and across the EU (Bartkowski *et al*., 2023).

In respect of agricultural production impacts, two possible futures are in play. Should the UK anticipate more shrinkage of its land area in production, with a preference for 'zoning' (as in the 'land sparing' approach, e.g. Fischer *et al*., 2014)? Or would an alternative and preferable future trend be towards more diversification of enterprises and business models, along with a growth in short(er) food supply chains and more pluri-activity?

We certainly anticipate a growing rapprochement with the EU in this arena, as in others, which could imply a rebuilding of food trade between the UK and Europe, as well as continuing expansion in trade beyond this continent, on both sides of the partnership.

Finally, we see potential for rural futures to diverge further across the four nations of the UK. As this happens, we could see increasingly divergent rural politics, bearing in mind Government uncertainty and the rise of populist agendas.

At national level, even if defence and security concerns lead to close ongoing partnership with the EU, the prospects for greater UK agri-rural policy alignment with Europe look poor in England, contrasting with the ongoing situation in Scotland and Northern Ireland. In Wales, the election in May 2026 significantly affected its wider political orientation but agri-rural policy will likely continue on its current path, relatively aligned to EU trends. London's UK policymakers may pursue a more globally-focused trade and open markets agenda, with difficult knock-on implications for farm business survival and adaptation. And while some new initiatives in rural and farm-related policy have now emerged in England (a review of farm productivity, an upland communities' project, and proposals for a Land Use Framework to aid multifunctional planning), the level of resources and attention given to rural issues remains modest.

Considering the urgency of transition and transformation in society in response to the climate emergency, we suggest it would be short-sighted for the UK government to ignore the potential and value of rural assets and services to support and enable successful net-zero shift. Within this transition, farming and rural enterprise have important roles to play, in food, diet and health as well as landscape management and public access for resilience and wellbeing. If politicians fully recognise the interlinkages between rural and urban futures, choices and developments, we may see enhanced rural policies both within and beyond farming. However, if this cannot be achieved, we fear continued stagnation of rural economies and domestic food production, through which UK dependence on other nations increases as its population continues to grow. This suggests increased efforts by Scottish, Welsh and Northern Irish policy makers to push back against English dominance of the agenda, increasing inter-UK political friction and divergence.

Of course, we acknowledge the limitations of our brief and narrative approach to envisioning based upon observation and interpretation, which could prove to have missed important influencing factors beyond our sphere of knowledge. Nevertheless, we encourage the UK government to invest in a strengthened and more inclusive rural vision and future policy agenda.

REFERENCES

AHDB (2022). *Defra announce Agricultural Policy transition plans for England* | AHDB. Agriculture and Horticulture Development Board. https://ahdb.org.uk/news/defra-announce-agricultural-policy-transition-plans-for-england (accessed September 2025).

Bartkowski B., Beckmann M., Bednář M., Biffi S., Domingo-Marimon C., Mesaroš M., Schüßler C., Šarapatka B., Tarčak S., Václavík T., Ziv G., Wittstock F. (2023). Adoption and potential of agri-environmental schemes in Europe: Cross-regional evidence from interviews with farmers. *People and Nature,* 5: 1610–1621. DOI: https://doi.org/10.1002/pan3.10526.

Berg A. (2024) *Weighed down by gravity: UK trade policy after Brexit*. Centre for European Reform. London.

DEFRA (2020). *The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024.* HMG, London. https://www.gov.uk/government/publications/agricultural-transition-plan-2021-to-2024#:~:text=show%20all%20updates-,19%20March%202024,30%20November%202020 (accessed 29 April 2026).

DEFRA (2022) *Tests and Trials Evidence Report. Schemes for environmental land management*. June 2022, Version: 1.0. DEFRA. Crown copyright 2023. https://assets.publishing.service.gov.uk/media/64cb763c47915a00142a91de/elm-tt-june22.pdf (accessed 1 May 2026).

DEFRA Welsh Government, Scottish Government, DAERA (2022). *Agriculture In the UK evidence Pack (Agriculture in the UK)*. DEFRA.

Defra Blog (2025). https://defrafarming.blog.gov.uk/2025/06/16/spending-review-2025-a-commitment-to-farming/.

Du J., Beyza Satoglu E., Shepotylo O. (2023): How did Brexit affect UK trade?, *Contemporary Social Science*. DOI: https://doi.org/10.1080/21582041.2023.2192043.

Erkkilä T., Chou M.-H., Mölsä J. (2025). Global models and post-Brexit discourses: ‘Singapore on Thames’ or ‘Nordic Scotland’? *The British Journal of Politics and International Relations*, 0(0).

European Commission (2021). *EU–UK Trade and Cooperation Agreement: Implementation and Border Procedures*. European Commission, Brussels.

Feng S., Patton M., Binfield J., Davis J. (2017). ‘Deal’ or ‘No Deal’? Impacts of Alternative Post- Brexit Trade Agreements on UK Agriculture. *Eurochoices* 16(3): 27-32.

Fischer J., Abson D., Johnson-Chappell M.J., Ekroos J., Hanspach J., Kuemmerle T., Smith H., von Wehrden H. (2014). Land Sparing Versus Land Sharing: Moving Forward. *Conservation Letters*. DOI: https://doi.org/10.1111/conl.12084. Conservation Letters.

Food and Drink Federation (2025). *Food exports to the EU drop by almost a quarter compared to pre-Brexit*. FDF, London.

FRC Food Research Collaboration (2023). *Food, Brexit and Northern Ireland: Critical Issues - Food Brexit Briefings*. Food Research Collaboration. https://foodresearch.org.uk/publications/food-brexit-northern-ireland/ (accessed February 2026).

Freeman R., Manova K., Prayer T., Sampson T. (2022). *“UK trade in the wake of Brexit”*. Discussion Paper, No 1847, Centre for Economic Performance, April 2022.

Hix S., van der Linden C., Savoie J. (2022). Where is the EU–UK relationship heading? A conjoint survey experiment of Brexit trade-offs. *European Union Politics,* 24 (1).

HM Government (2021a). *Wood packaging material for import and export [WWW Document]*. GOV.UK. https://www.gov.uk/guidance/import-or-export-wood-packaging-material (accessed 3 August 2026).

HM Government (2021b). *Border Operating Model: The Border with the European Union*. Cabinet Office, London.

House of Commons (2021). *Seafood and Meat Exports to the EU*. House of Commons - Library.

Jelliffe D., Gerval A. (2025). *European Agri-Food Trade and Brexit: The First 3 Years of the EU-UK Trade and Cooperation Agreement*. USDA Economic Research Service, Washington, DC. Economic Brief Number 41 March 2025.

Jelliffe J., Gerval A., Husby M., Jarell P., Williams B. (2023). *United Kingdom Agricultural Production and Trade Policy Post-Brexit* (Bulletin No. 250). USDA, Economic Research Service.

Kam H., Smith H., Potter C. (2023) Public money for public goods: The role of ideas in driving agriculture policy in the EU and post-Brexit UK. *Land Use Policy,* 129, 106618. https://www.sciencedirect.com/science/article/pii/S0264837723000844?via%3Dihub.

Lenormand T. (2023). *The Common Agricultural Policy: Towards a greener policy, a continuous evolution of a policy made of compromises. Further devolution and more possibilities*. Countryside and Community Research Institute, Cheltenham, UK.

LSE Centre for Economic Performance (2024). *Deep Integration and Trade: UK Firms in the Wake of Brexit*. London School of Economics, London.

UK Parliament (2017). Lords EU Committee report. https://publications.parliament.uk/pa/ld201719/ldselect/ldeucom/9/909.htm

National Farmers Union (2025). *UK-EU SPS negotiations: Influence and transition* [WWW Document]. URL https://www.nfuonline.com/news/uk-eu-sps-negotiations/uk-eu-sps-negotiations-influence-and-transition/ (accessed March 2026).

NICRE National Innovation Centre for Rural Enterprise (2021). *The effects of the Covid-19 pandemic on rural businesses: experiences and resilience*. State of Rural Enterprise Report No 1, January 2022. www.nicre.co.uk.

NICRE (2023). *The cost-of-doing-business crisis: rural impacts and adaptation*. State of Rural Enterprise Report No 4, November 2023. www.nicre.co.uk.

OECD (2023). *Agricultural Policy Monitoring and Evaluation 2023: Adapting Agriculture to Climate Change*. OECD, Paris. DOI: https://doi.org/10.1787/b14de474-en.

OECD (2025). *Agricultural Policy Monitoring and Evaluation 2025: Making the Most of the Trade and Environment Nexus in Agriculture*. OECD, Paris. DOI: https://doi.org/10.1787/a80ac398-en.

Rte Ireland (2016). *news release on the Irish government's publication of its Brexit planning framework*. https://www.rte.ie/documents/news/irish-government-brexit-contingency-plans-announced.pdf (accessed 28 April 2026).

UK Trade Policy Observatory (2022). *The UK–EU Trade and Cooperation Agreement: Early Evidence on Trade and Border Effects*. University of Sussex, Brighton.

Welsh Government (2025). announcement: https://www.gov.wales/basic-payment-scheme-tapering-payment-entitlements-and-closure-wales-regulations-2025-integrated-html.

Welsh Government (2026). *Rural Economy statistics*. WG, Cardiff.

Welsh Parliament (2025). *Farming in Wales in 2025: Challenges and Opportunities*. House of Commons Committee report. https://publications.parliament.uk/pa/cm5901/cmselect/cmwelaf/785/report.html#heading-4.

World Bank (2024). *Ukraine Economic Update: Agriculture and Trade Impacts of the War*. World Bank, Washington, DC.

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Research article

Understanding how milk-producing countries estimate costs of dairy production: A comparative review

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Abstract. Benchmarking milk cost of production (CoP) helps identify economic performance disparities, guide business decisions, and shape policy regulations across the dairy industry. However, the reliability of CoP data is heavily influenced by the methodologies employed. Comparisons remain challenging due to variations in farm business characteristics, accounting regulations, market dynamics, and political considerations. Therefore, this review aims to explore the diverse CoP methodologies to compare the cost frameworks and revenues of dairy enterprises in countries that are significant producers in the global market. The analysis includes countries from the EU27 (Germany, France, the Netherlands, Poland, Italy, and Ireland), along with the United States, Canada, Brazil, Australia, and New Zealand, in comparison with global dairy network benchmarks. The findings clearly demonstrate that methods for calculating milk CoP vary considerably among countries. In addition, discrepancies in CoP methods may distort the disparities in the economic performance of dairy operations. This study concludes that variations in cost frameworks across countries hinder effective cross-country comparisons of milk CoP, and that current harmonised frameworks provide decent estimations when compared to national calculations. To address this issue, it is recommended that global dairy networks develop harmonised methodologies that consider existing official national methods and local contexts, thereby enhancing policy relevance and improving comparison accuracy.

Keywords: dairy farming, milk price, milk production, production costs, Typical Farm Approach.
JEL codes: C81, Q12, Q14.

HIGHLIGHTS:

– Key cost components, such as feed and labour, are defined differently in various countries.

– Countries differ in including cattle sales and subsidies in milk cost of production calculations.
– Low milk prices in most milk-producing countries fail to cover full production costs.
– The Typical Farm Approach is a decent method but tends to underestimate the cost of production in pasture-based milk-producing countries.

1. INTRODUCTION

Cost of production (CoP) data provide valuable insights into the efficiency of agricultural production systems by illustrating the relationship between inputs and outputs (Hegazi, 2024). However, the reliability of CoP data is heavily influenced by the methodologies employed for its collection and interpretation (Langrell *et al*., 2012). Harmonising data from diverse sources into a unified database presents significant challenges, particularly in the absence of standardised international protocols (Hemme *et al*., 2014). A critical prerequisite for evaluating the suitability of existing CoP databases for comparative analysis is the understanding of the various methodologies and contexts across countries. Nations apply distinct methods to calculate CoP for agricultural commodities, yet the underlying principles remain consistent (Langrell *et al*., 2012). Although less globally tradable given the majority of global dairy products is consumed within the country of production (Ohlan, 2014), milk requires specialised CoP analysis due to the unique characteristics of the dairy industry. Milk production is regionally influenced by factors such as farm characteristics and management, feed resources, climate, and regulations (Britt *et al*., 2018; Stirm, St-Pierre, 2003), resulting in distinct cost structures. Unlike other commodities, the allocation of joint costs between livestock and crop enterprises, as well as between milk and beef production, further complicates cost calculations (Food and Agriculture Organisation of the United Nations [FAO], 2016; International Farm Comparison Network [IFCN] Dairy Network, 2022). In general, CoP methods are often influenced by political intentions (Belloin, 1998; Mykrantz, Bozic, 2022; Smith, 1974; Stanbury, 2002) and reflect national or organisational goals (Allain, Laurin, 2018; Quesado, Silva, 2021). Despite previous attempts to standardise methods at the regional level, substantial methodological differences persist, resulting in limited comparability of CoP data, even within geographically close regions. For example, the European Milk Board (EMB), a group of European dairy associations, has criticised the European Union (EU) Commission's harmonised CoP methods, arguing that they fail to capture the diversity of dairy production systems across Europe (EMB, 2021). Hence, comparing milk CoP valuations across countries remains a complex challenge, requiring greater collaboration and consensus among stakeholders at both the regional and international levels.

Efforts to harmonise CoP methods could enhance the comparability and relevance of milk CoP data at the global level. The IFCN, a global dairy network, has made strides towards this goal by collaborating with research partners to analyse typical dairy farming systems and report international production costs. The IFCN's methodology, however, lacks clarity in distinguishing between approaches. Previous research on milk CoP has focused on its unbiased measurements across countries (Belloin, 1998; Hemme *et al*., 2014) and the development of automated tool to efficiently benchmark dairy farms within countries (Freitas, Cabrera, 2025). While numerous scholars have broadly examined agricultural CoP (FAO, 2016; Langrell *et al*., 2012; Ronzon *et al*., 2014), these studies have not accounted for methodological differences specific to milk CoP. More specifically, three conceptual strategies have been proposed for global comparisons of CoP methods: (1) *minimalistic harmonisation*, which uses existing databases as-is to compare CoP data across nations with minimal adjustments; (2) *partial harmonisation*, advocating for a unified approach to data collection and CoP methods by governments; and (3) *full harmonisation*, aiming to establish global networks with standardised CoP methods and continuous refinement (Langrell *et al*., 2012).

Given the above background, this review aims to examine the differences and similarities in milk CoP calculations across selected countries, identifying the key national and international factors that influence these variations. While the primary focus is on CoP, farm revenue is also investigated to highlight disparities in economic performance. To achieve this, a minimalistic harmonisation strategy is first implemented using national-level databases for international comparisons, followed by a critical evaluation of a full harmonisation strategy based on current globally harmonised milk CoP methods. Then, economic performance is compared using two different conversion factors based solely on cost-revenue calculations. Finally, the implications of differing CoP methods on dairy trade policies are explored. This comprehensive approach may help identify fair comparisons, inform business decisions, and guide dairy trade policies.

2. DATA SOURCES AND METHODOLOGIES

2.1. Data sources for global comparative analysis and harmonisation methods

This review uses milk CoP data from multiple sources, as presented in Table 1. The inclusion of particular countries in this analysis is principally justified by their significant milk production volumes and the accessibility of comprehensive data relevant to the dairy industry under study. All datasets are made publicly available by government bodies, agricultural institutions, and dairy associations, thus ensuring a high level of transparency and reliability. For the sake of clarity, it is worth mentioning that differences in data collection, categorisation, and timeframes may affect the comparability of the data across countries. In addition, although these datasets are comprehensive, they vary in terms of representativeness: some of them cover a broad range of farms and others focus on specific regions or production systems.

Upon data collection, EU countries were classified as fully harmonised, as they have already reached a consensus on reporting milk CoP among member states. To ensure consistent comparison, minimised harmonisation for EU countries and others was applied to adjust disparities across the reviewed nations.

Full harmonisation

EU member states have made progress in standardising methodologies for calculating milk CoP, aiming for full harmonisation through uniform data collection and cost calculation systems. This effort involves restructuring national systems to standardise sampling strategies and to harmonise calculation frameworks. In this study, three full harmonisation methods are compared: the IFCN, the EMB, and the EU Commission. While the EMB and the EU Commission rely on standardised data from the Farm Accountancy Data Network (FADN), the IFCN uses primary data from its own surveys. The tilde symbol (~) is used to indicate approximate data from the IFCN. Regional data, where available, help highlight geographical variations in milk CoP, hence facilitating comparisons with the IFCN's Typical Farm Approach (TFA), the latter representing specific production systems, farm sizes, technologies, and milk volumes in each specific country/dairy region (CLAL.IT, 2024; Hemme *et al*., 2014). Regional milk CoP data for Canada is not available.

Minimalistic harmonisation

A minimalistic harmonisation approach for milk CoP uses existing databases without modifying national data collection systems. In this study, several adjustments are applied to make the data comparable across countries, including currency differences, milk cost units, inflation factors, and standardised milk quality (Table A.1). This approach is cost-effective and practical because it utilised existing data and minimises institutional changes (Langrell *et al*., 2012). Table A.1 presents the adjustments made to standardise milk CoP data, as the original datasets use various calculation units. First, weight units such as tons, hundredweight (cwt), hectolitres (hl), and litres were converted into kilograms (e.g., 1 cwt equals 45.359 kg). For data from Australia and New Zealand, 1 kg of milk solids was multiplied by the sum of fat and protein percentages divided by 100 to estimate the total milk weight. Second, the original currencies were converted into U.S. dollars (USD) to ensure comparability, utilising exchange rates from CLAL.IT (2024) and purchasing power parity (PPP) conversion factors from the World Bank (2025). PPP provides insights into the relative economic burden within countries by adjusting for cost of living and inflation, making it suitable for structural economic analysis. In contrast, the exchange rate method is more aligned with real-time financial conversions and international trade dynamics. However, using nominal exchange rates can be strongly misleading in cross-country price comparisons (Amat *et al*., 2014; Pant, Fisher, 2007). Thus, this study employed both

Table 1. Milk cost of production data sources.

Country	Abbreviation	Sources
European Union	EU	Eurostat/ EU Commission
United States of America	US	United States Department of Agriculture (USDA)
Canada	CA	Canadian Dairy Commission (CDC)
Brazil	BR	Companhia Nacional de Abastecimento (CONAB)
Australia	AU	DairyAustralia
New Zealand	NZ	DairyNZ

methods to provide complementary perspectives. Third, milk units were standardised to energy-corrected milk (ECM) based on percentage of fat (% fat) and crude protein (% crude protein) using the formula (IFCN Dairy Network, 2018):

$$ECM\ (kg) = Milk\ (kg) \times ((0.383 \times Fat\ \%) + (0.242 \times Crude\ Protein\ \%) + 0.7832)/3.1138$$

Finally, the producer price index (PPI) data from FAOSTAT (2025) were used to remove inflationary effects from nominal values, yielding real values of milk CoP in USD per 100 kg ECM, excluding the global milk farm gate price comparisons. In this study, the proportional and total milk CoP are presented as averages from 2018 to 2021, unless stated otherwise. Averaging the data minimises the effects of outliers and short-term fluctuations, providing a clearer understanding of regional cost structures by smoothing annual variations (Conigliani, Tancredi, 2009; Negrín, Vázquez-Polo, 2008).

2.2. Reporting practices and financial year considerations

Dairy operations may be based on different financial years for reporting, which can affect the comparability of financial data. Typically, the financial year for dairy operations aligns with the calendar year, such as January 1 to December 31 in the EU, the United States, and Brazil. Dairy operations follow a different financial year in Canada (August 1 to July 31) (Canadian Dairy Commision, 2024), Australia (July 1 to June 30) (Australian Bureau of Agricultural and Resource Economics and Sciences [ABARES], 2024), and New Zealand (April 1 to March 31) (DairyNZ, 2024). This variation in financial year reporting introduces a potential source of inconsistency in milk CoP data. For example, in cases where the financial year does not align with the calendar year, milk cost publication reports may state 2018/2019 because their calculations include portions of both 2018 and 2019. Therefore, this study assumes that the 2018/2019 milk CoP data from the reviewed countries reflects the year 2018, and similarly for other years. This assumption is based on the consistent seasonal patterns in milk production and minimal year-over-year variation observed in Canada, Australia, and New Zealand.

2.3. Methods for allocating joint farm costs

Joint cost allocation methods are commonly employed on mixed-use dairy farms to distribute costs among outputs such as milk and beef, which are derived from shared resources. Panel (a) on Figure 1a highlights yellow (1) and blue (2) areas representing different dairy animals included in the milk cost of production (CoP) calculation, which share feed production. Panel (b) shows the intersecting (3) and distinct resources utilised by animal and plant production, which share feed and cash crop costs. These methods vary by country and can impact the final milk CoP figures. For example, most countries consider only dairy cows (Figure 1a, number 1), while the EMB includes both dairy cows and other cattle (Figure 1a, number 2) when allocating feed costs, recognising that milk and beef are inseparable outputs. However, certain costs, such as farm management and

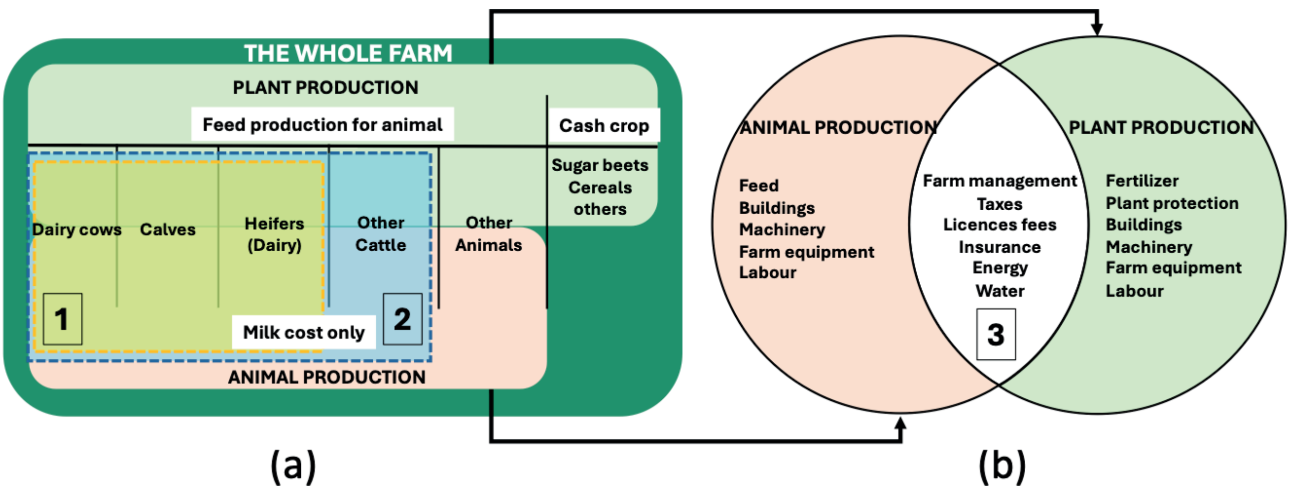

Figure 1. The structure of a mixed-use dairy farms: animal production (1) and plant production (2) and its intersecting (3). *Source*: Modified from and FAO (2016) and IFCN Dairy Network (2022).

energy (Figure 1b, number 3), remain difficult to allocate, regardless of the method used. Enterprise accounting methods can provide a more accurate allocation of these costs. On the other hand, the residual value method, which involves subtracting non-milk revenues (e.g., cattle sales) from total costs, or the proportional cost methods, which allocate costs based on revenue or specific cost items to calculate "milk cost only", often lack clear justification and can introduce variability into the CoP calculations. Nevertheless, due to the minimalistic approach employed and the lack of detailed information provided by the data sources for each country, no harmonisation of joint farm cost allocation was applied.

2.4. Cost component categorisation

In this study, cost components refer to the various categories of expenses, such as feed cost, labour cost, or depreciation, that collectively contribute to the total cost of milk production. The color-coding scheme in Table A.2, guided by expert judgment and relevant references, distinguishes between homegrown feed (dark green), purchased feed (light green), hired labour and imputed owner (dark blue), dairy related expenses (grey), general expenses (purple), and other expenses (orange). This approach simplifies comparisons. Variations in costing methodologies (e.g., full costing vs activity-based costing), however, introduce some degree of complexity. Activity-based costing allocates costs to activities before tracing them to specific cost objects (Quesado, Silva, 2021), while some countries group costs differently depending on their national accounting systems. For example, some countries categorise fuel and oil as part of homegrown feed, while others classify them as separate expenses under the general expenses group (fuel and oil expenses).

3. DAIRY FARM CHARACTERISTICS

Accurate comparisons of milk CoP across countries require understanding key dairy farm characteristics like breed, milk yield, farming structures, and practices (Parzonko *et al*., 2024). Disparities in milk production efficiency, farm structure, and per-cow yield are evident, as shown in Table 2. The EU, contributing 19% of global milk production (CLAL.IT, 2024), has numerous small farms with extensive herds (Arendonk, Liinamo, 2003), while the United States achieves the highest per-cow milk yield, with Canada showing similar productivity despite fewer farms. The TFA farm size does not represent the average farm size in the respective country (Table 2). Instead, it reflects the sample farm size used by the IFCN in specific regions for cost estimation (see further up in the paper, Figures 3 and 4). This value is part of a model that standardises farming practices, ensuring that the actual average farm size is not misinterpreted as representing the entire country. Brazil, with no more than 8% of the global dairy cow population (CLAL.IT, 2024), has the lowest per-cow yield due to traditional practices and limited technology (Bernardes, Rêgo, 2014). New Zealand and Australia focus on large-scale operations, but they present moderate per-cow productivity due to extensive grazing systems (Luo, Ledgard, 2021).

Breed and management practices influence milk yield, with Holsteins predominant in Germany, France, Italy, and Ireland, achieving over 8,000 kg per lactation (Coffey *et al*., 2016; Probo *et al*., 2024). In Poland, Holstein imports have boosted the daily yield by 62% since 2004 (Ziętara *et al*., 2024). Crossbreeding in Ireland has improved milk solids, while grazing systems in the Netherlands have maximised productivity (Coffey *et al*., 2016; Weigel *et al*., 2001). Holsteins and Jerseys are common in the United States, Canada, Australia, and New Zealand, with Holsteins offering higher yields and Jerseys producing more butterfat (Hagan *et al*., 2021; Harris, 2005; Lozada-Soto *et al*., 2022; Nguyen *et al*., 2017; Oliveira *et al*., 2019). In Brazil, crossbreeding Zebu with Holstein enhances yields (Freitas *et al*., 1998). A once-a-day (OAD) milking frequency in pasture systems, such as those in Ireland (Murphy *et al*., 2023) and New Zealand (Jayawardana *et al*., 2023), can reduce labour but may not be universally feasible (Edwards, 2020; Lazzarini *et al*., 2018). Twice-a-day (TAD) milking remains more common, yielding higher milk production despite higher feed costs (Correa-Luna *et al*., 2021), although OAD raises concerns about animal health and welfare (Murphy *et al*., 2023).

4. ESTIMATION OF MILK COP AND REVENUE

4.1. Milk CoP framework and typologies

Overview of milk CoP frameworks

The milk CoP framework for each country is detailed in Table A.2, with notations (e.g., A, B, C) to facilitate identification of calculations while preserving original cost item names. The EMB methodology adjusts for input costs using the "production value of beef" (Code B) and excludes non-dairy revenues but includes Common Agricultural Policy (CAP) payments to capture subsidy impacts. In contrast, the EU framework incor-

Table 2. Cross-country comparison of dairy production performance in 2020.

Country	Annual milk production[1] (thousands of tons)	Number of dairy cows[1] (thousands of heads)	Number of dairy farms[1]	Typical Farm Approach farm size[2] (heads)	Milk yield per cow per year[1] (quintals)
EU27	160,785	20,523	826,170	NA	78.3
Germany	33,165	3,921	54,310	154	84.6
France	25,235	3,406	56,200	74	74.1
Netherlands	14,522	1,569	15,730	103	92.5
Poland	14,503	2,126	174,290	52	68.2
Italy	12,712	1,638	36,230	154	67.9
Ireland	8,542	1,456	17,500	91	58.7
United States	101,292	9,442	1,992,820	80	107.3
Canada[3]	9,620[3]	1,401[3]	10,095[3]	66	66.7[3]
Brazil	36,376	15,954	1,822	180	22.8
Australia	9,064	1,388	5,055	307	63.6
New Zealand	22,351	4,904	6,046	397	44.6

Note: NA, not available.
Source: 1 CLAL.IT (2024); 2 IFCN Dairy Network (2022); 3 Canadian Dairy Commission (2024).

porates imputed family labour and opportunity costs (Code J). The IFCN methodology emphasises opportunity costs and "entrepreneurship's profit" (Code G), incorporating unpaid labour, land rent, and capital use for global benchmarking and profitability analysis. The U.S. framework incorporates unpaid labour and land opportunity costs in its profit calculations, while Canada includes government rebates and Brazil details tropical-specific input costs. New Zealand focuses on "freight and general" costs, reflecting its export orientation. Canada and Brazil prioritise milk CoP and exclude revenue sources, assuming milk prices as the sole income.

Opportunity cost in milk production refers to the benefits a farmer forgoes by dedicating resources, such as land, labour, or capital, to milk production instead of other activities (Mykrantz, Bozic, 2022). The IFCN Dairy Network (2022) defines it as costs related to using owned resources, including land and family labour. U.S. methodologies integrate unpaid labour and land opportunity costs into their financial assessments, while Canadian and Brazilian frameworks adjust for policy and tropical-specific costs. Cost typologies vary by farm scale and financial needs, with small farms focusing on direct, cash, and variable costs, and large farms addressing fixed and capital costs (Inna *et al*., 2024). Financial management distinguishes between cash and non-cash costs, while economic approaches incorporate opportunity costs to reflect alternative values, in contrast to accounting approaches that focus on actual payments (FAO, 2016; Ronzon *et al*., 2014).

Key milk CoP components

The key cost components of milk production, including feed, labour, imputed owner costs, and depreciation, are critical to the overall cost structure and profitability of dairy farming (Chamberlain, 2012). These components are categorised differently across countries, as outlined in Table A.2. Feed costs are divided into the home-grown and purchased categories. Home-grown feed includes grazed feed and harvested feed like silage and haylage, which incur costs for pasture planting, maintenance, and storage. Purchased feed includes green fodder and dry fodder, which are bought externally, as well as concentrates, which may be produced on-farm or purchased (Reeson *et al*., 2008). In Australia and New Zealand, agistment or support block costs, referring to external grazing land rental or on-farm land maintenance, are also considered part of the feed costs (Table A.2).

Labour costs are classified into hired and unpaid labour, with most countries accounting for both, although Brazil and Australia may exclude unpaid labour (Table A.2). Hired labour is valued at market wage rates, while unpaid labour, typically family labour, is valued differently depending on working hours, willingness to pay, or regional wages (FAO, 2016). Capital investment is valued variably across frameworks, with the IFCN and the United States using opportunity costs, the EU using imputed family factors, reflecting market wages or the payment based on willingness to pay (Agricultural & Applied Economics Association [AAEA], 2000). Brazil calls it factor income, and Australia labels it imputed owner costs (Table A.2). Depreciation, which accounts for the reduction in the useful life of assets such as machinery and breeding animals, also plays a significant role in cost structures. It is typically calculated using the straight-line method to align costs with long-term milk production (Berg, Moore, 1989; Williamson, Stutzman, 2016).

4.2. Proportional analysis of milk CoP components

Table 3 shows the average cost structure per kilogram of milk ECM from 2018 to 2021, offering a stable comparison of cost components across regions. Each country follows its own calculation method, as detailed in Table A.2. New Zealand and Australia, with their pasture-based systems, allocate a larger share of costs to home-grown feed, reducing overall production costs but also exposing them to risks from weather conditions or seasonal variations (Kamal, Noy, 2023). In contrast, Italy and Australia report the highest proportions of purchased feed and concentrate costs, making them more vulnerable to global commodity price fluctuations. These variations in feed costs illustrate the value of international comparisons and underscore the impact of production systems and market dependencies on cost structures (Ozawa *et al*., 2005).

Labour cost distributions vary across regions, reflecting differences in farming practices. Brazil has the highest proportion of labour costs, while the Netherlands and France report much lower labour costs due to efficient feed use and high milk production per cow (Thomassen *et al*., 2009). These differences highlight how labour efficiency influences milk CoP and profitability. Imputed owner costs also reveal structural differences in farming operations, with Poland and Canada showing higher proportions due to family-owned farms, while the United States reports lower imputed owner costs (Tian *et al*., 2020). General expenses, which reflect technological adoption and infrastructure, are highest in Germany and France, indicating substantial investments in farm efficiency (Ruzzante *et al*., 2021). These differences in cost structures impact regional competitiveness, resilience to economic shocks, and global market positioning (Beber *et al*., 2021).

4.3. Global variations in total milk CoP

The EU shows significant internal variation in average milk CoP from 2018 to 2021, with notable contrasts between Western and Eastern Europe (Table 4). Poland reports lower costs compared to the Netherlands, Italy, Germany, and France, due to differences in farm practices, labour costs, and technological adoption (Table 3). American producers generally face higher costs, with Canada notably impacted by high feed, labour, land, and machinery costs (Hemme *et al*., 2014). In contrast, Brazil's milk CoP is lower, reflecting intensive production methods and advanced technology use, while the United States remains more competitive. Oceania presents diverse profiles, with Australia maintaining relatively lower costs due to deregulation and economies of scale dynamics (Dobson, Wagner, 2000; Phillipov, Loyer, 2019), while New Zealand experiences higher costs due to rising input prices and tax policies (Frengley, Johnston, 1992; Kamal, Noy, 2023).

Table 3. Proportional percentage (%) contribution of each cost component to the total milk cost of production, based on average data from 2018 to 2021.

Country	Home grown feed	Purchased/ concentrate feed	Hired labour cost	Imputed owner	Dairy-related expenses	General expenses	Other expenses	Total
EU27	*9.7*	*22*	*5.3*	*17.4*	*0.6*	*33.1*	*12*	*100*
Germany	*7.6*	*19.6*	*6.8*	*15.8*	*0.8*	*36.8*	*12.7*	*100*
France	*8.1*	*19.1*	*2.5*	*13.5*	*0.4*	*39.3*	*17.2*	*100*
Netherlands	*6.9*	*22.7*	*1.7*	*17.4*	*0.5*	*34*	*16.9*	*100*
Poland	*14.2*	*17.3*	*3.8*	*28.6*	*0.9*	*30.2*	*5.1*	*100*
Italy	*13.7*	*32.2*	*5.7*	*19.6*	*0.7*	*19.9*	*8.2*	*100*
Ireland	*9.8*	*20.8*	*3.6*	*23.7*	*0.8*	*32.9*	*8.5*	*100*
United States	*15.3*	*32.2*	*9.2*	*7.9*	*4.2*	*29.4*	*2*	*100*
Canada	*4.2*	*23.4*	*4.9*	*29*	*2.3*	*23.4*	*12.8*	*100*
Brazil	*10.2*	*20.5*	*17.8*	*16.6*	*5*	*19.2*	*10.8*	*100*
Australia	*15.8*	*32.9*	*11.7*	*13.3*	*7.7*	*14.1*	*4.5*	*100*
New Zealand	*15.8*	*15.3*	*9.2*	*9.7*	*8.3*	*18.3*	*23.4*	*100*

Table 4. Contribution of each cost component to total milk cost of production (CoP) in U.S. dollars (USD)/100 kg energy-corrected milk (ECM), averaged from 2018 to 2021.

Country	Home grown feed	Purchased/ concentrate feed	Hired labour cost	Imputed owner	Dairy related expenses	General expenses	Other expenses	CoP_1	CoP_2
EU27	5	11.4	3	8.9	0.4	18.1	6.5	53.3	N.A.
Germany	4	10.2	3.6	8.3	0.4	19.3	6.7	52.5	31.8
France	4.1	9.5	1.2	6.8	0.2	19.7	8.6	50.1	31.5
Netherlands	4.0	13.0	1.0	9.9	0.3	19.4	9.6	57.2	37.1
Poland	6	7.3	1.6	9.3	0.4	12.8	2.2	39.6	58.3
Italy	6.3	14.9	2.6	9.1	0.3	9.2	3.8	46.2	25.0
Ireland	4.6	9.7	1.7	11.1	0.4	15.4	4.0	46.9	32.4
United States	7.6	16.0	4.6	3.9	2.1	14.6	1.0	49.8	49.8
Canada	2.8	15.3	3.2	18.9	1.5	15.3	8.4	65.4	102.4
Brazil	5.3	10.3	9.1	9.2	2.6	10	5.7	52.2	508.0
Australia	6.9	14.4	5.1	5.8	3.3	6.2	2.0	43.7	88.4
New Zealand	8.3	8.0	4.8	5.1	4.4	10.1	11.7	52.4	112.1

Note: CoP_1 refers to the total milk cost of production calculated using exchange rate calculation. CoP_2 refers to the total cost based on the purchasing power parity (PPP) approach calculation.
Source: Data and calculations are based on the European Commission (2021) for the EU27, USDA (2024) for the United States, the Canadian Dairy Commission (2024) for Canada, CONAB (2020) for Brazil, DairyAustralia (2024) for Australia, and DairyNZ (2024) for New Zealand.

Moreover, milk CoP calculated using the PPP approach is significantly lower than when using exchange rates, with differences ranging from 10 to 20 USD/100 kg ECM in EU countries. This discrepancy arises because nominal exchange rates fluctuate around their PPP values rather than precisely reflecting them (Sercu *et al*., 1995). Consequently, calculations based on exchange rates may overvalue production costs, especially in countries with a higher proportion of non-tradable inputs and elevated general price levels, as these rates do not accurately capture local purchasing power. By comparing PPP-adjusted costs, we can evaluate the relative efficiency of milk production across countries (Biesebroeck, 2009; Bureau, Butault, 1992). Lower PPP-adjusted costs may suggest more efficient production processes or favourable economic conditions (McNown, Wallace, 1989), as observed in most EU countries in this study, excluding Poland (Table 4). However, it is understandable that Brazil exhibits extremely high milk PPP-adjusted costs due to its economy with high inflation (McNown, Wallace, 1989).

4.4. Farm gate milk price comparisons

In this section, we analyse prices from the milk trader's perspective, where nominal values reflect current market prices and provide a direct snapshot of price competitiveness and market dynamics, which are key for assessing trade positions and pricing strategies in global markets. Farm gate milk prices experienced fluctuations but stabilised after the EU abolished its milk quota in 2015, averaging 42.87 USD/100 kg ECM from 2016 to 2024 (Figure 2). Prices within the EU varied significantly, with Poland recording the lowest average price, reflecting its production efficiency (40.55 USD/100 kg ECM) (Ziętara *et al*., 2024), while Italy reported higher average prices (45.28 USD/100 kg ECM), influenced by consumer preferences for local and differentiated products (Bimbo *et al*., 2016). From February 2020, farm gate milk prices began to rise due to supply concerns linked to coronavirus 2019 (COVID-19) restrictions, with a sharp peak following the Russia-Ukraine conflict in February 2022. Disruptions in Ukraine, a key supplier of agricultural inputs, further increased costs (Brunk, Hakimi, 2022). By 2023, milk prices declined due to adjustments in global supply and demand.

Globally, the average milk price was 41.55 USD/100 kg ECM, with notable regional variations (Figure 2). New Zealand's price of 36.82 USD/100 kg ECM reflects its export-oriented, grass-based system but also highlights its vulnerability to market and climatic fluctuations (FAO, 2023; Kamal, Noy, 2023). The United States averaged 42.24 USD/100 kg ECM, while Canada recorded the highest price at 59.59 USD/100 kg ECM, due to its supply management system, which balances stable farmer income with reduced international competitive-

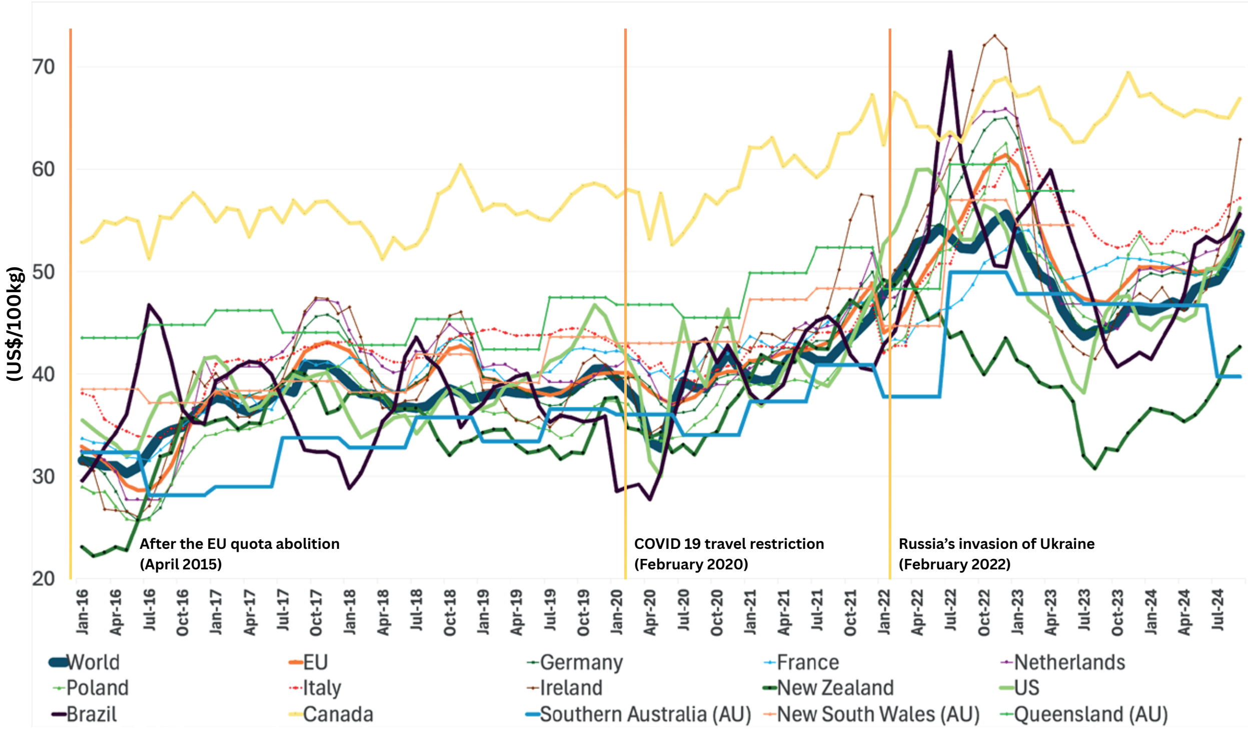

Figure 2. Farm gate milk nominal price (without inflation adjustment) from 2016 to 2024, with key global events highlighted. *Source*: Based on data from ABARES (2024); Canadian Dairy Commission (2024); CLAL.IT (2024); Dairy Australia (2024); Dairy NZ (2024); USDA (2024).

ness. Brazil's price of 41.87 USD/100 kg ECM is competitive, driven by cost advantages in inputs, although it still faces infrastructure challenges. In Australia, milk prices remained relatively stable due to alignment with the dairy financial year, with regional variations including 37.64 USD/100 kg ECM in Southern Australia, 43.62 USD/100 kg ECM in New South Wales, and 47.84 USD/100 kg ECM in Queensland (Figure 2). These regional differences are influenced by climatic conditions and operational practices (ABARES, 2024), reflecting how local factors impact overall farm gate milk prices.

4.5. Quantitative insights into cost and revenue margin estimates

The comparison of 2021 data using the IFCN, EMB, and EU Commission milk CoP methodologies reveals both consistent patterns and significant disparities (Figure 3). The EMB consistently reports higher milk CoP, with France at 63.06 USD/100 kg ECM, compared to 50.77 USD/100 kg ECM reported by the EU Commission and 47 USD/100 kg ECM reported by the IFCN. These differences reflect the varying methodologies, such as the EMB's inclusion of additional cost factors (e.g., other livestock roughage eaters). The IFCN methodology consistently yields the lowest CoP, except in Italy, while higher CoP results are seen in the Americas, particularly in Canada and Brazil (Figure 4). These discrepancies underline the impact of the methodology on CoP estimates, which can affect farmers' understanding of their cost structures. Such international comparisons are crucial for assessing regional competitiveness and understanding local influences on CoP.

In Australia and New Zealand, excluding financial components like interest and taxes creates discrepancies compared to the IFCN estimates. For example, in Canterbury, excluding these charges reduces CoP from 54.98 USD/100 kg ECM to 43.43 USD/100 kg ECM (DairyNZ calculation), whereas the IFCN estimate is lower at 34 USD/100 kg ECM. New Zealand's milk production costs, driven by feed, wages, and interest charges, reflect additional financial burdens placed on farmers (Kamal, Noy, 2023; Ozawa *et al.*, 2005). These regional variations in cost structures provide valuable insight into the factors influencing CoP across diverse dairy systems.

The disparity between milk CoP and farm gate prices reveals significant financial challenges in the dairy sector (Figure 5). Most regions experience persis-

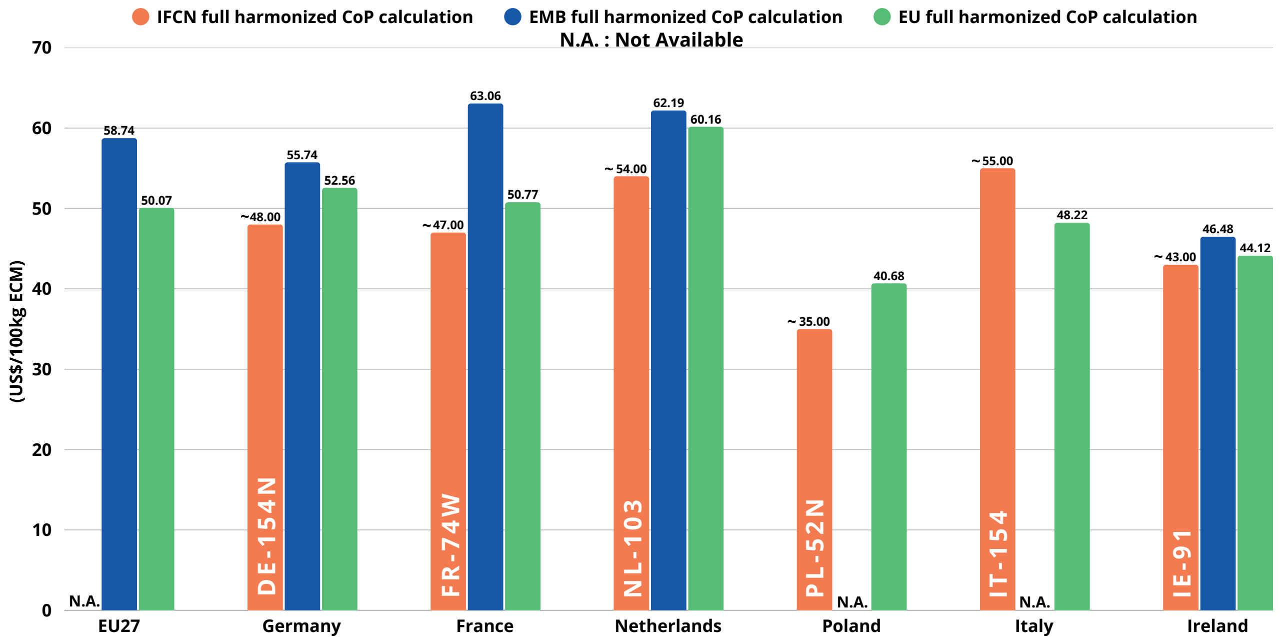

Figure 3. Comparison of milk cost of production (CoP) across five European Union (EU) milk-producing countries in 2021 using different fully harmonised CoP calculation methods.

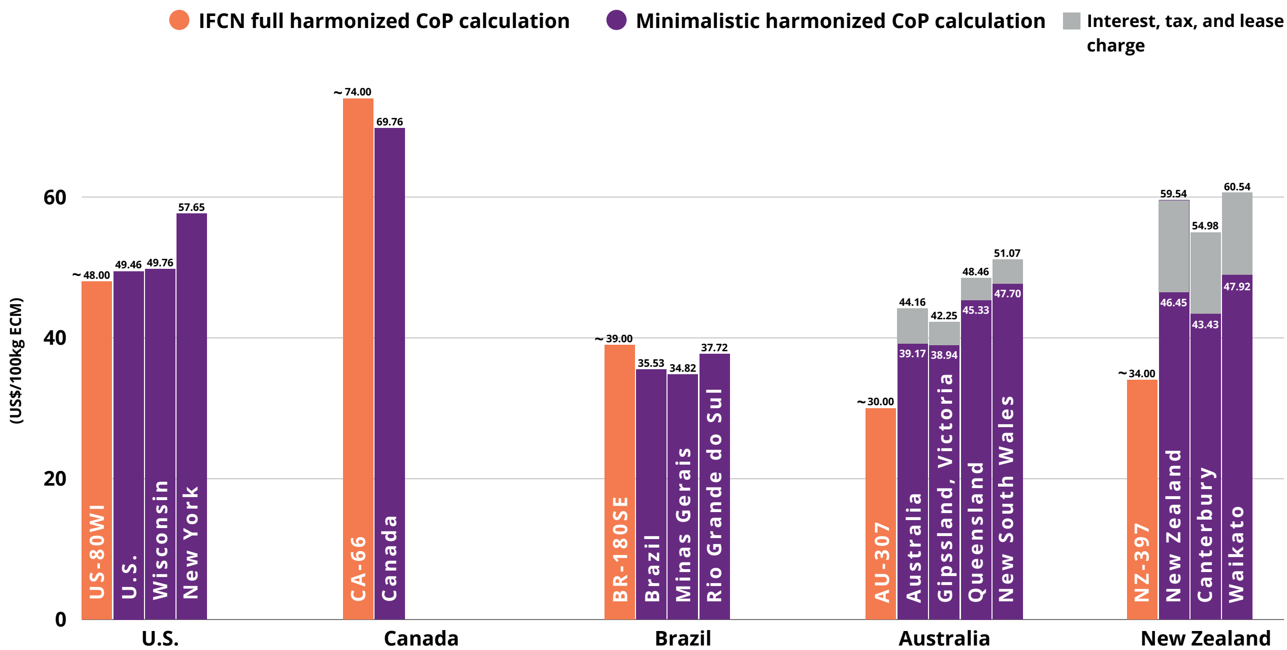

Figure 4. Comparison of milk cost of production (CoP) across non-European Union (EU) milk-producing countries in 2021, and the IFCN's Typical Farm Approach (TFA) data.

tent shortfalls in covering production costs, although New Zealand and Italy manage to align prices with or exceed CoP, offering better profitability. New Zealand's grass-based system helps keep costs low, while Italy's premium dairy products, such as specialty cheeses, drive higher prices (Chatellier, 2021). In contrast, the United States faces the largest shortfall of 9.15 USD/100 kg ECM from 2018 to 2021, indicating significant cost pressures. When using PPP-adjusted costs, the discrepancies in milk cost and price are smaller, with Brazil showing a positive margin, suggesting that in real terms, Brazilian producers may achieve profitability. This comparison demonstrates how different CoP methods, including or excluding cost items, may distort the disparities in the economic performance of dairy operations. Further, this study highlights the potential bias interpretation in the dataset used for CoP estimates, which should be considered a limitation (Figure 5). Indeed, the choice between typical farms and farm samples can impact both costs and revenues, while structural efficiency and milk prices vary significantly across farms. This variability may explain the apparent profitability of milk production in countries like Italy, despite a decline in production and farm closures in recent years (European Commision, 2021).

5. DISCUSSION AND CONCLUDING REMARKS

The diversity in cost categorisations complicates global comparative analysis and policy development, as inconsistencies across countries arise from differences in the components of each cost category. For example, Canada's "total cash costs" focus solely on direct monetary outflows, excluding non-monetary costs (Canadian Dairy Commision, 2024), while Brazil's "total variable cost" includes financial aspects (CONAB, 2020). New Zealand's "farm working expenses" cover a wide range of variable costs (DairyNZ, 2024), while Australia's "variable costs" are tied to milk production levels (DairyAustralia, 2024) and the "operating costs" in the United States define all the costs of expendables be allocated to the generic group (AAEA, 2000). The EU's "operating cost" includes both specific and non-specific expenses, aiding in the calculation of gross margins for different production types (European Commision, 2021). These differences highlight that direct comparisons of milk CoP across countries are not feasible without fully harmonised CoP methods to standardise cost typologies.

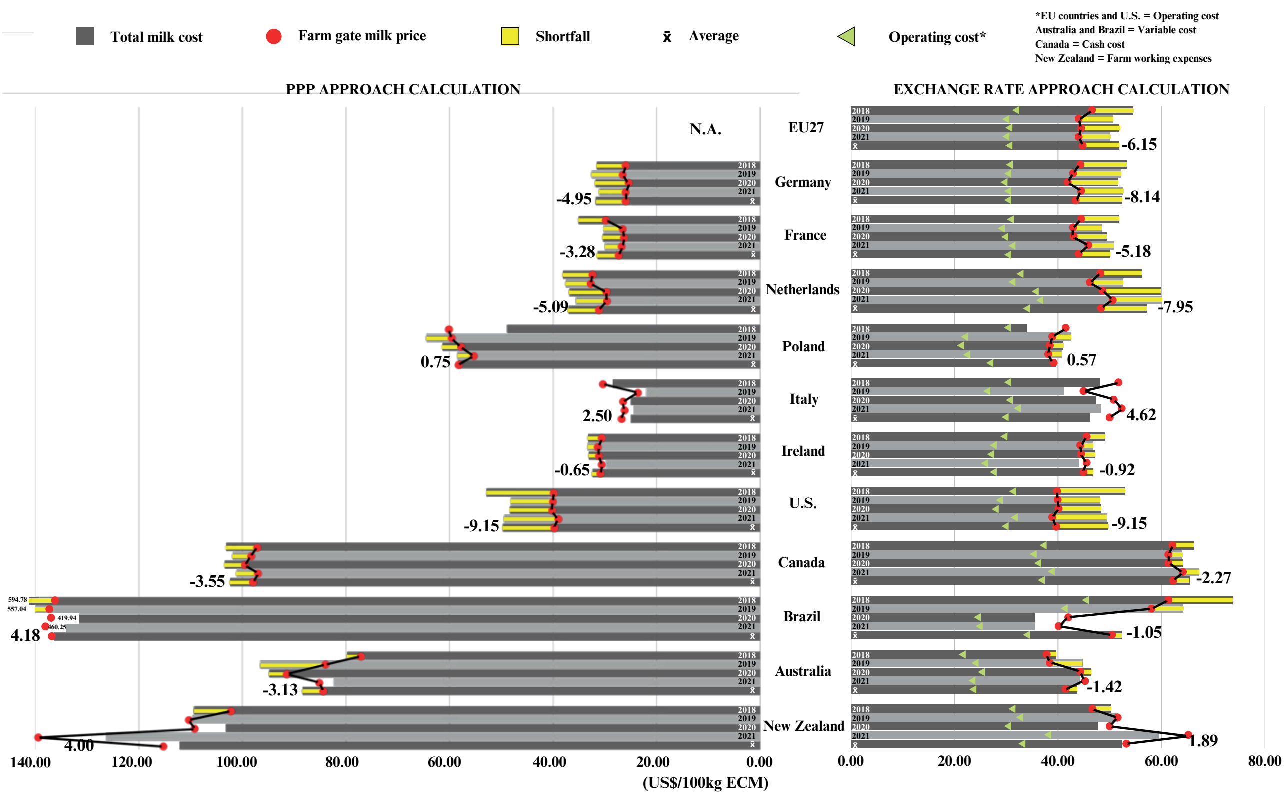

Figure 5. Development of dairy farm economic performance from 2018 to 2021. *Source*: Data and calculations are based on the European Commission (2021) for the EU27, USDA (2024) for the United States, the Canadian Dairy Commission (2024) for Canada, CONAB (2020) for Brazil, DairyAustralia (2024) for Australia, and DairyNZ (2024) for New Zealand.

The categorisation of key cost components, such as feed, hired labour, capital, and depreciation, varies significantly across countries (Table A.2), reflecting differences in economic and agricultural contexts. Feed costs, which account for at least 28% of total milk CoP (Atzori *et al*., 2021), are a key indicator of dairy farm performance. Hired labour costs are important for assessing farm competitiveness (Antonioli *et al*., 2023), while capital and depreciation provide insights into technology adoption (Upton *et al*., 2015). Based on these discrepancies, caution is needed when comparing milk CoP across countries, as differing frameworks result in divergent cost assessments.

This review reveals contrasting approaches to valuing land resources and unpaid labour. The IFCN, U.S., and EU frameworks incorporate opportunity costs, while others prioritise real expenditures based on actual transactions. The U.S. approach links opportunity cost pricing to more stable milk prices and reduced regulatory costs (Mykrantz, Bozic, 2022), whereas in the EU, opportunity costs lead to significant regional differences in farming income (Špička, Dereník, 2021). These costs may also misrepresent the viability of small-scale farms reliant on family labour and owned resources (Viira *et al*., 2009), while overlooking non-financial motivations and policy concerns (Ocean, Howley, 2023). Incorporating opportunity costs provides a more accurate representation of farm economics, addressing regional factors that influence decision-making (AAEA, 2000; European Commision, 2021; IFCN Dairy Network, 2022). This approach is critical for understanding the true cost of decisions, including the opportunity cost of resources used in milk production.

The inclusion of cattle sales and subsidies in milk CoP calculations introduces further complexity. For example, the EU includes herd renewal costs and subsidies but excludes cattle sales from milk revenue, while the United States includes cattle sales and omits subsidies (Table A.2). These structural differences affect CoP outcomes, as the EMB consistently reports higher CoP across EU countries due to the inclusion of additional livestock roughage eaters (Figure 3). Moreover, regional differences in the economic significance of cattle sales and subsidies are highlighted by regions reliant on dual-purpose breeds, where cattle sales offer a more comprehensive representation of farm economics (Zanon *et al*., 2020, 2023). This is particularly relevant in regions with high beef prices, where dual-purpose systems integrate milk and meat production more cost-effectively (Krupová *et al*., 2016).

Our study illustrates how milk CoP methods differ among milk-producing countries and how these differences may impact business decisions and dairy trade policies. The price competitiveness of dairy trade is heavily impacted by cost assumptions. In Canada, assuming a low local cost structure turns Canada into a major exporter under free trade, while high-cost assumptions suggest losses and contraction (McLachlan, Van Kooten, 2022). Countries that exclude capital, opportunity, or compliance costs may appear artificially competitive, affecting their resistance to tariff cuts and driving demands for special protection in trade negotiations (Langley *et al*., 2006; McLachlan, Van Kooten, 2022). For example, the EU imposes a 40% tariff on Canadian dairy products, while Canada applies a 230.38% import tariff on EU products (Sanjuán *et al*., 2023). Furthermore, subsidies also play a crucial role in boosting trade by making dairy exports seem more efficient. However, when subsidies are viewed as cost reductions rather than revenue support, they may mask dependence on public funds, distorting the World Trade Organization's Aggregate Measure of Support calculations and influencing subsidy reform debates (Kondaridze, Luckstead, 2023; Langley *et al*., 2006; Milić *et al*., 2023).

Non-tariff measures (NTMs), such as sanitary and phytosanitary (SPS) measures, represent significant costs, with an average 10% *ad valorem* equivalent (AVE; the percentage increase in import costs due to trade barriers) in EU dairy trade (Sanjuán *et al*., 2023). These measures, designed to protect health and safety, can distort trade when exporters include or exclude SPS compliance costs in their price calculations, so AVE estimates and perceptions of "too strict" NTMs are not comparable (Kondaridze *et al*., 2025; Sanjuán *et al*., 2023). Though harmonising with EU rules may reduce SPS costs, it benefits only highly competitive exporting countries (Sanjuán *et al*., 2023). Furthermore, efficiency and investment decisions in the dairy sector are influenced by trade liberalisation, which shifts production towards low-cost, pasture-based systems, such as those in New Zealand and Ireland (Dillon *et al*., 2008; Langley *et al*., 2006). If countries miscalculate inefficiencies (i.e., by assuming the inclusion of full cost items), they may over-invest in protection or fail to design effective stabilising measures (Biden *et al*., 2020). For example, Serbia's low milk prices, aimed at consumer protection, were regulated by importing dairy products from the EU under free trade agreements, leading to protests from farmers (Milić *et al*., 2023).

Given the methodological disparities, global comparisons of milk CoP require careful consideration of local contexts and farm systems. The IFCN's TFA aligns well with national calculations in many regions, but its limitations are evident in areas with distinct farm systems, such as Australia and New Zealand (Figure 4). Indeed, further refinement of the TFA is necessary to better capture regional variations and to make rankings of low- versus high-cost regions more meaningful for trade and investment decisions. While standardisation is important for policy and benchmarking, harmonising an entire country's CoP methods is expensive. Therefore, we argue that existing CoP methods from global dairy networks, such as the IFCN, which have developed harmonised methodologies alongside national approaches and local contexts, could serve as a valuable alternative to the PPIs provides by the FAO. This approach may enhance future studies on international competitiveness and help prevent distortions in international dairy trade by utilising consistent data, rather than relying on country-specific accounting practices.

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AUTHOR CONTRIBUTIONS

AT: methodology, investigation, data curation, formal analysis, writing (original draft), and visualization; TZ: conceptualization, supervision, formal analysis, data curation, methodology, investigation, writing (review and editing), funding acquisition, and visualization; MC: data curation, methodology, and writing (review and editing); CF: formal analysis, data curation, methodology, supervision, funding acquisition, and writing (review and editing); MG: conceptualization, supervision, project administration, funding acquisition, writing (review and editing), and visualization.

REFERENCES

AAEA (2000). *Commodity Costs and Returns Estimation Handbook*. United States Department of Agriculture, Washington, D.C. http://ageconsearch.umn.edu.

ABARES (2024). *Farm surveys definitions and methods*, Departement of Agriculture, Fisheries, and Forestry, Australian Government, Canberra. https://www.agriculture.gov.au/abares/research-topics/surveys/farm-definitions-methods#references.

Allain E., Laurin C. (2018). Explaining implementation difficulties associated with activity-based costing through system uses. *Journal of Applied Accounting Research*, 19(1): 181-198. DOI: https://doi.org/10.1108/JAAR-11-2014-0120.

Amat C., Michalski T.K., Stoltz G. (2014). Forecasting exchange rates better than the random walk thanks to machine learning techniques. *SSRN Electronic Journal*. DOI: https://doi.org/10.2139/ssrn.2448655.

Antonioli F., Severini S., Vigani M. (2023). Visa for competitiveness: Foreign workforce and Italian dairy farms' performance. *European Review of Agricultural Economics*, 50(1): 115-150. DOI: https://doi.org/10.1093/erae/jbab045.

Arendonk J.A.M., van Liinamo A.-E. (2003). Dairy cattle production in Europe. *Theriogenology*, 59(2): 563-569. DOI: https://doi.org/10.1016/S0093-691X(02)01240-2.

Atzori A.S., Valsecchi C., Manca E., Masoero F., Cannas A., Gallo A. (2021). Assessment of feed and economic efficiency of dairy farms based on multivariate aggregation of partial indicators measured on field. *Journal of Dairy Science*, 104(12): 12679-12692. DOI: https://doi.org/10.3168/jds.2020-19764.

Beber C.L., Langer G., Meyer J. (2021). Strategic actions for a sustainable internationalization of agri-food supply chains: The case of the dairy industries from Brazil and Germany. *Sustainability*, 13(19), 10873. DOI: https://doi.org/10.3390/su131910873.

Belloin J.C. (1998). *Milk and dairy products: Production and processing costs*, Food and Agriculture Orzanization of the United Nations, Rome. https://www.fao.org/4/x6931e/X6931E00.htm#TOC.

Berg M., Moore G. (1989). The choice of depreciation method under uncertainty. *Decision Sciences*, 20(4): 643-654. DOI: https://doi.org/10.1111/j.1540-5915.1989.tb01409.x.

Bernardes T.F., do Rêgo A.C. (2014). Study on the practices of silage production and utilization on Brazilian dairy farms. *Journal of Dairy Science*, 97(3): 1852-1861. DOI: https://doi.org/10.3168/jds.2013-7181.

Biden S., Ker A.P., Duff S. (2020). Impacts of trade liberalization in Canada's supply managed dairy industry. *Agricultural Economics*, 51(4): 535-552. DOI: https://doi.org/10.1111/agec.12570.

Biesebroeck J.V. (2009). Disaggregate productivity comparisons: Sectoral convergence in OECD countries. *Journal of Productivity Analysis*, 32(2): 63-79. DOI: https://doi.org/10.1007/s11123-009-0132-z.

Bimbo F., Bonanno A., Liu X., Viscecchia R. (2016). Hedonic analysis of the price of UHT-treated milk in Italy. *Journal of Dairy Science*, 99(2): 1095-1102. DOI: https://doi.org/10.3168/jds.2015-10018.

Britt J.H., Cushman R.A., Dechow C.D., Dobson H., Humblot P., Hutjens M.F., Jones G.A., Ruegg P.S., Sheldon I.M., Stevenson J.S. (2018). Invited review: Learning from the future—A vision for dairy farms and cows in 2067. *Journal of Dairy Science*, 101(5): 3722-3741. DOI: https://doi.org/10.3168/jds.2017-14025.

Brunk I. (Wuerth), Hakimi M. (2022). Russia, Ukraine, and the future world order. *American Journal of International Law*, 116(4): 687-697. DOI: https://doi.org/10.1017/ajil.2022.69.

Bureau J.C., Butault J.-P. (1992). Productivity gaps, price advantages and competitiveness in E.C. agriculture. *European Review of Agricultural Economics*, 19(1): 25-48. DOI: https://doi.org/10.1093/erae/19.1.25.

Canadian Dairy Commission (2024). *Cost of production survey*, Canadian Dairy Commission, Ottawa. https://cdc-ccl.ca/node/643.

Chamberlain T. (2012). Understanding the economics of dairy farming. Part 2: Identifying the factors that drive profitability. *Livestock*, 17(6): 25-28. DOI: https://doi.org/10.1111/j.2044-3870.2012.00150.x.

Chatellier V. (2021). Review: International trade in animal products and the place of the European Union: Main trends over the last 20 years. *Animal*, 15, 100289. DOI: https://doi.org/10.1016/j.animal.2021.100289.

CLAL.IT (2024). *Dairy by country*, CLAL Srl, Sermide e Felonica. https://www.clal.it/en/index.php.

Coffey E.L., Horan B., Evans R.D., Berry D.P. (2016). Milk production and fertility performance of Holstein, Friesian, and Jersey purebred cows and their respective crosses in seasonal-calving commercial farms. *Journal of Dairy Science*, 99(7): 5681-5689. DOI: https://doi.org/10.3168/jds.2015-10530.

CONAB (2020). *Norma metodologia do custo de produção 30.302*, Companhia Nacional de Abastecimento, Brasília. https://www.conab.gov.br/images/arquivos/normativos/30000_sistema_de_operacoes/30.302_Norma_Metodologia_de_Custo_de_Producao.pdf.

Conigliani C., Tancredi A. (2009). A Bayesian model averaging approach for cost-effectiveness analyses. *Health Economics*, 18(7): 807-821. DOI: https://doi.org/10.1002/hec.1404.

Correa-Luna M., Donaghy D., Kemp P., Shalloo L., Ruelle E., Hennessy D., López-Villalobos N. (2021). Productivity, profitability and nitrogen utilisation efficiency of two pasture-based milk production systems differing in the milking frequency and feeding level. *Sustainability*, 13(4), 2098. DOI: https://doi.org/10.3390/su13042098.

DairyAustralia (2024). *Dairy farm monitor project*, Diary Australia, Melbourne. https://www.dairyaustralia.com.au/industry-reports/dairy-farm-monitor-project.

DairyNZ (2024). *Farm economics*, DairyNZ, Hamilton. https://connect.dairynz.co.nz/content/89ba1084-42c5-4786-882b-cc91b8016d05/.

Dillon P., Hennessy T., Shalloo L., Thorne F., Horan B. (2008). Future outlook for the Irish dairy industry: A study of international competitiveness, influence of international trade reform and requirement for change. *International Journal of Dairy Technology*, 61(1): 16-29. https://doi.org/10.1111/j.1471-0307.2008.00374.x

Dobson W.D., Wagner J. (2000). *The deregulation and rationalization of Australia's dairy industry-Implications for the U.S. and world dairy industries*, University of Wisconsin-Madison, Babcock Institute for International Dairy Research and Development, Madison. DOI: https://doi.org/10.22004/ag.econ.37661.

Edwards J.P. (2020). A comparison of profitability between farms that milk once or twice a day. *Animal Production Science*, 60(1): 102. DOI: https://doi.org/10.1071/AN18528.

EMB (2021). *Milk production costs in eight European countries, EU average costs and organic milk production costs What is the cost of producing milk?*, European Milk Board, Brussels. www.milcherzeuger.eu.

European Commission (2021). *EU dairy farms report based on 2018 FADN data*, European Commision. https://agriculture.ec.europa.eu/document/download/19e9af1c-82af-4e95-8c3a-8df09dafd2f9_en?filename=fadn-dairy-report-2021_en.pdf.

FAO (2016). *Agricultural cost of production statistics guidelines for data collection, compilation and dissemination publication prepared in the framework of the Global Strategy to Improve Agricultural and Rural Statistics*. Food and Agriculture Organization, Rome.

FAO (2023). *Dairy market review: Emerging trends and outlook in 2023*, Food and Agriculture Organization, Rome. https://openknowledge.fao.org/server/api/core/bitstreams/68f7f25d-b3cb-418e-b04d-5708e5bcea1e/content.

FAOSTAT (2025). *Producer prices*, Food and Agriculture Organization of the United Nations, Rome. https://www.fao.org/faostat/en/#data/PP.

Freitas A.F., Wilcox C.J., Costa C.N. (1998). Breed group effects on milk production of Brazilian crossbred dairy cows. *Journal of Dairy Science*, 81(8): 2306-

2311. DOI: https://doi.org/10.3168/jds.S0022-0302(98)75811-4.

Freitas E.N.A., Cabrera V.E. (2025). Dairy Victory Platform: A novel benchmarking platform to empower economic decisions on dairy farms. *JDS Communications*, 6(1): 69-73. DOI: https://doi.org/10.3168/jdsc.2024-0617.

Frengley G.A.G., Johnston W.E. (1992). Financial stress and consumption expectations among farm households: New Zealand's experience with economic liberalisation. *Journal of Agricultural Economics*, 43(1): 14-27. DOI: https://doi.org/10.1111/j.1477-9552.1992.tb00194.x.

Hagan B.A., Moro-Mendez J., Cue R.I. (2021). Realized genetic selection differentials in Canadian Ayrshire, Jersey, and Brown Swiss dairy cattle populations. *Journal of Dairy Science*, 104(2): 1951-1966. DOI: https://doi.org/10.3168/jds.2019-17938.

Harris B.L. (2005). Breeding dairy cows for the future in New Zealand. *New Zealand Veterinary Journal*, 53(6): 384-389. DOI: https://doi.org/10.1080/00480169.2005.36582.

Hegazi M.O. (2024). A novel approach for simulating and optimizing the production costing system. *Heliyon*, 10(24), e40932. DOI: https://doi.org/10.1016/j.heliyon.2024.e40932.

Hemme T., Uddin M.M., Ndambi O.A. (2014). Benchmarking cost of milk production in 46 countries. *Journal of Reviews on Global Economics*, 3: 254-270. DOI: https://doi.org/10.6000/1929-7092.2014.03.20.

IFCN Dairy Network (2018). *IFCN dairy report 2021: The dairy research network*, The International Farm Comparison Network, Kiel. https://ifcndairy.org/ifcn-products-services/dairy-report/.

IFCN Dairy Network (2022). *IFCN dairy report 2021: The dairy research network*, The International Farm Comparison Network, Kiel. https://ifcndairy.org/ifcn-products-services/dairy-report/.

Inna B., Tetiana Y., Anatolii B., Oleksandr K., Liudmyla Y., Svitlana B. (2024). *Features of enterprise cost management*. In Alareeni B., Elgedawy I. (eds) Opportunities and Risks in AI for Business Development. Studies in Systems, Decision and Control, vol. 545 (pp. 699-709). Springer, Cham. DOI: https://doi.org/10.1007/978-3-031-65203-5_61.

Jayawardana J.M.D.R., Lopez-Villalobos N., Hickson R.E., McNaughton L.R. (2023). Estimation of genetic parameters and individual and maternal breed, heterosis, and recombination loss effects for production and fertility traits of spring-calved cows milked once daily or twice daily in New Zealand. *Journal of Dairy Science*, 106(1): 364-380. DOI: https://doi.org/10.3168/jds.2022-22053

Kamal S., Noy I. (2023). Impact of droughts on farms' financing choices: Empirical evidence from New Zealand. *Weather, Climate, and Society*, 15(1): 121-132. DOI: https://doi.org/10.1175/WCAS-D-21-0193.1.

Kondaridze M., Liu X., Luckstead J. (2025). Dairy trade reconsidered: Gravity and the distributional effect of non-tariff barriers and distance. *Agricultural Economics*, 57(1), e70081. DOI: https://doi.org/10.1111/agec.70081.

Kondaridze M., Luckstead J. (2023). Determinants of dairy-product trade: Do subsidies matter? *Journal of Agricultural Economics*, 74(3): 857-873. DOI: https://doi.org/10.1111/1477-9552.12536.

Krupová Z., Krupa E., Michaličková M., Wolfová M., Kasarda R. (2016). Economic values for health and feed efficiency traits of dual-purpose cattle in marginal areas. *Journal of Dairy Science*, 99(1): 644-656. DOI: https://doi.org/10.3168/jds.2015-9951.

Langley S.V., Somwaru A., Normile M.A. (2006). *Trade liberalization in international dairy markets: Estimated impacts*, Economic Research Report Number 16, United States Department of Agriculture, Washington, D.C. DOI: https://doi.org/10.22004/AG.ECON.7214.

Langrell S., Ciaian P., Paloma S.G., Cunningham D.L., Garnier J.-F., Isermeyer F., Mishra A.K. (2012). *Sustainability and production costs in the global farming sector: Comparative analysis and methodologies*. European Commission.

Lazzarini B., Lopez-Villalobos N., Lyons N., Hendrikse L., Baudracco J. (2018). Productive, economic and risk assessment of grazing dairy systems with supplemented cows milked once a day. *Animal*, 12(5): 1077-1083. DOI: https://doi.org/10.1017/S1751731117002853.

Lozada-Soto E.A., Tiezzi F., Jiang J., Cole J.B., VanRaden P.M., Maltecca C. (2022). Genomic characterization of autozygosity and recent inbreeding trends in all major breeds of US dairy cattle. *Journal of Dairy Science*, 105(11): 8956-8971. DOI: https://doi.org/10.3168/jds.2022-22116.

Luo J., Ledgard S. (2021). New Zealand dairy farm systems and key environmental effects. *Frontiers of Agricultural Science and Engineering*, 8(1): 148. DOI: https://doi.org/10.15302/J-FASE-2020372.

McLachlan B.A., Van Kooten G.C. (2022). Reforming Canada's dairy supply management scheme and the consequences for international trade. *Canadian Journal of Agricultural Economics/Revue Canadienne* *d'agroeconomie*, 70(1): 21-39. DOI: https://doi.org/10.1111/cjag.12305.

McNown R., Wallace M.S. (1989). National price levels, purchasing power parity, and cointegration: A test of four high inflation economies. *Journal of International Money and Finance*, 8(4): 533-545. DOI: https://doi.org/10.1016/0261-5606(89)90035-1.

Milić D., Novaković T., Tekić D., Matkovski B., Đokić D., Zekić S. (2023). Economic sustainability of the milk and dairy supply chain: Evidence from Serbia. *Sustainability*, 15(21), 15234. DOI: https://doi.org/10.3390/su152115234.

Murphy J.P., O'Donovan M., McCarthy K., Delaby L., Sugrue K., Galvin N., Murphy C., Kennedy E. (2023). A three-year comparison of once-a-day and twice-a-day milking in seasonal-calving pasture-based systems. *Journal of Dairy Science*, 106(12): 8910-8925. DOI: https://doi.org/10.3168/jds.2023-23379.

Mykrantz J.L., Bozic M. (2022). Opportunity cost: An economic concept that may improve the functioning of federal milk marketing orders and the U.S. dairy industry. *Journal of Agricultural and Applied Economics*, 54(4): 606-620. DOI: https://doi.org/10.1017/aae.2022.29.

Negrín M.A., Vázquez-Polo F.-J. (2008). Incorporating model uncertainty in cost-effectiveness analysis: A Bayesian model averaging approach. *Journal of Health Economics*, 27(5): 1250-1259. DOI: https://doi.org/10.1016/j.jhealeco.2008.03.005.

Nguyen T.T.T., Bowman P.J., Haile-Mariam M., Nieuwhof G.J., Hayes B.J., Pryce J.E. (2017). Short communication: Implementation of a breeding value for heat tolerance in Australian dairy cattle. *Journal of Dairy Science*, 100(9): 7362-7367. DOI: https://doi.org/10.3168/jds.2017-12898.

Ocean N., Howley P. (2023). Which benefits would make farmers happier, and which would they choose? *Land Economics*, 99(3): 458-476. DOI: https://doi.org/10.3368/le.99.3.112321-0139R.

Ohlan R. (2014). Growth and instability in dairy production and trade: A global analysis. *International Journal of Trade and Global Markets*, 7(2): 145. DOI: https://doi.org/10.1504/IJTGM.2014.062856.

Oliveira H.R., Lourenco D.A.L., Masuda Y., Misztal I., Tsuruta S., Jamrozik J., Brito L. F., Silva F.F., Cant J.P., Schenkel F.S. (2019). Single-step genome-wide association for longitudinal traits of Canadian Ayrshire, Holstein, and Jersey dairy cattle. *Journal of Dairy Science*, 102(11): 9995-10011. DOI: https://doi.org/10.3168/jds.2019-16821.

Ozawa T., Lopez-Villalobos N., Blair H.T. (2005). Dairy farming financial structures in Hokkaido, Japan and New Zealand. *Animal Science Journal*, 76(4): 391-400. DOI: https://doi.org/10.1111/j.1740-0929.2005.00281.x.

Pant H.M., Fisher B.S. (2007). Alternative measures of output in global economic-environmental models: Purchasing power parity or market exchange rates? —Comment. *Energy Economics*, 29(3): 375-389. DOI: https://doi.org/10.1016/j.eneco.2006.10.006.

Parzonko A., Parzonko A.J., Bórawski P. (2024). Economic competitiveness of dairy farms from the top milk-producing countries in the EU: Assessment in 2014-2021. *Agriculture (Switzerland)*, 14(1). DOI: https://doi.org/10.3390/agriculture14010123.

Phillipov M., Loyer J. (2019). In the wake of the supermarket 'milk wars': Media, farmers and the power of pastoral sentimentality. *Discourse, Context Media*, 32, 100346. DOI: https://doi.org/10.1016/j.dcm.2019.100346.

Probo M., Atashi H., Hostens M. (2024). Lactation performances in primiparous Holstein cows following short and normal gestation lengths. *Frontiers in Veterinary Science*, 11. DOI: https://doi.org/10.3389/fvets.2024.1289116.

Quesado P., Silva R. (2021). Activity-based costing (ABC) and its implication for open innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, 7(1): 41. DOI: https://doi.org/10.3390/joitmc7010041.

Reeson A.F., McAllister R.R.J., Whitten S.M., Gordon I.J., Nicholas M., McDouall S.S. (2008). The agistment market in the northern Australian rangelands: Failings and opportunities. *The Rangeland Journal*, 30(3): 283. DOI: https://doi.org/10.1071/RJ06042.

Ronzon T., Ciaian P., Paloma S.G., Delince J. (2014). *Literature review on cost of production methodologies*, Technical Paper Series GO-04-2014. DOI: https://doi.org/10.13140/RG.2.2.30101.12008.

Ruzzante S., Labarta R., Bilton A. (2021). Adoption of agricultural technology in the developing world: A meta-analysis of the empirical literature. *World Development*, 146, 105599. DOI: https://doi.org/10.1016/j.worlddev.2021.105599.

Sanjuán A.I., Philippidis G., Ferrer Pérez H., Gracia De Rentería P. (2023). Empirical insights on the dynamics of SPS trade costs: The role of regulatory convergence and experience in EU dairy trade. *Food Policy*, 119, 102524. DOI: https://doi.org/10.1016/j.foodpol.2023.102524.

Sercu P., Uppal R., Hulle C.V. (1995). The exchange rate in the presence of transaction costs: Implications for tests of purchasing power parity. *The*

Journal of Finance, 50(4): 1309. DOI: https://doi.org/10.2307/2329354.

Smith B.J. (1974). Estimating comparative costs of producing milk among the Southern states. *Journal of Agricultural and Applied Economics*, 6(1): 221-228. DOI: https://doi.org/10.1017/S0081305200011754.

Špička J., Dereník P. (2021). How opportunity costs change the view on the viability of farms? Empirical evidence from the EU. *Agricultural Economics (Zemědělská Ekonomika)*, 67(2): 41-50. DOI: https://doi.org/10.17221/412/2020-AGRICECON.

Stanbury W.T. (2002). *The politics of milk in Canada*, The Fraser Institute, Vancouver. https://www.fraserinstitute.org/sites/default/files/PoliticsofMilkinCanada.pdf.

Stirm J.E.W., St-Pierre N.R. (2003). Identification and characterization of location decision factors for relocating dairy farms. *Journal of Dairy Science*, 86(11): 3473-3487. DOI: https://doi.org/10.3168/jds.S0022-0302(03)73952-6.

Thomassen M.A., Dolman M.A., van Calker K.J., de Boer I J.M. (2009). Relating life cycle assessment indicators to gross value added for Dutch dairy farms. *Ecological Economics*, 68(8-9): 2278-2284. DOI: https://doi.org/10.1016/j.ecolecon.2009.02.011.

Tian R., Yang Z., Shao Q. (2020). Effects of host country resource endowment and labour cost on China's investment in overseas cultivated land. *Environmental Science and Pollution Research*, 27(36): 45282-45296. DOI: https://doi.org/10.1007/s11356-020-10373-3.

Upton J., Murphy M., de Boer I.J.M., Koerkamp P.W.G.G., Berentsen P.B.M., Shalloo L. (2015). Investment appraisal of technology innovations on dairy farm electricity consumption. *Journal of Dairy Science*, 98(2): 898-909. DOI: https://doi.org/10.3168/jds.2014-8383.

USDA (2024). *Milk cost of production estimates*, United States Department of Agriculture, Washington, D.C. https://www.ers.usda.gov/data-products/milk-cost-of-production-estimates/.

Viira A.-H., Põder A., Värnik R. (2009). The factors affecting the motivation to exit farming - Evidence from Estonia. *Food Economics - Acta Agriculturae Scandinavica, Section C*, 6(3-4): 156-172. DOI: https://doi.org/10.1080/16507541.2010.481899.

Weigel K.A., Rekaya R., Zwald N.R., Fikse W.F. (2001). International genetic evaluation of dairy sires using a multiple-trait model with individual animal performance records. *Journal of Dairy Science*, 84(12): 2789-2795. DOI: https://doi.org/10.3168/jds.S0022-0302(01)74734-0.

Williamson J.M., Stutzman S. (2016). Tax policy and farm capital investment: Section 179 expensing and bonus depreciation. *Agricultural Finance Review*, 76(2): 246-269. DOI: https://doi.org/10.1108/AFR-07-2015-0031.

World Bank. (2025). *Data Bank World Development Indicators*, World Bank Group, Washinton, D.C. https://databank.worldbank.org/metadataglossary/world-development-indicators/series/PA.NUS.PPP.

Zanon T., Fichter G., Mittermair P., Nocker L., Gauly M., Peratoner G. (2023). Quantifying methane emissions under field conditions under 2 different dairy production scenarios: Low-input versus high-input milk production. *Journal of Dairy Science*, 106(7): 4711-4724. DOI: https://doi.org/10.3168/jds.2022-22804.

Zanon T., König S., Gauly M. (2020). A comparison of animal-related figures in milk and meat production and economic revenues from milk and animal sales of five dairy cattle breeds reared in Alps region. *Italian Journal of Animal Science*, 19(1): 1318-1328. DOI: https://doi.org/10.1080/1828051X.2020.1839361.

Ziętara W., Pietrzak M., Malak-Rawlikowska A. (2024). Polish dairy farm transformations and competitiveness 20 years after Poland's accession to the European Union. *Animals*, 14(13), 2013. DOI: https://doi.org/10.3390/ani14132013.

APPENDIX

Table A.1. Standardized adjustments for milk CoP data for minimalistic harmonization.

Country	Currency	Milk cost unit	Year	USD Exchange	%Fat	%CP	PPI	PPP
EU27	EUR	ton	2018	0.848	*4.02*	*3.47*	102.56	N.A.
			2019	0.893	*4.06*	*3.47*	104.08	N.A.
			2020	0.880	*4.09*	*3.43*	102.49	N.A.
			2021	0.846	*4.10*	*3.43*	114.11	N.A.
Germany	EUR	ton	2018	0.848	*4.06*	*3.68*	111.95	0.70
			2019	0.893	*4.13*	*3.66*	109.09	0.70
			2020	0.880	*4.13*	*3.47*	109.47	0.70
			2021	0.846	*4.15*	*3.46*	115.43	0.70
France	EUR	ton	2018	0.848	*4.01*	*3.38*	104.22	0.80
			2019	0.893	*4.06*	*3.46*	108.32	0.70
			2020	0.880	*4.07*	*3.27*	107.24	0.70
			2021	0.846	*4.09*	*3.27*	111.83	0.70
Netherlands	EUR	ton	2018	0.848	*4.37*	*3.55*	99.91	0.80
			2019	0.893	*4.42*	*3.57*	101.08	0.80
			2020	0.880	*4.42*	*3.58*	92.30	0.70
			2021	0.846	*4.45*	*3.59*	101.83	0.70
Poland	EUR	ton	2018	0.848	*3.95*	*3.26*	111.76	1.70
			2019	0.893	*3.98*	*3.26*	112.34	1.70
			2020	0.880	*4.05*	*3.31*	114.75	1.70
			2021	0.846	*4.10*	*3.31*	130.28	1.70
Italy	EUR	ton	2018	0.848	*3.71*	*3.37*	100.57	0.70
			2019	0.893	*3.65*	*3.36*	107.83	0.60
			2020	0.880	*3.77*	*3.45*	98.87	0.60
			2021	0.846	*3.76*	*3.44*	103.44	0.60
Ireland	EUR	ton	2018	0.848	*4.10*	*3.58*	116.15	0.80
			2019	0.893	*4.17*	*3.65*	111.46	0.80
			2020	0.880	*4.20*	*3.55*	112.93	0.80
			2021	0.846	*4.23*	*3.55*	131.26	0.80
US	USD	cwt	2018	N.A.	*3.89*	*3.00*	84.78	1.00
			2019	N.A.	*3.92*	*3.37*	97.02	1.00
			2020	N.A.	*3.95*	*3.18*	95.04	1.00
			2021	N.A.	*4.01*	*3.20*	96.55	1.00
Canada	CAD	hectoliter	2018	1.298	*3.96*	*3.30*	96.28	1.20
			2019	1.327	*4.03*	*3.30*	101.31	1.20
			2020	1.344	*4.05*	*3.32*	101.98	1.20
			2021	1.254	*4.07*	*3.34*	104.14	1.20
Brazil	BRL	liter	2018	3.666	*3.90*	*3.30*	100.86	2.20
			2019	3.943	*3.90*	*3.30*	107.54	2.20
			2020	5.137	*3.90*	*3.30*	142.85	2.30
			2021	5.397	*3.90*	*3.30*	173.01	2.40
Australia	AUD	kg MS	2018	1.343	*4.00*	*3.30*	102.39	1.50
			2019	1.438	*3.83*	*3.35*	96.67	1.50
			2020	1.460	*4.04*	*3.39*	96.94	1.40
			2021	1.332	*4.01*	*3.40*	102.30	1.40
New Zealand	NZD	kg MS	2018	1.450	*4.86*	*3.87*	120.71	1.50
			2019	1.517	*4.82*	*3.89*	114.42	1.40
			2020	1.548	*4.84*	*3.92*	123.44	1.40
			2021	1.415	*4.84*	*3.92*	128.90	1.50

EMB

Code	Variable
	Purchased feed
	Fodder production
	Seeds
	Fertilizers
	Plant protection products
	Livestock costs
	Veterinary costs
	Insemination
	Building & machinery upkeep
	Energy
	Contract work
	Wages paid
	Other farming overheads
	Rent paid
	Depreciation
	Interest and taxes
A	**Total input costs**
B	Production value of beef
C	**Paid costs of milk production (milk only) (A-B)**
D	Income variable (labor costs)
E	**Total costs (C+D)**
F	CAP Payments
G	**Milk Production costs (E-F)**
H	Net Investments
I	**Milk Production costs inc net investments (G+H)**

IFCN

Code	Variable
	Crop and home grown feed related expenses
	Dairy related expenses
	General expenses
	paid land rent
	paid wages
	paid interest on liabilities
A	**Total expenses**
	Dairy receipts
	Milk
	Cull cows, calves, etc
	Government payments (coupled)
	Other (manure, etc)
B	**Total receipts**
C	**Net cash farm income (B-A)**
	Depreciation
D	**Non-cash adjustments**
E	**Farm income (C-D)**
	Interest on own capital
	Cost for own quota
	Rent on land
	Cost for own labor
F	**Total opportunity costs**
G	**Entrepreneurship's profit (E-F)**

EU Countries

Code	Variable
	Feed
	Homegrown feed
	Purchased feed
	Herd renewal purchases
	Other specific costs
	Milk levy
A	**Total specific costs**
	Machinery and building upkeep
	Energy (fuel, electricity)
	Contract work
	Taxes
	Other direct inputs
B	**Total non specific costs**
C	**Total operating costs (A+B)**
	Price
	Coupled payments (incl. Art.69)
D	**Total revenues from milk**
E	**Gross margin with coupled payments (D-C)**
F	**Gross margin (Excl-coupled payments)**
	Depreciation
	External factors
	Wages
	Rent
	Interest
G	**Total depreciation and external factors**
H	**Net margin with coupled payments (E-G)**
I	**Net margin (F-G) (Excl-coupled payments)**
	Family labor costs
	Own capital unpaid cost
J	**Total imputed family factors**
K	**Net economic margin with coupled payments (H-J)**
L	**Net economic margin (I-J) (Excl-coupled payments)**

U.S.

Code	Variable
	Total feed costs
	Purchased feed
	Homegrown harvested feed
	Grazed feed
	Veterinary and medicine
	Bedding and litter
	Marketing
	Custom services
	Fuel, lube, and electricity
	Repairs
	Other, operating costs
	Interest on operating capital
A	**Total operating costs**
	Hired labor
	Opportunity cost of unpaid labor
	Capital recovery of machinery and equipment
	Opportunity cost of land
	Taxes and insurance
	General farm overhead
B	**Total allocated overhead**
C	**Total costs (A+B)**
	Milk sold
	Cattle
	Other income
D	**Total gross value of production**
E	**Value of production less operating costs (D-A)**
F	**Value of production less total costs (D-C)**

CANADA

Code	Variable
	Purchased feed
	Artificial insemination
	Promotion, transportation, and fees
	Machinery, equipment repairs
	Fuel and oil
	Costum work
	fertilizer and herbicides
	Seed and plants
	Other Misc. (Professional fees)
	Other Misc. (Animal costs)
	Other Misc. (Crop costs)
	Land and building repairs
	Property taxes
	Hydro and telephone
	Hired labor
	Purchase or sale of animals
	Dairy inventory value adjustment
A	**Total cash costs**
	Interest paid
	Building depreciation
	Machinery and equipment depreciation
	Return on equity
B	**Total capital cost**
	Direct labor
	Return to management
C	**Total producer labor**
D	**Government rebates and others**
E	**Total production costs (A+B+C+D)**
	Milk Sales
F	**Total gross income**
G	**Gross margin (F-E)**

BRAZIL

Code	Variable
	Labor hired for herd management
	Specialized Services
	Pasture maintenance
	Weeding maintenance
	Sugarcane field maintenance
	Silage
	Concentrates
	Calf milk
	Mineral salt
	Medicines
	Hormones
	Milking equipment
	Milk transport
	Energy and fuel
	Artificial insemination
	Taxes and fees
	Repairs of improvements
	Machine repairs
	Other costing expenses
	Administrative expenses (5% of the cost)
A	**Total cost expenses**
	Interest
B	**Total financial expenses**
C	**Total variable cost (A+B)**
	Depreciation of improvements/facilities
	Depreciation of machinery and implements
	Depreciation of service animals
	Depreciation of non-annual forages
D	**Total depreciation**
	Foremanship fee
	Social charges
	Fixed capital insurance
E	**Total other fixed costs**
F	**Total fixed cost (D+E)**
G	**Operating cost (C+F)**
	Expected remuneration on fixed capital
	Land
H	**Total factor income (H)**
I	**Total cost (G+H)**
	Milk price
J	**Total revenue**
K	**Profit (J-I)**

AUSTRALIA

Code	Variable
	Feed cost
	Forage costs/Home grown feed
	Fertliser
	Fuel and oil
	Pasture and crop cost
	Irrigation costs
	Hay and silage making cost
	Agistment
	Other feed cost
	Concentrates and supplements/Purchased feed
	Grain and concentrates
	Fodder, silage and hay
	Other purchase feed
	Feed inventory (+/-)
	Herd costs
	Animal health
	Herd improvement
	Calf rearing
	Shed costs
	Dairy shed - power
	Dairy shed- supplies
A	**Total variable costs**
	Employed labor costs
	Other overheads
	Repairs & maintenance
	Motor vehicle expenses
	Rates
	Farm insurance
	Depreciation
	Imputed owner
B	**Total overhead costs**
C	**Total costs (A+B)**
	Milk revenue
	Fresh milk sales
	Other farm income
	Livestock sales less purchases (dairy)
	Feed sales
	Other farm cash income
D	**Total gross income**
E	**EBIT (D-C)**
	Interest costs
	Land lease costs
F	**Total interest and lease charges**
G	**Net farm income (E-F)**

NEW ZEALAND

Code	Variable
	Net feed made, purchased, cropped
	Weed & pest
	Regrassing
	Irrigation
	Fertiliser (incl Nitrogen)
	Winter cow grazing
	Support block lease
	Young & dry stock grazing
	Farm dairy
	Calf rearing (excluding labor)
	Animal health
	Breeding & herd improvement
	Wages
	Vehicles
	Fuel
	Electricity
	Repairs & maintenance (land & building)
	Repairs & maintenance (plant & equipment)
	Freight & general
	Administration
	Insurance
	Accident Compensation Corporation (ACC)
	Rates
A	**Farm working expenses**
	Value of change in dairy livestock
	Labor adjustment (unpaid)
	Labor adjustment (management)
	Feed inventory adjustment (+/-)
	Owned support block adjustment
	Depreciation
B	**Net adjustments**
C	**Dairy operating expenses (A-B)**
	Milk sales
	Net livestock sales (sales - purchases)
	Other dairy cash income
D	**Net dairy cash income**
E	**Cash operating surplus (D-A)**
F	**Dairy operating profit (D-C)**
	Rent (excl support block)
	Interest
	Tax
G	**Total interest, tax and lease charges**
H	**Net cash operating surplus (E-G)**
	Net non-dairy cash income
	Net off-farm income
I	**Total additional income**
J	**Discretionary Cash (H+I)**
K	**Net farm income (F-G+I)**

Table A.2. The framework of milk CoP and revenue in reviewed countries.Homegrown feed (dark green), purchased feed (light green), hired labour and imputed owner (dark blue), dairy related expenses (grey), general expenses (purple) and other expenses (orange).

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Research article

Evaluating the applicability of the european voluntary sustainability reporting standards for agrifood small- medium-sized enterprises

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Abstract. Sustainability reporting is a corporate social responsibility tool that engages businesses in sustainable practices and enables them to communicate their impacts to stakeholders. In the Italian Agrifood sector, small and medium-sized enterprises (SMEs) have an important role in the value chain but often lack the resources and skills to properly report their sustainability impacts. This study evaluates the potential capacity of agrifood SMEs to comply with and apply the Voluntary Sustainability Reporting Standards for Non-listed SMEs (VSME), using the Global Reporting Initiative (GRI) framework as a proxy. Using content analysis, 16 sustainability reports by Italian agrifood SMEs are examined in terms of material topics, use and informative coverage of GRI standards, and their correspondence with VSME indicators. The results reveal that social and environmental GRI topics and indicators are more frequently disclosed by SMEs, while economic topics receive limited attention. Moreover, comparison between GRI use and VSME requests highlights the absence of some specific agrifood sector indicators (biodiversity, soil health, pesticide use, local community impact, and product quality). Furthermore, the value chain perspective is weak in the VSME guidelines and in SME reporting. In conclusion, the VSME framework represents a starting point that requires refinement and dialogue between stakeholders to better support SME reporting. This study provides empirical insight into the underexplored segment of the sustainability reporting of agrifood SMEs.

Keywords: sustainability reporting, SMEs, agrifood, GRI, ESRS.
JEL codes: Q56, M48.

HIGHLIGHTS

- The VSME framework can represent a starting point for agrifood SME reporting, but it requires refinement and dialogue between stakeholders.
- The VSME framework lacks detail on some environmental (biodiversity, soil health, and pesticide use) and social (local community and product quality) indicators, which are key to the sustainability commitments of agrifood SMEs.
- The inclusion of supply chain impacts is still weak.

– Associations and intermediary bodies could act as facilitators, supporting SMEs in sustainability reporting.

1. INTRODUCTION

The European Union's Green Deal Industrial Plan, established within the broader framework of the European Green Deal, underscores Europe's ambition to become a global leader in the sustainability transition, targeting climate neutrality by 2050 (EEA, 2024). A pivotal component driving this agenda is Directive 2022/2464 of the European Parliament and of the Council, known as the Corporate Sustainability Reporting Directive (CSRD), which contains the European Sustainability Reporting Standards (ESRS) developed by the European Financial Reporting Advisory Group (EFRAG). According to the Directive (EU) 2022/2464 (2022: 42), conceptually "sustainability reporting" means "reporting information related to sustainability matters", and this includes disclosing all activities, impacts, and commitments of the reporting entity – whether public or private – from an environmental, social, and governance (ESG) perspective. This practice enables businesses to communicate their sustainability efforts and outcomes to a diverse group of stakeholders, including investors, customers, and policymakers. Specifically, the aim of the ESRS is to align and enhance transparency and comparability in companies' sustainability performance reporting on ESG impacts, which are key drivers of decisions for investors and stakeholders (Baumüller, Grbenic, 2021; Arkoh *et al*., 2023; Fornasari, Traversi, 2024). Indeed, the ESRS were developed from a collaboration between EFRAG and other independent standards organisations, chiefly the Global Reporting Initiative (GRI).

The agrifood sector stands out in this context because its transition represents a key step towards a sustainable Europe, as emphasised by the European Green Deal. The latter, through the Farm to Fork Strategy (F2FS), is centred on the agrifood sector (European Commission, 2020) due to its significant sustainability impacts on: air, water and soil pollution (Castillo-Díaz *et al*., 2023); greenhouse gas emissions and climate change effects (European Commission, 2020; Tubiello *et al*., 2022); living standards, human health implications, and working conditions (Myers *et al*., 2017). The sector's systemic importance is evident in its role across production, consumption, and waste management, with impacts on the European economy, environment, and social structures.

A fundamental characteristic of the European agrifood industrial ecosystem, which includes upstream, midstream, and downstream businesses, is that over 99% of it is composed of small and medium-sized enterprises (SMEs), which account for 40.1% of the sector's turnover and employ 56.7% of sector operators (Eurostat data 2021 in FoodDrinkEurope, 2024). Italy is a European leader in the food and beverage sector, accounting for 17% of EU enterprises and generating 12.5% of the total sector turnover in the EU in 2022 (FoodDrinkEurope, 2024). Within the Italian manufacturing industry, in 2022 the food and beverage sector accounted for 14.5% of all enterprises, 12.9% of total manufacturing turnover, and 11.3% of all employees. The structure of the Italian food and beverage sector is predominantly composed of SMEs, which make up almost 99% of the industry, generate 40.6% of the sector's total turnover, and employ 69.3% of its workforce (SACE, 2024).

Despite the relevance and prevalence of SMEs, highlighting their potential influence and impact in the value chains, sustainability reporting is still an unfamiliar practice to many (Rodríguez-Gutiérrez *et al*., 2021). This is due to the many challenges they face: (i) a limited amount of data to produce quality information (Girella *et al*., 2019; Marconati, 2024); (ii) limited data collection systems and capacity to process data (Girella *et al*., 2019; Marconati, 2024); (iii) a lack of skills and specialised personnel (Del Baldo, 2017; Girella *et al*., 2019; Marconati, 2024); (iv) a lack of entrepreneurial vision and attitudinal and cultural barriers linked to resistance to change (Del Baldo, 2017; Marconati, 2024; Tombolesi, 2024); (v) internal organisation and governance often based on a family-owned structure (Del Baldo, 2017; Marconati, 2024); (vi) a lack of financial resources and increasing bureaucratic and administrative burdens (Rodríguez-Gutiérrez *et al*., 2021; Giarratana, 2023; Marconati, 2024; Briamonte, Scarpato, 2025); and (vii) a lack of standardised criteria and indicators for the preparation of non-financial reports (Giarratana, 2023; Marconati, 2024). This phenomenon is particularly relevant in Italy, where micro and small businesses demonstrate difficulty in reporting their actions, especially those that are led by informal, non-codified procedures. Such actions fall within the area of 'health and safety in the workplace', the 'internal organisational dimension', 'training', and 'benefits and services for employees' (Briamonte, Hinna, 2008).

Overall, the main benefit expected by SMEs from sustainability reporting is the acquisition of financial benefits by leveraging reports to enhance their reputation and legitimacy (Rodríguez-Gutiérrez *et al*., 2021; Marconati, 2024). In fact, the literature confirms the positive relationship between sustainability performance and financial benefits (Tombolesi, 2024). On the one hand, businesses that are attentive to environmental and social issues and have a good governance system are less exposed to the risks arising from changes in the economic system (Tombolesi, 2024). On the other hand, the development of medium- to long-term sustainability strategies makes it possible to acquire competitive advantages and identify strategic opportunities (Marconati, 2024). Moreover, Briamonte, Hinna (2008) suggest that accountability tools can offer a competitive edge to agrifood businesses in general, allowing them to report on additional quality elements such as country of origin, the nutritional content, and ethical and social factors, including workers' rights and welfare. Nevertheless, there is still a risk that reporting could become abstract, with good intentions failing to translate into actionable measures.

The centrality of both the agrifood sector and SMEs is highlighted by the ESRS framework. First, separate ESRS guidelines for the 'Agriculture, Farming and Fishing Sector' and the 'Food & Beverage Sector' are under development, but this work is currently in a very early stage. Second, SMEs are considered key actors as 'suppliers or clients in the value chains' and are considered in terms of the administrative and financial difficulties that they encounter. EFRAG has developed two specific sets of ESRS, although they have not yet been adopted: one for listed SMEs – Sustainability Reporting standard for Listed SMEs (LSME) – obliged to report on sustainability impacts (EFRAG, 2025a), and one for those who will voluntarily report – Voluntary Sustainability Reporting Standards for Non-listed SMEs (VSME). The latter is of particular importance in this study as it applies to the majority of Italian SMEs. Indeed, an analysis of the 127 Italian listed SMEs in 2024, published by the National Commission for Companies and the Stock Exchange (CONSOB, 2025), reveals that less than 5% operate in the agrifood sector. Thus, most agrifood SMEs fall under the VSME set.

There is growing academic interest in studies on sustainability reporting (Calabrese *et al.*, 2019; Elalfy *et al.*, 2021; Arkoh *et al.*, 2023), including for SMEs (Del Baldo, 2017; Girella *et al.*, 2019; Steinhöfel *et al.*, 2019; Donnari, 2023; Giarratana, 2023; Marconati, 2024; Tombolesi, 2024) and sectors with a high environmental impact, specifically the food and beverage industry (Topp-Becker, Ellis, 2017; Stranieri *et al.*, 2019; Arkoh *et al.*, 2023; Briamonte *et al.*, 2024). However, there has been little research on how SMEs in the agrifood sector approach sustainability reporting (Briamonte, Scarpato, 2025), highlighting the need for further exploration (Celli *et al.*, 2024; Ortiz-Martínez, Marín-Hernández, 2023). This study aims to fill this gap by analysing the current sustainable reporting of agrifood SMEs, seeking to understand whether the new VSME is applicable and consistent with the agrifood sector. To this end, this study includes a comparative analysis between the two reporting frameworks, GRI and VSME, and an applicability analysis of the VSME by agrifood SMEs that adopt the GRI framework. Specifically, the study aims (i) to analyse the GRI in terms of the material topics and standards predominantly used by agrifood SMEs; (ii) to compare the potential use of the VSME by agrifood SMEs; and (iii) to evaluate the differences between the GRI standard and the VSME with a focus on shortcomings in the sustainability assessment of businesses in the agrifood sector.

The rest of this paper is organised as follows. Section 2 describes the conceptual framework for this paper, focusing on the ESRS and GRI reporting systems and especially on the VSME. Section 3 defines the sample and describes the qualitative methodology adopted in the analysis. Section 4 presents the main results in terms of materiality, GRI usage, and the potential adoption of the ESRS by agrifood SMEs. Section 5 discusses the results. Finally, Section 6 concludes the paper.

2. CONCEPTUAL FRAMEWORK: THE ESRS AND GRI REPORTING SYSTEMS

The alignment and standardisation of sustainability reporting is guaranteed by the collaboration between EFRAG and many existing entities, standards, and accountability frameworks (EFRAG, 2025b). In particular, the ESRS were developed in cooperation with the GRI under the July 2021 expertise-sharing agreement, to unify accountability principles at the European level through the technical guidance of EFRAG (GRI, EFRAG, 2023; EFRAG, 2025b). Moreover, the GRI framework is characterised by the considerable freedom and flexibility afforded to businesses in its adoption, favouring a high degree of subjectivity. Although this characteristic allows the framework to be adopted by any business, it also makes it challenging to apply properly, especially for SMEs (Bellantuono *et al.*, 2018; Calabrese *et al.*, 2019; Torelli *et al.*, 2020).

The GRI is an independent international organisation that was founded in 1997 in Boston (United States) to develop accountability guidelines in matters of sustainability (Massari, Giannoccaro, 2023; Zharfpeykan, Akroyd, 2023; GRI, 2025a). The GRI standards have been recognised as the most credible and have been used internationally (Arena, Azzone, 2012; Girella *et al.*, 2019; Stranieri *et al.*, 2019; Rodríguez-Gutiérrez *et al.*, 2021; Zharfpeykan, Akroyd, 2023). Over the years, GRI development efforts have contributed to the spread of non-financial reporting practices across various sectors thanks to the provision of guidelines and standards (Bartolacci *et al.*, 2020). Indeed, the GRI standards provide a flexible framework that is adaptable to any sector and management strategy (Massari, Giannoccaro, 2023).

The GRI framework suggests starting reporting activities with the materiality assessment. This consists of identifying relevant topics to the business, considering both internal and external perspectives (Zharfpeykan, Akroyd, 2023). The latter refers to the involvement of stakeholders, considering their opinion on the impacts of business activities (GRI, 2022). This process provides thematic guidelines for businesses to cover all relevant aspects of sustainability in the economic, environmental, and social spheres. The GRI standards are divided into Universal Standards (transversal standards relating to fundamental principles, general disclosures, and material topics), Sector Standards (sector-specific sets of standards and material topics), and Specific Standards. The latter are grouped into three series: (i) GRI 200 (economic disclosures), (ii) GRI 300 (environmental disclosures), and (iii) GRI 400 (social disclosures) (Massari, Giannoccaro, 2023; GRI, n.d.). Moreover, each Specific and Universal Standard provides a list of disclosures, indicating information requirements, recommendations, and guidelines. None of the disclosures are mandatory, nor do they present precise calculation indicators: businesses that decide to report on individual disclosures will find the corresponding required, recommended, and guideline information.

In this context, the ESRS were introduced to streamline and standardise reporting requirements, providing unique guidance for reporting businesses and helping recipients (e.g., investors) read and compare information (Baumüller, Grbenic, 2021). As stated in the CSRD and in the Commission Delegated Regulation (EU) 2023/2772, the ESRS are structured into 12 standards grouped as follows: (i) two general (1 – General requirements; 2 – General disclosures), (ii) five environmental (E1 – Climate change; E2 – Pollution; E3 – Water and marine resources; E4 – Biodiversity and ecosystems; E5 – Resource use and circular economy), (iii) four social (S1 – Own workforce; S2 – Workers in the value chain; S3 – Affected communities; S4 – Consumers and end-users), and (iv) one governance (G1 – Business conduct). The specific LSME and VSME sets provide additional simplifications to meet the needs of SMEs.

The VSME is structured as follows: the Basic Module comprises 11 reportable standards (the minimum required), and the Comprehensive Module covers additional issues that are likely to be requested by banks, investors, and corporate clients. This simplification is underscored by the central principle guiding the reporting: instead of the materiality assessment, which involves stakeholders' interests and perceptions, the VSME is based on the 'if applicable' principle (EFRAG, 2024). Moreover, the ESRS are designed to provide a more simplified approach to sustainability reporting, offering specific indicators and streamlining the topics that need to be addressed while maintaining an alignment with the previous GRI framework.

3. RESEARCH DESIGN

In light of the robust interoperability between the ESRS and GRI (GRI, EFRAG, 2023) and the latter's adaptability to the context of SMEs (Rodríguez-Gutiérrez *et al.*, 2021), this study uses the GRI as a proxy for the potential use of the ESRS by agrifood SMEs. Each ESRS (G – governance, S – social, and E – environmental) corresponds to one or more GRI standards covering the same disclosure topics, demonstrating the interoperability between the two frameworks (Figure 1). For example, Standard E2 (pollution) is covered by GRI 303 (water and effluents) and GRI 305 (emissions). Moreover, GRI Universal Standards 2 and 3 intersect with all ESRS due to their transversal and methodological scope. Through a concordance approach between frameworks, the applicability of the VSME was investigated indirectly by analysing GRI reports.

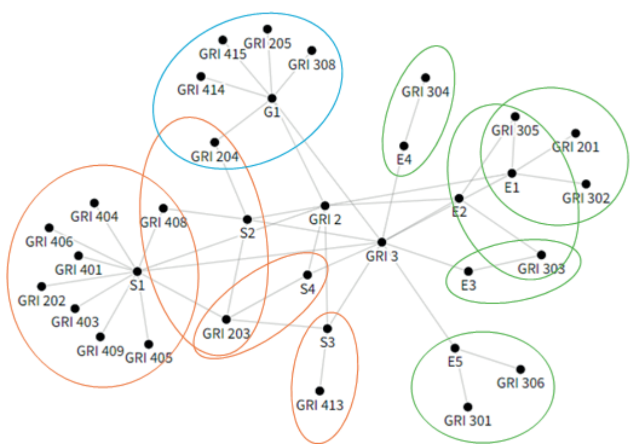

Figure 1. Alignment of the GRI standards and the ESRS. Note: ▪ Governance; ▪ Social; ▪ Environmental. *Source*: authors' elaboration based on GRI (2023b).

3.1. Sample selection

To analyse the adoption of sustainability reporting by agrifood SMEs in the national context, the sustainability reports of Italian businesses meeting the following criteria were selected and analysed:

- qualification as SMEs: fewer than 250 employees, turnover of less than 50 million euros, or a total balance sheet of less than 43 million euros;
- operating in the agrifood sector;
- adherence to the GRI reporting framework (Stranieri *et al*., 2019).

The analysis focused on the Emilia-Romagna region in north-east Italy. Known as the 'Food Valley' of Italy, Emilia-Romagna is renowned for its agrifood production sector, characterised by its exceptional variety of high-quality agricultural products (Leardini, Serventi, 2016). Emilia-Romagna's agrifood sector accounts for over 15% of Italy's export value, is composed of more than 60,000 businesses, and employs nearly 150,000 people, highlighting its socioeconomic importance. Its economic relevance is also reflected in the region's added value per capita, which is €2150 – well above Italy's average of €1332 (Regione Emilia-Romagna, 2024). Furthermore, Emilia-Romagna has the second highest percentage of SMEs in the agrifood sector (2%) in Italy after Umbria (2.9%), exceeding the Italian average (1.6%) by 0.4% in 2023 (Confindustria, Cerved, 2023). Therefore, Emilia-Romagna is a relevant context for analysing the sustainability commitment of businesses.

The sample was built consulting the 'Top 500' businesses list edited by KPMG Emilia-Romagna in collaboration with Confindustria Emilia-Romagna, based on an analysis of public financial statements. A sample of 204 SMEs operating in the agrifood sector in Emilia-Romagna was formed from:

- the ninth edition of Top 500 Parma businesses in terms of turnover based on 2022 data in the province of Parma (110 agrifood SMEs – 54% of the total sample);
- the ninth edition of Top 500 Bologna businesses in terms of turnover based on 2022 data in the province of Bologna (41 agrifood SMEs – 20% of the total sample);
- the ninth edition of Top 500 Piacenza businesses in terms of turnover based on 2022 data in the province of Piacenza (42 agrifood SMEs – 21% of the total sample).

To broaden the sample and to support the research with positive examples, other sources were consulted:

- a report by *Corriere della Sera* (2022) in collaboration with the Bologna Business School on 51 businesses that received awards for their sustainability reports (7 agrifood SMEs – 3% of the total sample);
- the suggestions of academic experts in the field (4 agrifood SMEs – 2% of the total sample).

Out of the sample of 204 agrifood SMEs, 63.73% (130 businesses) do not report on their sustainability commitments. The remaining 36.27% (74 businesses) communicate their sustainability efforts in different ways. Specifically, 31.08% have a dedicated section on their corporate website where they present their vision, commitments, and often the goals they have achieved in terms of sustainability. However, the content of these sections varies considerably across businesses, and the level of detail and depth is largely at the discretion of each business, making this source unsuitable for systematic analysis. The same applies to non-GRI reports (10.81%), which are not systematically comparable. By contrast, 21.62% (17 businesses) adopt the GRI standards as their reporting framework. Because this method provides a comprehensive document that usually also includes the information available on corporate websites and certifications, the sustainability reports of these 17 businesses were analysed (Table 1).

Of the 17 businesses with a GRI Report (7.84% of the total sample), one had to be excluded because it did not declare the GRI Specific Standards it adopted. The 16 selected businesses are medium-sized (with the exception of one small company) and belong to the following commodity sectors: chocolate (1 business), dressing products (1 business), flours (1 business), vegetable oil (2 businesses), pasta (1 business), seafood (2 businesses), fruit and vegetable products (2 businesses), cured meats (2 businesses), wine products (2 businesses), and multiple food products (2 businesses).

Table 1. Reporting methods used by businesses in the sample to communicate their sustainability commitment.

Sustainability communication method	% in the sample
Dedicated section on corporate website	*31.08*
GRI report	*21.62*
Environmental certifications	*20.27*
EMAS verified environmental management statement	*18.92*
Non-GRI report	*10.81*
Integrated corporate policy	*9.46*
Corporate social responsibility policy	*4.05*
Corporate environmental policy	*2.70*

Note: the percentage is calculated based on 74 of the 204 agrifood SMEs in the sample (36.27%). This is because some businesses adopt multiple methods for communicating their sustainability efforts.
Source: authors' elaboration based on data from business databases.

3.2. Content analysis

The 16 sustainability reports were analysed using content analysis, 'a research method that uses a set of procedures to make valid inferences from text' (Weber, 1990: 9). This method allows information in text to be coded, transforming qualitative data into quantitative forms. This characteristic makes content analysis particularly effective in the analysis of corporate reporting documents (Torelli *et al*., 2020) and social and environmental accountability reporting (Guthrie, Abeysekera, 2006; Arkoh *et al*., 2023).

To overcome the potential limitation in assessing the quality of reporting – usually focused more on quantity – the frequency of reporting (Guthrie, Parker, 1990) and the extent of the information disclosed (Deegan, Gordon, 1996; Deegan, Rankin, 1996) were considered to deduce quality (Guthrie, Abeysekera, 2006). As such, content analysis focused on the following aspects:

- Material topics and stakeholder categorisation:
  - the list of stakeholders involved in the materiality assessment was grouped into categories, and the frequency of citation of each stakeholder category was calculated;
  - the list of material topics declared was labelled according to the GRI Specific Standards (GRI, 2024) and the material topics listed in the GRI 13 Sector Standard (GRI, 2023a). When a direct correspondence with GRI nomenclature was missing, the topics were organised by adopting alternative labels, as in the case of 'stakeholder engagement', 'ethics and integrity', 'innovation, research and development', and 'human rights'. Afterwards, the organised topics were grouped into the social, environmental, and economic categories.
- GRI frequency of use was calculated as the percentage of SMEs adopting each GRI Specific Standard relative to the total number of SMEs analysed. This metric identified the most commonly used GRI Specific Standards.
- GRI disclosure coverage was calculated for each GRI standard as the average percentage of disclosures reported by the SMEs analysed relative to the total requested, the metric assesses the completeness of the reports.

3.3. Comparative analysis between the GRI standards used and the ESRS framework

Finally, a comparative analysis was conducted between the VSME set and GRI disclosures using ESRS-GRI Standards data point mapping (GRI, 2023b; EFRAG, 2023b) as a benchmark. This tool facilitated a cross-reference between the adoption of the GRI standards and their corresponding VSME standards and indicators. Consequently, this approach makes it possible to evaluate the alignment between the material topics of SMEs, their ability to translate them into GRI standards, and their potential capacity to comply with and apply the VSME framework.

4. RESULTS

4.1. Categorisation of the material topics

Although SMEs are not required to conduct materiality assessment, 12 out of 16 SMEs in the final sample (75%) chose reporting standards based on a materiality assessment involving their main stakeholders (Table 2). The main stakeholders involved are the key actors engaged with the operational activities of the reporting businesses, such as employees and partners, which are considered internal actors, and suppliers and business-to-business (B2B) clients, which are external actors. Strong consideration is also given to external actors connected with the territory and local society, such as local associations and non-governmental organisations (NGOs), civil society, and local and public institutions. Finally, the sampled businesses also questioned final consumers, universities, banks, and professional unions, albeit less frequently.

The results show that in most cases, the identified material topics address social aspects (44.69%), followed by environmental (33.33%), economic (17.95%), and socio-economic (4.03%) aspects (Figure 2). More specifically, the most commonly cited topics are: 'local communities' (8.6%), 'marketing and labelling' (7.8%) and 'occupational health and safety' (6.7%), for the social category; 'waste' (7.1%) and 'emissions' (6%), for the environmental category; and 'economic performance' (7.8%), for the economic category. The material topic 'ethics and integrity' (4.1%) addresses both economic and social issues. In fact, each business interpreted it by addressing various topics, such as corporate governance and vision, corporate ethics behaviour (e.g., anti-corruption and anti-competitive), and child labour. Note that this heading is not included among the GRI but has been proposed by the businesses themselves.

4.2. Frequency of use and disclosure coverage of the GRI standards

The 16 sampled food businesses use an average of 17.6 GRI standards in their reports, or 56.85% of those availa-

Table 2. Types of stakeholders involved in the materiality assessment by the sample.

Stakeholders	Type of stakeholder	Frequency	
		Number	%
Employees and partners	Internal	12	*100.0*
Suppliers	External	12	*100.0*
B2B clients	External	11	*91.7*
Local community and civil society	External	10	*83.3*
Institutions and public authorities	External	10	*83.3*
Professional unions	External	8	*66.7*
Customers	External	8	*66.7*
Media and press	External	8	*66.7*
Research institutions and universities	External	7	*58.3*
Insurance companies, banks and lending institutions	External	7	*58.3*
Shareholders and investors	Internal/external	5	*41.7*
Labour unions	External	3	*25.0*
Internal governance	Internal	3	*25.0*
Certifying and auditing bodies	External	2	*16.7*
Competitors	External	1	*8.3*

ble. In general, the results highlight that standards are not used in the same way by businesses in terms of frequency of use or disclosure coverage. The majority are used by less than 50% of the sample and the full range of disclosures requested is never completely covered (Figure 3).

Specifically, GRI Universal Standards 1, 2, and 3 are not always reported by the sample, except for GRI 2 (100% frequency of use), even though their consultation represents the first step in the proper application of the GRI framework. In particular, the frequency of use and disclosure coverage of GRI 1 (50% for each) are not considered entirely reliable because GRI 1 does not indicate the information to be reported, but only the general principles at the head of the GRI framework (GRI, 2024). GRI 2, meanwhile, focuses on the chosen reporting practices of the business and its internal organisational policies and governance (GRI, 2024). All SMEs (100%) report it, covering on average 68% of their disclosures. On the one hand, information related to internal governance (i.e., the election of boards of directors, responsibility, performance evaluation, and remuneration) and internal policies for the management and mitigation of impacts generated are discussed less often. On the other hand, general information on the period of reporting, employees, organisational details, and sustainable development strategies are widely declared. Finally, GRI 3 has an 88% frequency of use and an average disclosure coverage of 79%. The disclosure reported least often is the 'management of material topics'.

Regarding the GRI Specific Standards used, there is some correspondence with the material topics chosen. Indeed, the most used Specific Standards (with a ≥ 50% frequency of use) are GRI 403 (occupational health and safety), GRI 401 (employment), GRI 405 (diversity and equal opportunity), GRI 404 (training and education), GRI 417 (marketing and labelling), GRI 416 (customer health and safety), GRI 406 (no discrimination), and GRI 413 (local communities) in the social area; GRI 302 (energy), GRI 305 (emissions), GRI 306 (waste), GRI 301 (materials), and GRI 303 (water and effluents) in the environmental area; and GRI 201 (economic performance) in the economic area.

In general, there is a significant disparity in usage across different standards. For instance, only one business explicitly refers to GRI 13, indicating its limited adoption. Economic standards (the 200 series) are notably underrepresented, while environmental and social standards are more commonly addressed. Despite high usage rates for some standards, the actual coverage of disclosures varies widely, indicating the issues SMEs have in covering all of the information required.

Regarding the frequently used social standards, GRI 403 (occupational health and safety) shows the highest frequency of use (94%) and disclosure coverage of 63%, mainly regarding health and safety management systems, the identification of hazards and risks, accident assessment, and work-related injuries. GRI 401 (employment) and GRI 405 (diversity and equal opportunity) each have a frequency of use of 88% and disclosure coverage of 56% and 66%, respectively. The former mainly regards the characteristics and diversity of governance bodies and employers in terms of gender, age, and hir-

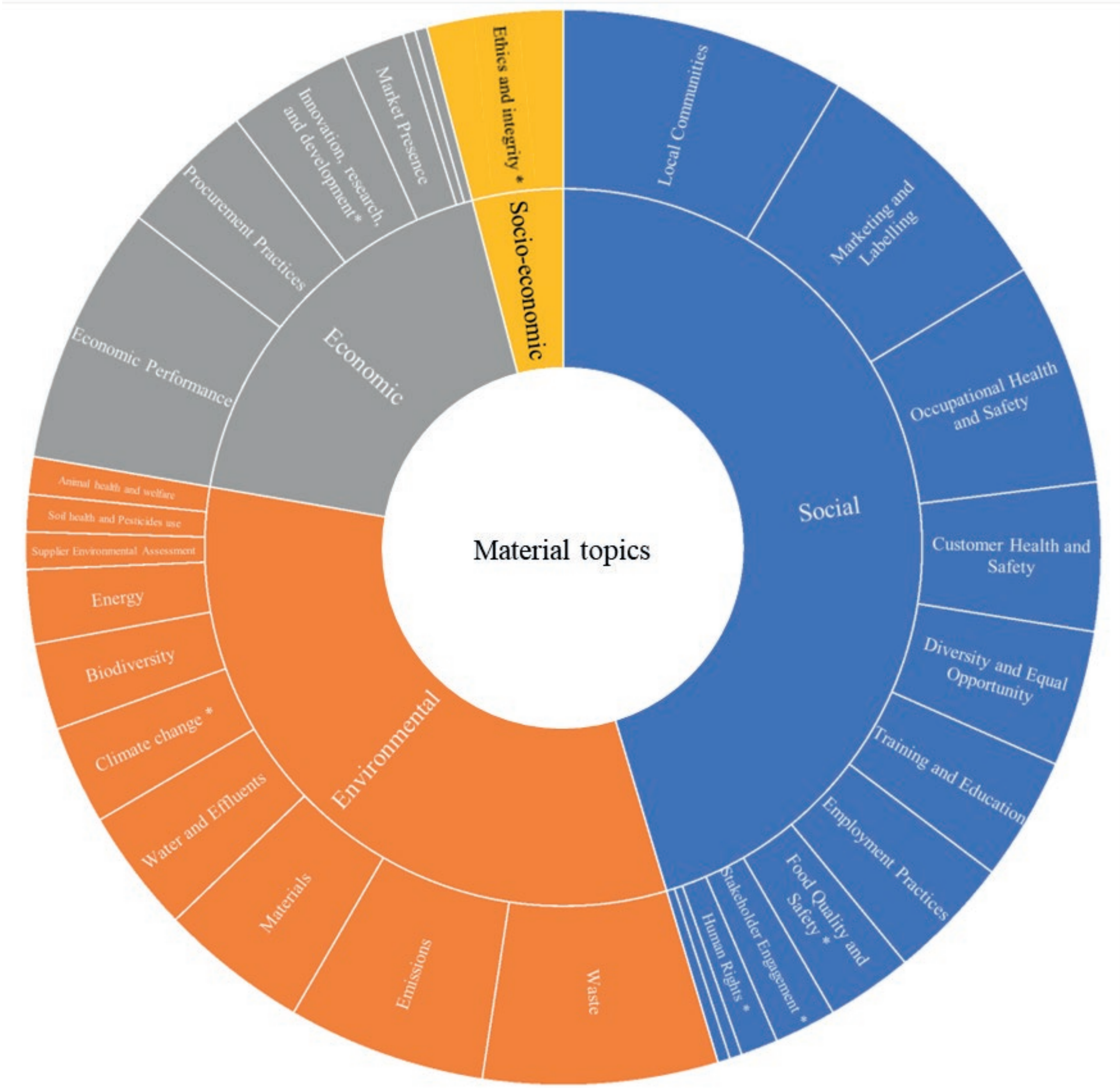

Figure 2. Material topics cited in the analysed reports of the businesses in the sample. Note: the size of the sections corresponds to the frequency with which the material topics are cited. (*) Headings not included in the GRI (2023a, 2024) but are present in the analysed reports.

ing and turnover rates. However, information is lacking on parental leave rules for GRI 401 and on remuneration diversity between women and men for GRI 405. Finally, GRI 404 (training and education) has a frequency of use of 75% but low disclosure coverage (33%). In fact, apart from the average yearly hours of training provided to employees, information on employee skills upgrading programmes and the evaluation of performance and career development is missing.

In the environmental area, GRI 302 (energy) has the highest frequency of use (94%), but a disclosure coverage of 34%. The main information for this standard concerns energy consumption and intensity internal to the business, while information is missing on outside consumption and reductions in consumption and the energy requirements of outputs. GRI 305 (emissions) has a frequency of use of 88%, but a relatively low disclosure coverage (38%). Again, disclosures regarding outside

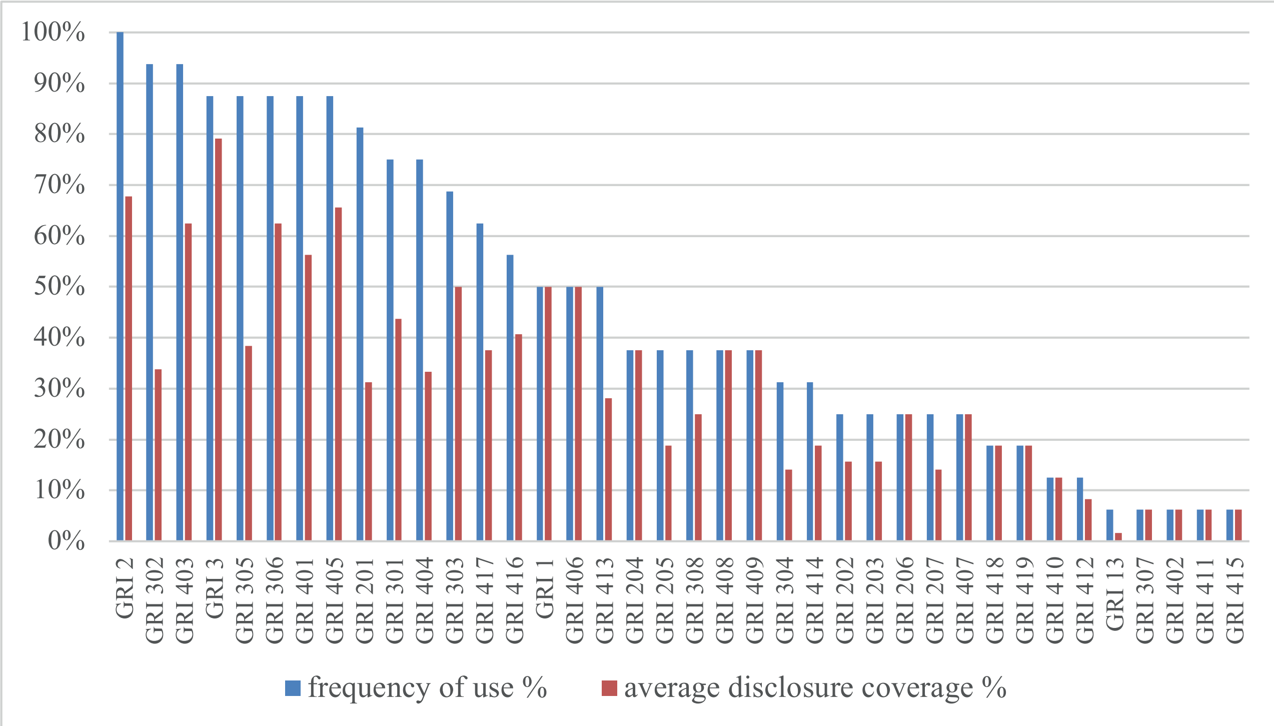

Figure 3. Comparison of the frequency of use and average disclosure coverage of the GRI standards.

emissions indirectly affected by the business (Scope 3) and reductions are missing. Moreover, GRI 306 (waste) shows a high frequency of use (88%) and reasonable disclosure coverage of 63%. Finally, GRI 301 (materials) also exhibits a notable frequency of use (75%) but disclosure coverage of 44%. There is a lack of information on every disclosure, particularly on the recovery rates of product packaging materials, as well as the percentage of recycled materials used in production, highlighting a gap in communicating real sustainability practices.

Within the economic area, GRI 201 has a high frequency of use (81%), but disclosure coverage of only 31%. The focus is on financial implications and risks and opportunities related to climate change, benefits and pension plans, and governmental financial assistance received. All the other GRI Specific Standards on economic issues (the 200 series) show a frequency of use of less than 38%.

4.3. Potential adoption of the VSME for agrifood SMEs

To better understand how the subsample of 16 SMEs (out of 204) describes their actions in relation to specific topics for the food system, the correspondence between ESRS disclosures requested in the VSME set and the GRI standards used by the sample was determined (Table 3).

Within the social dimension, the VSME set identifies three aspects: general characteristics (B8); health and safety (B9); and remuneration, collective bargaining, and training (B10). The first two aspects are comprehensively covered by GRI 2, 403, and 405 and widely and consistently reported by the sample, with a frequency of use ranging from 87.5% to 93.8%. In contrast, reporting on B10 shows greater variability. Specifically, disclosures on minimum wage (GRI 202) are minimal (6.3%), while the gender pay gap (GRI 405) is reported by 43.8% of the sample. Coverage for collective bargaining (GRI 2) and annual training hours (GRI 404) reaches 75%. These findings align with the material topics prioritised by businesses, which demonstrate strong engagement with occupational health and safety and broader employment practices. Notably, other socially relevant topics – such as training and education, consumer communication on product quality, and local community support – are addressed by over 50% of the sample via GRI standards that are absent from the VSME set.

Analysis of environmental disclosures indicates high coverage for energy use and greenhouse gas (GHG) (B3), with 81.3% to 93.8% of the sample reporting on these topics. Exceptions include GHG intensity indicators, reported by only 31.3% of SMEs. Pollution of air, water, and soil (B4) is less consistently covered, as GRI standards do not fully encompass water and soil pollution. Air emissions are addressed under GRI 305, but only 25% of SMEs report this information. Biodiversity (B5) presents further challenges, with GRI 304 capturing only the number and area of sites near or within Biodiversity Sensitive Areas; this is reported by 18.8% of the sample. Water-related disclosures (B6) under GRI 303 show more frequent reporting of general water withdrawal (68.8%) than water consumption and discharge (37.5%). Resource use, circular economy, and waste management (B7) exceed 50% reporting for total waste generation, waste diverted from disposal, and hazardous versus non-hazardous waste, as captured by GRI 306. It is also notable that materials – a topic of high interest and disclosure capacity for SMEs through GRI – are not included in the VSME set.

Regarding governance, convictions and fines for corruption and bribery (B11), reported under GRI 2, appear in 56.3% of the sample. From an economic perspective, SMEs demonstrate strong engagement with value

Table 3. Comparison between the ESRS indicators requested in the VSME set and the GRI standards used in the analysed sample.

VSME standard	VSME indicator	GRI standard and disclosure*	Content of the GRI disclosure	% sample adopting the GRI disclosure
Environmental				
B3 – Energy and greenhouse gas emissions	Total energy consumption in MWh (fossil fuels) broken down into: - total - renewable sources - non-renewable sources	302_1a 302_1b	Total fuel consumption within the organisation from renewable and non-renewable sources (in GJ or Wh and multiples)	*93.8*
	Total energy consumption in MWh (electricity expressed in utility bills) broken down into: - total - renewable sources - non-renewable sources	302_1e	Total energy consumption within the organisation (in GJ or multiples)	*93.8*
	Scope 1 (from owned or controlled sources) in tCO_2eq: GHG Emissions, Fuel = Activity Data Fuel × EFGHG, Fuel × GWPGHG	305_1a	Gross direct (Scope 1) GHG emissions in metric tons of CO_2 equivalent	*87.5*
	Scope 2 (location-based) in tCO_2eq: GHG Emissions = Activity Data × EF	305_2a	Gross location-based energy indirect (Scope 2) GHG emissions in metric tons of CO_2 equivalent	*81.3*
	Total GHG Emissions: Scope 1 + Scope 2	305_1a 305_2a	Total GHG emissions (Scope 1 + Scope 2 Location Based) in metric tons of CO_2 equivalent	*87.5* *81.3*
	GHG intensity: (Total Scope 1 + Scope 2)/turnover	305_4a, b, c	a) GHG emissions intensity ratio for the organisation b) Organisation-specific metric (the denominator) chosen to calculate the ratio c) Types of GHG emissions included in the intensity ratio; whether direct (Scope 1), energy indirect (Scope 2), and/or other indirect (Scope 3)	*31.3*
B4 – Pollution of air, water and soil	Amount of pollutants emitted in undertaking's own operations in water (kg of emissions)	-	GRI does not provide a direct match	-
	Amount of pollutants emitted in undertaking's own operations in soil (kg of emissions)	-	GRI does not provide a direct match	-
	Amount of pollutants emitted in undertaking's own operations in air (kg of emissions)	305_7a	Significant air emissions, in kilograms or multiples, for each of the following: NOx, SOx, POP, VOC, HAP, PM, and others	*25.0*

(Continued)

Table 3. (Continued).

VSME standard	VSME indicator	GRI standard and disclosure*	Content of the GRI disclosure	% sample adopting the GRI disclosure
B5 – Biodiversity	Number and area (in hectares) of sites that the undertaking owns, has leased, or manages in or near Biodiversity Sensitive Areas (BSA)	304_1a	Operational sites owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity value outside protected areas	*18.8*
	Total use of land (in hectares or m^2): - previous year - reporting year - % change	304_1	GRI does not provide a direct match; in the notes to 304-1 it is only suggested as a valid support	*18.8*
	Total sealed area (in hectares or m^2): - previous year - reporting year - % change	-	GRI does not provide a direct match	-
	Total nature-oriented area on-site (in hectares or m^2): - previous year - reporting year - % change	-	GRI does not provide a direct match	-
	Total nature-oriented area off-site (in hectares or m^2): - previous year - reporting year - % change	-	GRI does not provide a direct match	-
B6 – Water	Total Water Withdrawal = ∑ of any withdrawal sources (public water as in utility bills + groundwater from own well + water from rivers and lakes + other sources – rainwater collected or stored)	303_3a	Total water withdrawal from all areas in megalitres	*68.8*
	Water Consumption = Water Withdrawal – Water discharges	303_5a	Total water consumption from all areas in megalitres	*37.5*
B7 – Resource use, circular economy, and waste management	Total annual generation of waste expressed in units of weight (kg or t) diverted to recycling or reuse and per type: - hazardous - non-hazardous	306_3a	Total weight of waste generated in metric tons, and a breakdown of this total by composition of the waste	*81.3*
		306_4a, b, c	a) Total weight of waste diverted from disposal in metric tons, and a breakdown of this total by composition of the waste. b-c) Total weight of hazardous and non-hazardous waste diverted from disposal in metric tons, and a breakdown of this total by the following recovery operations: i. Preparation for reuse; ii. Recycling; iii. Other recovery operations	*56.3*
	Annual mass-flow of relevant materials used (if the undertaking belongs to a sector using significant material flows – e.g., used lubricants and oils classified as hazardous)	EMAS certification	GRI does not provide a direct match but suggests covering this information with EMAS certification if held	-

(Continued)

Table 3. (Continued).

VSME standard	VSME indicator	GRI standard and disclosure*	Content of the GRI disclosure	% sample adopting the GRI disclosure
Social				
B8 – Workforce – general characteristics	a) Total number of employees (by full time equivalent or head count) by type of employment contract (temporary or permanent)	2_7b	Total number of employees by type of employment contract, broken down by gender and region	*93.8*
		2_7a	Total number of employees, broken down by gender and by region	*93.8*
	b) Total number of employees (by full time equivalent or head count) by gender;	405_1b	Percentage of employees per employee category in each of the following diversity categories: gender; age group; and other indicators of diversity where relevant	*87.5*
	c) Total number of employees (by full time equivalent or head count) by country of the employment contract (if applicable)	2_7b	c) Total number of employees (by full time equivalent or head count) by country	*93.8*
	Employee turnover (when ≥ 50 employees): (number of employees who left during reporting year / Average number of employees during reporting year) × 100	401_1b	Total number of employee turnover during the reporting period, by age group, gender and region.	*87.5*
B9 – Workforce – health and safety	Number of recordable work-related accidents and Rate = (number of accidents in the reporting year / total number of hours worked by all employees in a year) × 200	403_9a.ii-v	Number of work-related injuries	*93.8*
	Number of fatalities as a result of work-related injuries and work-related ill health	403_9a.i	The number and rate of fatalities as a result of work-related injury	*93.8*
B10 – Workforce – remuneration, collective bargaining, and training	a) Minimum wage: verification that employees pay is ≥ minimum wage (determined directly by the national minimum wage law or through a collective bargaining agreement)	202_1a, b, c	Ratios of standard entry level wage by gender compared to the local minimum wage	*6.3*
	b) Gender pay gap (when at least 150 employees) = [(average gross hourly pay of male employees – average gross hourly pay of female employees)/ average gross hourly pay of male employees] × 100	405_2a	Ratio of the basic salary and remuneration of women to men for each employee category, by significant locations of operation	*43.8*
	c) % of collective bargaining coverage = (number of employees covered by collective bargaining agreements / number of employees) × 100	2_30a	Report the percentage of total employees covered by collective bargaining agreements	*75.0*
	d) Average number of annual training hours per employee broken down by gender	404_1a	Average hours of training that the organisation's employees have undertaken during the reporting period, by: gender; employee category	*75.0*
Business conduct				
B11 – Convictions and fines for corruption and bribery	Number of convictions (verdict of criminal court) incurred for the violation of anti-corruption and anti-bribery laws	2_27a	Report the total number of significant instances of non-compliance with laws and regulations during the reporting period	*56.3*
	Total amount of fines (monetary penalties) incurred for the violation of anti-corruption and anti-bribery laws	2_27b	Report the total number and the monetary value of fines for instances of non-compliance with laws and regulations that were paid during the reporting period	*56.3*

creation as a material topic through GRI disclosures, although this area is not included in the VSME set.

5. DISCUSSION

The scarcity of companies adopting a GRI-based reporting system compared to the number of companies analysed indicates the difficulty or lack of interest of agrifood SMEs in adhering to this practice, as highlighted in the literature (Del Baldo, 2017; Girella *et al*., 2019; Rodríguez-Gutiérrez *et al*., 2021; Giarratana, 2023; Marconati, 2024; Tombolesi, 2024; Briamonte, Scarpato, 2025). However, the growing institutional pressure to draw up sustainability reports requires reflection on the usefulness of this tool for agrifood SMEs. The trend observed at the institutional level is leading to greater simplification of the reporting frameworks to facilitate the use of shared standards. However, this process cannot ignore two important aspects: first, the need for specific indicators for the agrifood sector, which are currently scarce, and second, the impact that a business can have on the entire agrifood system.

Concerning the first aspect, the VSME lack indicators on social aspects that assess the impact on the local community and other elements that characterise product quality which agrifood SMEs are generally capable of and interested in communicating (Briamonte, Hinna, 2008). Indeed, the analysis confirms that businesses adopt the GRI standards to highlight their impact on the local community, disclosing, for example, the launch of educational initiatives, collaboration with charitable organisations and local associations, and the inclusion of disadvantaged people. Meanwhile, SMEs also provide information on product quality, including the adoption of transparent labelling in terms of materials used, information on product characteristics and consumption, and certifications in compliance with European regulations. Moreover, the GRI and VSME frameworks demonstrate limited attention to sustainable practices geared towards preserving biodiversity, soil health, and pesticide use, which, in turn, are key to the agrifood sector's ability to achieve Sustainable Development Goal (SDG) 15 (Life on Land) and SDG 12 (Sustainable Practices). The businesses do present some qualitative indicators on sustainable agricultural practices to preserve or promote biodiversity in their reports, albeit to a limited extent. The lack of coverage of this critical topic could be due to the actual lack of interest of businesses in the issues or related to an inability to find suitable indicators to produce communicable information. Indeed, it can be argued that it is inherently difficult to quantify and measure the impact of agricultural materials on biodiversity. The available indicators are often closely linked to subjective assumptions and do not consider complex dynamics such as the comparison of on-farm versus off-farm impacts on biodiversity (Wesseler, 2022). Other potential indicators to assess the biodiversity of a habitat, proposed in the academic literature, are the QBS-ar method (Biological Soil Quality) based on the soil micro-arthropod community analysis (Parisi, 2001; Parisi *et al*., 2005) and the Shannon diversity index, a statistical measure quantifying the biodiversity of a habitat (Kok *et al*., 2020; Shannon, Weaver, 1949 in Dabkiene *et al*., 2021). The GRI itself has updated its Biodiversity Standard to the new GRI 101, which will be in force beginning in January 2026. This requires businesses to determine the sites, products, and services in their supply chain that have the most significant impacts on biodiversity, both in terms of protection and loss, and their evolution over time with a clear value chain perspective. This new approach also requires businesses to report on the potential or actual biodiversity impacts of upstream and, if desired, downstream suppliers, and on the effects of the business's activities on local communities and other stakeholders (GRI, 2025b).

The second aspect is related to the lack of supply chain impact assessments, which highlights the fact that businesses have poor awareness of their responsibility to influence the sustainability of the entire supply chain in which they operate. Considering the upstream level, businesses infrequently disclose the evaluations of suppliers and report only on material usage. Concerning the downstream level, reporting is focused on 'food safety' information for the consumer. Although a comprehensive supply chain perspective is crucial for achieving a positive sustainability impact, it is not required in the VSME. Despite their small size, SMEs have a significant impact on the environmental, social, and economic sustainability of food supply chains due to their prevalence, widespread distribution, and key role along the entire value chain (Schmerber *et al*., 2022; UN Global Compact, 2024). The EFRAG has proposed an Implementation Guidance draft specific to reporting the impact on the value chain. First, this guidance considers the value chain as a whole, defined as the entire supply chain and all its interactions with the external environment, including resources, activities, and human relations, from the upstream to downstream levels. Second, it provides instructions on how businesses should report on how they impact the value chain. These initial implementation steps demonstrate the increasing focus on the concept of value chain impact that the future ESRS intend to incorporate, which will also increasingly engage SMEs (EFRAG, 2023a).

Therefore, it also emphasises the need for future advances in reporting this type of impact.

Considering these aspects, the analysis conducted in this study raises questions about the meaning of reporting: is it intended to be a tool that represents minimum standards to be achieved or a strategic tool with multiple objectives for driving the sustainable transition? In the latter case, reporting can be useful (i) to monitor corporate performance in terms of sustainability, which SMEs lack; (ii) to access financial or credit benefits; (iii) to demonstrate a company's ability to produce positive externalities in line with the SDGs; and (iv) to create a reputational return on image that increases the perceived value of products. While the first three aspects can bring more immediate results in the short term, the fourth requires more time and the ability to communicate with civil society (Casalino, 2024). Consequently, the tool must be easy to complete, covering aspects relevant to the agrifood system and its key stakeholders, and be clearly communicated externally.

6. CONCLUSIONS

This study conducted a comparative analysis between the GRI and VSME reporting frameworks, analysing the applicability of the VSME for agrifood SMEs. Content analysis was used to examine the sustainability reports of 16 Italian agrifood SMEs to determine the use of the GRI standards and the ability to adopt the VSME. Sustainability reporting can represent an innovative tool for assessing the sustainable practices of businesses and acquiring benefits in terms of reputational and financial returns. However, the results show that although the latest VSME framework reduces complexity and resource requirements compared to the GRI, it still lacks sector-specific indicators for the agrifood industry as well as a value chain perspective. These gaps limit the potential efficacy of sustainability reporting practices for agrifood SMEs. Furthermore, because the adoption of these reporting frameworks requires significant economic investment by SMEs, it is important that agrifood SMEs perceive sustainability reporting as a useful tool, and not just a compliance exercise. In fact, sustainability reporting can be a management tool to support decision-making processes and a commitment to sustainability transitions.

Considering the missing disclosures in the VSME and the difficulties SMEs face in collecting data and reporting certain indicators, the VSME can be considered a starting point rather than a definitive solution. In this sense, the development of a reporting framework tailored to the agrifood sector and the capabilities of SMEs should be considered an evolving work in progress. Associations and intermediary bodies could be involved as consultants (i.e., Tombolesi, 2024) or facilitators between the business and its stakeholders, to understand the interests of the stakeholders and to support the drafting of the report and the communication of the company's activities. A valuable example is Confcooperative Parma (Emilia-Romagna), which has established the external 'Omnia Service' office to provide specific services for their associates, such as support in the transition towards and reporting on sustainability. At the same time, they work as intermediaries between businesses and financial institutions to achieve financial benefits. Continuous refinement and dialogue between policymakers, standard-setting bodies, intermediary institutions, and businesses could be key to creating a reporting system that is feasible for SMEs and capable of promoting a meaningful transition towards sustainability in the agrifood sector.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.T., M.G. and F.A.; Methodology, T.T. and M.G.; Investigation, T.T. and M.G.; Writing - Original Draft, T.T. and M.G.; Writing –Review & Editing, T.T., M.G. and F.A.; Funding Acquisition, F.A.; Resources, F.A.; Supervision, F.A.

REFERENCES

Arena M., Azzone G. (2012). A process-based operational framework for sustainability reporting in SMEs. *Journal of Small Business and Enterprise Development*, 19(4): 669-686. DOI: https://doi.org/10.1108/14626001211277460.

Arkoh P., Costantini A., Scarpa F. (2023). Determinants of sustainability reporting: A systematic literature review. *Corporate Social Responsibility and Environmental Management*, 31(3): 1578-1597. DOI: https://doi.org/10.1002/csr.2645.

Bartolacci F., Caputo A., Soverchia M. (2020). Sustainability and financial performance of small and medium sized enterprises: A bibliometric and systematic literature review. *Business Strategy and the Environment*, 29(3): 1297-1309. DOI: https://doi.org/10.1002/bse.2434.

Baumüller J., Grbenic S.O. (2021). Moving from non-financial to sustainability reporting: Analyzing the EU Commission's proposal for a Corporate Sustainability Reporting Directive (CSRD). *Facta Universitatis, Series: Economics and Organization*, (1): 369-381. DOI: https://doi.org/10.22190/FUEO210817026B.

Bellantuono N., Pontrandolfo P., Scozzi B. (2018). Guiding materiality analysis for sustainability reporting: the case of agri-food sector. *International Journal of Technology, Policy and Management*, 18(4): 336-359. DOI: https://doi.org/10.1504/IJTPM.2018.096181.

Briamonte L., Hinna L. (2008). *La responsabilità sociale per le imprese del settore agricolo e agroalimentare*. Edizioni Scientifiche Italiane, Napoli.

Briamonte L., Scarpato D. (2025). From soft law to hard law: Legal transitions and sustainable challenges in the Italian agri-food sector. *Sustainability*, 17(19), 8952. DOI: https://doi.org/10.3390/su17198952.

Briamonte L., Pergamo R., Salerno C., Uliano A., Nazzaro C. (2024). Measuring social sustainability in the Italian agri-food sector: Proposed key performance indicators. *Foods*, 13(17), 2849. DOI: https://doi.org/10.3390/foods13172849.

Calabrese A., Costa R., Levialdi Ghiron N., Menichini T. (2019). Materiality analysis in Sustainability Reporting: A tool for directing corporate sustainability towards emerging economic, environmental and social opportunities. *Technological and Economic Development of Economy*, 25(5): 1016-1038. DOI: https://doi.org/10.3846/tede.2019.10550.

Casalino M.V. (2024). *La pianificazione strategica della sostenibilità alla luce della Direttiva n. 2022/2464 Corporate Sustainability Reporting Directive*, Tesi di Laurea Magistrale in Amministrazione, Finanza e Controllo, Università Ca' Foscari di Venezia.

Castillo-Diaz F.J., Belmonte-Urena L.J., Lopez-Serrano M.J., Camacho-Ferre F. (2023). Assessment of the sustainability of the European agri-food sector in the context of the circular economy. *Sustainable Production and Consumption*, 40: 398-411. DOI: https://doi.org/10.1016/j.spc.2023.07.010.

Celli M., Arduini S., Beck T. (2024). Corporate sustainability reporting directive (CSRD) and his future application scenario for Italian SMEs. *International Journal of Business and Management*, 19(4): 1-44. DOI: https://doi.org/10.5539/ijbm.v19n4p44.

Confindustria, Cerved (2023). *Rapporto regionale PMI 2023*, Report 2023, Confindustria and Cerved, Roma.

CONSOB (2025). *SMEs – Small and medium-sized enterprises*, Commissione Nazionale per le Società e la Borsa, Rome. https://www.consob.it/web/consob-and-its-activities/smes.

Corriere della Sera (2022). *Bilancio di sostenibilità: ecco le aziende che si raccontano meglio*, Corriere della Sera, Milan. http://www.corriere.it/buone-notizie/22_aprile_11/bilancio-sostenibilita-ecco-aziende-che-si-raccontano-meglio-d1b8620c-b6c1-11ec-b39d-8a197cc9b19a.shtml.

Dabkiene V., Balezentis T., Streimikiene D. (2021). Development of agri-environmental footprint indicator using the FADN data: Tracking development of sustainable agricultural development in Eastern Europe. *Sustainable Production and Consumption,* 27: 2121-2133. DOI: https://doi.org/10.1016/j.spc.2021.05.017.

Deegan C., Gordon B. (1996). A study of the environmental disclosure policies of Australian corporations. *Accounting and Business Research*, 26(3): 187-199. DOI: https://doi.org/10.1080/00014788.1996.9729510.

Deegan C., Rankin M. (1996). Do Australian companies report environmental news objectively? An analysis of environmental disclosures by firms prosecuted successfully by the Environmental Protection Authority. *Accounting, Auditing and Accountability Journal*, 9(2): 50-67. DOI: https://doi.org/10.1108/09513579610116358.

Del Baldo M. (2017). The implementation of integrating reporting in SMEs: Insights from a pioneering experience in Italy. *Meditari Accountancy Research*, 25(4): 505-532. DOI: https://doi.org/10.1108/MEDAR-11-2016-0094.

Donnari A. (2023). *Il report di sostenibilità nelle PMI: un'indagine sul livello preliminare di allineamento ai nuovi standard VSME-ESRS*, Tesi di Laurea Magistrale in Economia e Management, Università Politecnica delle Marche.

EEA (2024). *Trends and projections in Europe 2024*, Report n. 11, European Environment Agency, Copenhagen. DOI: https://doi.org/10.2800/7574066.

EFRAG (2023a). *Draft EFRAG IG 2: Value chain implementation guidance*, European Financial Reporting Advisory Group, Brussels.

EFRAG (2023b). *Draft EFRAG IG 3 List of ESRS Data Points*, European Financial Reporting Advisory Group, Brussels.

EFRAG (2024). *EFRAG Voluntary Sustainability Reporting Standard for non-listed SMEs (VSME)*, European Financial Reporting Advisory Group, Brussels.

EFRAG (2025a). *SMEs*, European Financial Reporting Advisory Group, Brussels. https://www.efrag.org/en/sustainability-reporting/esrs-workstreams/smes.

EFRAG (2025b). *Interoperability*, European Financial Reporting Advisory Group, Brussels. https://www.efrag.org/en/sustainability-reporting/esrs-workstreams/interoperability.

Elalfy A., Weber O., Geobey S. (2021). The Sustainable Development Goals (SDGs): A rising tide lifts all boats? Global reporting implications in a post SDGs world. *Journal of Applied Accounting Research*, 22(3): 557-575. DOI: https://doi.org/10.1108/JAAR-06-2020-0116.

European Commission. (2020). *Farm to Fork Strategy: For a fair, healthy and environmentally-friendly food system*. COM/2020/381, Brussels.

FoodDrinkEurope (2024). *Data & Trends: EU Food and Drink Industry,* 2024 Edition, FoodDrinkEurope, Brussels. https://www.fooddrinkeurope.eu/wp-content/uploads/2025/01/FoodDrinkEurope-Data-Trends-2024.pdf.

Fornasari T., Traversi M. (2024). The impact of the CSRD and the ESRS on non-financial disclosure. *Symphonya. Emerging Issues in Management*, (1): 117-133. DOI: https://doi.org/10.4468/2024.1.07fornasari.traversi.

Giarratana E. (2023). *L'evoluzione della reportistica di sostenibilità: nuove sfide per le PMI*, Tesi di Laurea Magistrale in Economia e Legislazione d'Impresa, Università di Pavia.

Girella L., Zambon S., Rossi P. (2019). Reporting on sustainable development: A comparison of three Italian small and medium-sized enterprises. *Corporate Social Responsibility and Environmental Management*, 26(4): 981-996. DOI: https://doi.org/10.1002/csr.1738.

GRI (2022). The materiality madness: Why definitions matter, *The GRI Perspective*, 3: 1-4.

GRI (2023a). *GRI 13: Agriculture, Aquaculture and Fishing Sectors 2022 - Sector Standard*, Global Reporting Initiative, Amsterdam.

GRI (2023b). *ESRS-GRI Standards data point mapping*, Global Reporting Initiative, Amsterdam. https://www.globalreporting.org/media/muajmnbl/draft-esrs-gri-standards-data-point-mapping.xlsx.

GRI (2024). *Consolidated set of the GRI Standards*, Global Reporting Initiative, Amsterdam.

GRI (2025a). *Vision, mission and history*. Global Reporting Initiative, Amsterdam.

GRI (2025b). *GRI 101: Biodiversity 2024 - Topic Standard*, Global Reporting Initiative, Amsterdam.

GRI (n.d.). *A short introduction to the GRI Standards*, Global Reporting Initiative, Amsterdam.

GRI, EFRAG (2023). *[draft] GRI-ESRS Interoperability Index*, Global Reporting Initiative and European Financial Reporting Advisory Group, Amsterdam. https://www.efrag.org/en/sustainability-reporting/esrs-workstreams/interoperability.

Guthrie J., Abeysekera I. (2006). Content analysis of social, environmental reporting: What is new? *Journal of Human Resource Costing and Accounting*, 10(2): 114-126. DOI: https://doi.org/10.1108/14013380610703120.

Guthrie J., Parker L.D. (1990). Corporate social disclosure practice: A comparative international analysis. *Advances in Public Interest Accounting*, 3: 159-175.

Kok A., De Olde E.M., De Boer I.J.M., Ripoll-Bosch R. (2020). European biodiversity assessments in livestock science: A review of research characteristics and indicators. *Ecological Indicators*, 112, 105902. DOI: https://doi.org/10.1016/j.ecolind.2019.105902.

Leardini A. C., Serventi S. (2016). The cultural landscape of food: The infrastructure resilience of Via Emilia. In Roggema R. (eds) *Sustainable Urban Agriculture and Food Planning* (pp. 38-52). Routledge, London. DOI: https://doi.org/10.4324/9781315646039.

Marconati L. (2024). *PMI e rendicontazione di sostenibilità: Analisi del quadro normativo e del contesto di applicazione*, Tesi di Laurea Magistrale in Economia e Gestione delle Aziende, Università Ca' Foscari di Venezia.

Massari G.F., Giannoccaro I. (2023). Adopting GRI standards for the circular economy strategies disclosure: The case of Italy. *Sustainability Accounting, Management and Policy Journal*, 14(4): 660-694. DOI: https://doi.org/10.1108/SAMPJ-07-2021-0284.

Myers S.S., Smith M.R., Guth S., Golden C.D., Vaitla B., Mueller N.D., Dangour A.D., Huybers P. (2017). Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, 38(1): 259-277. DOI: https://doi.org/10.1146/annurev-publhealth-031816-044356.

Ortiz-Martínez E., Marín-Hernández S. (2023). Sustainability information in European small- and medium-sized enterprises. *Journal of the Knowledge Economy*, 15: 7497-7522. DOI: https://doi.org/10.1007/s13132-023-01386-7.

Parisi V. (2001). The biological soil quality, a method based on microarthropods. *Acta Naturalia de L'Ateneo Parmense*, 37: 97-106.

Parisi V., Menta C., Gardi C., Jacomini C., Mozzanica E. (2005). Microarthropod communities as a tool to assess soil quality and biodiversity: A new approach in Italy. *Agriculture, Ecosystems & Environment*, 105(1-2): 323-333. DOI: https://doi.org/10.1016/j.agee.2004.02.002.

Regione Emilia-Romagna (2024). *Il sistema agro-alimentare dell'Emilia-Romagna: Rapporto 2023*, Report 2023, Regione Emilia-Romagna and Unioncamere Emilia-Romagna and ART-ER, Bologna.

Rodríguez-Gutiérrez P., Guerrero-Baena M. D., Luque-Vílchez M., Castilla-Polo F. (2021). An approach to using the best-worst method for supporting sustainability reporting decision-making in SMEs. *Journal of Environmental Planning and Management*, 64(14): 2618-2640. DOI: https://doi.org/10.1080/09640568.2021.1876003.

SACE (2024). *SACE Sector Kit 2024: The food and beverage industry in Italy*, SACE, Rome.

Schmerber L., Tõnnisson R., Veliste M. (2022). *Supporting the agrifood sector. A policy brief from the policy learning platform on SME competitiveness*. Interreg Europe, Lille.

Steinhöfel E., Galeitzke M., Kohl H., Orth R. (2019). Sustainability reporting in German manufacturing SMEs. *Procedia Manufacturing*, 33: 610-617. DOI: https://doi.org/10.1016/j.promfg.2019.04.076.

Stranieri S., Orsi L., Banterle A., Ricci E.C. (2019). Sustainable development and supply chain coordination: The impact of corporate social responsibility rules in the European Union food industry. *Corporate Social Responsibility and Environmental Management*, 26(2): 481-491. DOI: https://doi.org/10.1002/csr.1698.

Tombolesi R. (2024). Performance di sostenibilità e fattori ESG. Una nuova opportunità per le PMI italiane. *Quaderni di ricerca sull'artigianato*, 12(2): 193-204.

Topp-Becker J., Ellis J.D. (2017). The role of sustainability reporting in the agri-food supply chain. *Journal of Agriculture and Environmental Sciences*, 6(1): 17-29. DOI: https://doi.org/10.15640/jaes.v6n1a2.

Torelli R., Balluchi F., Furlotti K. (2020). The materiality assessment and stakeholder engagement: A content analysis of sustainability reports. *Corporate Social Responsibility and Environmental Management*, 27(2): 470-484. DOI: https://doi.org/10.1002/csr.1813.

Tubiello F.N., Karl K., Flammini A., Gütschow J., Obli-Laryea G., Conchedda G., Pan X., Yue Qi S., Halldórudóttir Heiðarsdóttir H., Wanner N., Quadrelli R., Rocha Souza L., Benoit P., Hayek M., Sandalow D., Mencos Contreras E., Rosenzweig C., Rosero Moncayo J., Conforti P., Torero M. (2022). Pre-and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth System Science Data*, 14(4): 1795-1809. DOI: https://doi.org/10.5194/essd-14-1795-2022.

UN Global Compact (2024). The unique role of SMEs and supply chains in charting a positive future, *The Compact Journal*, 03 February 2025.

Weber R.P. (1990). *Basic Content Analysis*. Sage, London.

Wesseler J. (2022). The EU's farm-to-fork strategy: An assessment from the perspective of agricultural economics. *Applied Economic Perspectives and Policy,* 44(4): 1826-1843. DOI: https://doi.org/10.1002/aepp.13239.

Zharfpeykan R., Akroyd C. (2023). Evaluating the outcome effectiveness of the global reporting initiative transitions. *Sustainability Accounting, Management and Policy Journal*, 14(6): 1101-1125. DOI: https://doi.org/10.1108/SAMPJ-07-2022-0365.

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Research article

Biodistricts as institutional innovations fostering agroecology transitions: the case of Chianti (Tuscany, Italy)

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Abstract. Agroecology transitions require institutional innovations that can reshape governance arrangements and actor coalitions to deliver positive socio-ecological feedback. It is still unclear how such transformations can take root in highly specialised European agrifood systems, where market concentration and path dependency constrain change. Biodistricts are examples of territorial initiatives that integrate organic farming with participatory governance. Although they have gained prominence, there is insufficient understanding of their underlying socio-ecological mechanisms. This study provides evidence from the Chianti Biodistrict (Tuscany, Italy), a bottom-up governance innovation that has emerged within a specialised, export-oriented viticultural landscape. Ostrom's socio-ecological systems framework is applied to the case study through qualitative empirical methods, within the frame of a 4-year participatory research project. The analysis aims to show how multi-actor coalitions configure deliberation spaces; co-design strategies; and foster the adoption of practices such as interrow cover, composting hubs, and collective pest monitoring. The findings highlight four mechanisms that enable systemic redesign: coalition mobilisation; reconfiguration of the linkages among resource systems, resource units, actors, and governance system; ecological-institutional feedback loops; and the mitigation of structural lock-ins through coordination and stronger knowledge systems. These findings advance understanding of biodistricts as institutional innovations and show the value of the socio-ecological systems framework as both an analytical lens and a boundary object for participatory territorial governance research. Theoretical grounding and anchoring to theoretical propositions support analytical generalisation and clarify conditions for transferability to other likewise (European) agroecology initiatives.

Keywords: socio-ecological system, agroecology, institutional innovation, biodistrict, territorial governance.
JEL codes: Q10, Q18, Q19.

HIGHLIGHTS:

- Ostrom's socio-ecological systems framework is applied to analyse the Chianti Biodistrict as a governance innovation fostering agroecology, using qualitative methods and participatory research to explore systemic

redesign in a specialised, market-oriented viticultural context
- Civic leadership, public brokers, and advisory actors co-created strategies, enabling agroecological practices (interrow cover, composting hubs, and pest monitoring) and integrating ecological improvements with policy and market instruments through feedback loops that sustained change
- Territorial governance tools (integrated plans, thematic groups, and a helpdesk) created enabling conditions for experimentation and learning, linking ecological practices with institutional and economic innovations to operationalise territorial agroecology
- Research and policy should strengthen advisory capacity, bridge research-practice gaps, and design flexible, actor-driven governance frameworks to overcome systemic lock-ins and enable territorial strategies for scaling agroecology.

1. INTRODUCTION

Many prevailing agricultural systems are structurally tied to logics that perpetuate environmental and social problems, demonstrating significant resistance to more sustainable approaches like agroecology (Sherwood *et al.*, 2016). Institutional failures, such as entrenched power dynamics, institutional capture, and limited social capital, continue to hinder innovation in rural areas. Agricultural research has played a key role in advancing productivity, but its orientation has often aligned with dominant market priorities. This has contributed to the development of technologies and knowledge systems that are not always accessible or inclusive, thereby limiting innovation in areas such as social equity, and ecological sustainability (Bellon, Ollivier, 2018; Madureir, Torre, 2019; Montenegro de Wit, 2022). This context demands not only technical solutions but also institutional innovations, that is, new actor arrangements (norms, rules, and tools) that reshape governance and networks to drive systemic change towards sustainability and market integration (Gava *et al.*, 2025). This is especially true for Mediterranean farming systems that are highly vulnerable to climatic hazards and face growing risks of environmental degradation and productivity decline due to combined environmental changes (Hoegh-Guldberg *et al.*, 2018; Mrabet *et al.*, 2020) and socio-economic drivers such as innovation lock-ins and the dual dynamics of land abandonment and intensification (Dax *et al.*, 2021; Debolini *et al.*, 2018; Doblas-Miranda *et al.*, 2017; Long *et al.*, 2016).

Agroecology transitions strengthen resilience by adapting practices to local socio-ecological contexts and rethinking market and governance arrangements to foster institutional innovation (Pimbert, 2025). These transitions rely on collaborative networks involving farmers, value-chain actors, public administrations, researchers, and consumers (Alarcon *et al.*, 2020; Horlings, Marsden, 2011; Teschner, Orenstein, 2021). Such networks can help territorialise agroecology through iterative learning and the integration of traditional, technical, and scientific knowledge (Aguilera *et al.*, 2020; Méndez *et al.*, 2016; Wezel *et al.*, 2020). In Italy, biodistricts defined areas where organic farming is integrated with local governance and citizen participation, offer a concrete example of this territorial governance approach (FAO, 2017). The growing prominence of biodistricts (or other similar initiatives) also reflects the ambitions of the European Union's Farm to Fork strategy, which calls for territorially grounded governance innovations able to support agroecology transitions across diverse EU farming systems.

Researchers have investigated multiple aspects of biodistricts, including their potential to generate cross-sectoral synergies (Poponi *et al.*, 2021), including through social innovation (Pomponi *et al.*, 2026), upscale agroecology (Dara Guccione *et al.*, 2024; Guareschi *et al.*, 2020), and informed policy design (Assiri *et al.*, 2021; Dias *et al.*, 2021; Zanasi *et al.*, 2020). Previous studies have examined governance structures and policy frameworks (Gava *et al.*, 2025). However, important research gaps remain. Little attention has been paid to how biodistricts act as institutional innovations, by creating new rules, norms, and actor coalitions that reshape governance within socio-ecological systems (SES). The socio-ecological characteristics and dynamics needed to overcome systemic lock-ins are critical to enabling biodistricts to function as institutional innovations that support agroecology (Assiri *et al.*, 2021; Padró *et al.*, 2020; Tittonell *et al.*, 2020; Williams *et al.*, 2024).

This article addresses these research gaps through a case study of the Chianti Biodistrict (Tuscany, Italy), which has emerged through spontaneous, voluntary self-organisation led by local actors rather than through top-down policy design. It is located in the eponymous, globally recognised wine-producing region, which faces environmental pressures from the high agricultural specialisation and intensive use of hilly landscapes. Chianti provides a relevant case study to examine how a biodistrict can catalyse institutional change within a highly specialised and market-oriented setting, where governance innovation is essential to balance economic competitiveness with environmental sustainability. The aim of this research is to uncover the mechanisms through which the Chianti Biodistrict functions as an institutional innovation within a SES, and how it can contribute to agroecology transitions.

Among the frameworks available for the analysis of transitions, this study adopts Ostrom's SES framework (McGinnis, Ostrom, 2014; Ostrom, 2009) to analyse governance transformations, actor interactions, and enabling conditions, due to its emphasis on governance and the role of actors. Compared with other frameworks for the analysis of transitions – such as the multi-level perspective, strategic niche management, transition management, innovation systems or practice-based approaches (Lachman, 2013; Loorbach *et al*., 2017; for agroecology-specific reviews, see El Bilali, 2019; Ollivier *et al*., 2018) – the SES framework offers a diagnostic lens that allows fine-grained analysis of how governance arrangements, rules-in-use, and actor coalitions interact with biophysical dynamics to shape transition pathways, especially at the territorial scale where collective action and social mediation unfold. Moreover, when applied to agroecology, other approaches often remain aspatial or overlook key biophysical drivers, feedback loops, and socially shaped behavioural dynamics, limiting their ability to capture the coupled social-ecological processes underpinning lock-ins and transitions (Angeon *et al*., 2024; Ruggieri *et al*., 2023, 2025; Suwannadi *et al*., 2026). Building on this literature, our article contributes by using the SES focus on action situations, institutional change, and feedback loops to explain how biodistricts operate as institutional innovations within territorial agroecology, complementing and extending frameworks that primarily emphasise technological niches, regime shifts or innovation networks.

Our analysis uses qualitative methods. The empirical work builds on a 4-year participatory research process (2018-2022) involving researchers and local stakeholders (Schwarz *et al*., 2022; Zawalińska *et al*., 2022). Data collection was guided by the SES framework and its adaptation to the agricultural sector (Marshall, 2015) and combines primary data (gathered on the ground through interviews for this specific research) with secondary data from related research activities under the same project. This article advances knowledge by (i) showing the potential role of biodistricts in reconfiguring governance and rules-in-use; (ii) applying the SES framework as both an analytical lens and a boundary object for participatory planning; and (iii) offering insights useful beyond the case study level for embedding biodistricts or likewise initialises into multi-actor governance strategies.

2. THEORETICAL AND ANALYTICAL FRAMEWORK

2.1. The SES perspective on agroecology transitions

The SES framework (McGinnis, Ostrom, 2014; Ostrom, 2009) offers a structured approach to analyse interactions between ecological resources, actors, and governance arrangements. Originally developed to study common-pool resource dilemmas, this framework has evolved into a diagnostic tool for diverse sustainability challenges, where governance and actor agency are central to mitigating negative outcomes and resolving resource conflicts (Hinkel *et al*., 2015; Partelow, 2018). The SES framework identifies four core subsystems:

1. Resource system – biophysical units providing goods and services (e.g., farming landscapes);
2. Resource units – tangible outputs managed and appropriated (e.g., crops, livestock, and water);
3. Actors – individuals or organisations managing or influencing the resource system;
4. Governance system – formal and informal institutions shaping decision-making and collective action.

These subsystems are embedded within broader social, economic, and political settings and related ecosystems, which influence and are influenced by the focal SES.

Interactions occur within focal action situations – social spaces where actors make decisions, exchange goods, and negotiate rules – shaping outcomes that feed back into the system (Ostrom, 2011). This recursive structure makes the SES framework particularly suited to studying transitions that require both technological and institutional change.

Recent research has expanded SES applications to agriculture and food systems, recognising its capacity to integrate physical resources, market and institutional environments, and farmer decision-making (Vallejo-Rojas *et al*., 2016). Some examples include applications to land-use changes (Schneider *et al*., 2020), water quality protection (Amblard, 2019), beekeeping (Patel *et al*., 2020), and smallholder resilience (Seghezzo *et al*., 2020). SES adaptations have involved vertical adjustments, refining variables within subsystems to fit sector-specific needs (Basurto *et al*., 2013; Partelow, 2018) and/or horizontal adjustments adding new subsystems or second-tier variables, such as technological transformation activities in agriculture (Marshall, 2015; Wohlfahrt *et al*., 2019).

Institutional innovations are defined as novel arrangements among diverse actors (norms, regulations, and practices) designed to foster sustainable agricultural practices and market linkage (Loconto *et al*., 2017). Such innovations are essential for enabling sustainability transitions in agriculture, particularly through collaborative action among farmers, researchers, advisory services, private actors, civil society organisations, and public authorities (Gaba, Bretagnolle, 2020; Gutiérrez Cano *et al.*, 2023; Jia, 2021). From this perspective, multi-stakeholder approaches can create systemic capacity for innovation, thus enabling the move from linear, technology-oriented to more integrated, system-oriented changes. This is achieved by creating a space that facilitates experimentation, learning, interaction, negotiation, and collective action (Bellon, Ollivier, 2018; Blesh *et al.*, 2023; Schut *et al.*, 2016). Innovation intermediaries play a key role in bridging gaps within Agricultural Knowledge and Innovation Systems. These actors (individuals or organisations) facilitate knowledge exchange, technology transfer, and learning processes, helping to close cognitive, informational, and systemic gaps (Gutiérrez Cano *et al.*, 2023; Jia, 2021; Loconto *et al.*, 2017).

Agroecology transitions are inherently territorial, requiring coordination among local actors and supportive institutional changes that foster learning and co-creation of knowledge. Territorial governance approaches are crucial for addressing institutional failures and building social capital (Lamine *et al.*, 2023; Wezel *et al.*, 2016). European examples such as the Austrian *Ökoregion* and the French *Biovallée* illustrate early attempts to embed sustainability at territorial scale (Schermer, 2006; Stotten *et al.*, 2018; Sturla, 2021). The concept of agroecology territories refers to regions where agroecological practices are scaled beyond individual farms and embedded in broader farming systems (FAO, 2018; Padró *et al.*, 2020; Wezel *et al.*, 2016). In Italy, biodistricts represent a practical attempt to operationalise agroecology territories, by aiming to align agricultural practices with multidimensional sustainability goals (Pomponi *et al.*, 2026). Over the last decade, the model (also known as ecoregion) has spread internationally through the IN.N.E.R. network (IN.N.E.R., 2021) and has been compared with similar territorial food governance initiatives in other European contexts (Lamine *et al.*, 2023).

2.2. Theoretical propositions

Given the above background, four theory-driven propositions (P) guide the empirical analysis and enable analytical generalisation of the findings.

P1: Agroecology transitions at the territorial level tend to emerge when cross-disciplinary actors form stable cross-scale coalitions that repeatedly activate focal action situations, thereby reshaping rules-in-use and strengthening collective action capacity (Amblard, 2019; Blanco, 2011; Hinkel *et al.*, 2015; McGinnis, Ostrom, 2014; Patel *et al.*, 2020).

P2: In a given territory, agroecological practices are more likely to change when focal action situations reorganise interactions among resource systems, resource units, actors, and governance, enabling iterative experimentation and coordinated adjustments (Basurto *et al.*, 2013; Marshall, 2015; Partelow, 2018; Wohlfahrt *et al.*, 2019).

P3: Agroecology transitions tend to stabilise when positive ecological and institutional outcomes generate feedback on actor perceptions and governance mechanisms, reinforcing shared norms, reducing perceived risks, and increasing commitment to redesigned practices (Hinkel *et al.*, 2015; Landert *et al.*, 2020; McGinnis, Ostrom, 2014; Schneider *et al.*, 2020; Seghezzo *et al.*, 2020).

P4: Structural lock-ins in specialised agrifood systems are more likely to be overcome when improvements in advisory capacity, boundary-spanning functions and knowledge flows co-occur with economic incentives that shift actor dependencies (Marshall, 2015; McGinnis, Ostrom, 2014; Partelow, 2018; Patel *et al.*, 2020; Wohlfahrt *et al.*, 2019).

2.3. Empirical strategy

This study applies the SES framework to analyse the Chianti Biodistrict as a territorial governance innovation supporting agroecology transitions in a highly specialised, market-oriented viticultural system. The framework serves a dual purpose: (i) as an analytical lens to examine how governance arrangements, actor networks, and rules-in-use are reconfigured to overcome systemic lock-ins; and (ii) as a boundary object in participatory research, offering a shared conceptual map that facilitated stakeholder dialogue and co-construction of transition strategies (Hertz, Schlüter, 2015).

The analysis centres on focal action situations, such as deliberation, investment decisions, and knowledge exchange, where institutional innovations emerge and reshape governance dynamics. These interactions occur within territorial collaboration spaces, represented by the biodistrict, where diverse actors co-design enabling conditions for agroecology. Agroecology transitions require aligning technological change with governance innovation, creating synergies between biophysical subsystems (resource systems and units) and human subsystems (actors and governance). These processes depend on shifts in actor agency and are reinforced by positive outcomes, such as diversification strategies, new norms, and collaborative practices (Gava *et al.*, 2025; Schwarz *et al.*, 2022). To support these dynamics, focal action situations must foster inclusive spaces where institutions, social movements, farmers, and organisations co-design strategies that integrate technical and institutional solutions (Tittonell, 2014; Wezel *et al.*, 2020). The governance system plays a pivotal role by delivering market and policy instruments that: (i) remove lock-ins caused by path

Table 1. List of selected second-tier variables for application at the case study level in this research.

Subsystems (codes)	Second-tier variables
Resource system (RS)	Sector; clarity of system boundaries; size of the resource system; human-constructed facilities; productivity of the system; equilibrium properties; predictability of system dynamics; location; inputs
Resource units (RU)	Resource unit mobility; growth or replacement rate; interaction among resource units; economic value; number of units; distinctive characteristics; spatial and temporal distribution; marketing characteristics
Governance system (GS)	Policy area; geographic scale of governance system; size of population involved or affected; regime type; rule-making organisations; rules-in-use; property-rights system; repertoire of norms and strategies; network characteristics; history
Actors (A)	Number of actors; socio-economic attributes; history or past experiences; location; leadership/entrepreneurship; norms (trust-reciprocity)/social capital; knowledge of SES/mental models; importance of resource (dependence); technologies
Interactions (I)	Harvesting; information sharing; deliberative processes; conflicts; investment activities; lobbying activities; self-organising activities; networking activities; monitoring and sanctioning activities; evaluative activities
Outcomes (O)	Social performance measures; ecological performance measures; externalities to other SES
Social, economic, and political settings	Economic development; demographics; social and cultural settings; political stability; other governance systems; other markets; media organisation; other technology and infrastructure; history
Related ecosystems	Climate patterns; pollution patterns; flows into and out of focal SES

Source: Authors' own elaboration based on Marshall (2015).

dependency and mitigate barriers to practice adoption (e.g., capital investment needs); and (ii) leverage enabling conditions such as machinery-sharing cooperatives and premium markets for agroecological products (Campbell *et al.*, 2017; Ingram, 2017; Laforge *et al.*, 2021).

Each SES element is characterised using second-tier variables tailored to the research aim, enabling a coherent understanding of the sub-systems (Eelderink *et al.*, 2020). In this study, second-tier variables were identified based on the relevant literature (Marshall, 2015), under an overarching project-wide framework (Guisepelli *et al.*, 2018) (Table 1).

The qualitative analysis followed a deductive coding logic derived from the SES second-tier variable, nested within (first-tier) subsystems. In-depth information about individual variables are available from Guisepelli *et al.* (2018); the definitions applied in this research are available in the Supplementary Materials.

3. DATA AND CASE STUDY

3.1. Data collection

Face-to-face interviews were conducted with actors involved in the case study's multi-actor platform (MAP), a forum for co-learning and co-creation bringing together a multiplicity of actors (researchers, policy-makers, and civil society) (Gava *et al.*, 2025; Zawalińska *et al.*, 2022). These interviews constituted one element within a broader 4-year participatory process of the UNISECO project (2018-2022), during which the MAP met repeatedly, through local and project-level workshops both in-person and online, to co-design and validate agroecology transition strategies. Table 2 presents the subset of local MAP actors selected to characterise the SES variables in this case study.

To guide the interviews, a structured table listing second-tier SES variables and their definitions was used (see the Supplementary Materials), aligning with the project-wide framework (Guisepelli *et al.*, 2018). The respondents were given ample time to reflect and respond in an open-ended format. They were not required to answer all questions. Instead, they were invited to contribute based on their specific areas of expertise, identifying the variables for which they could provide informed responses. The small sample size was appropriate for the complexity of the SES variables and the need for expert participation (McDermott, 2023). Most engaged actors requested additional time due to the complexity and level of detail required. The respondents could consult relevant documents to verify or elaborate on their responses. Following the interviews, each respondent received the data collection table via email, including variables and definitions and their preliminary answers, so that they could revise and/or complete the questionnaire, ensuring accuracy and allowing for deeper reflection. Asynchronous refinement aimed at reducing recall bias and ensure accuracy.

To complement and triangulate the findings, the primary data from the interviews were supplemented

Table 2. Sample of the multi-actor platform respondents for socio-ecological system data collection.

Actor category	Description	Number of respondents
Public	Tuscany region (local administrative organisation)	3 (of which 1 female)
Farm and value chain*	Farmers and winemakers and producer organisation	3
Civic	Environmental non-governmental organisation	1 (female)
AKIS professionals	Professionals in the creation and diffusion of formal knowledge (i.e., advisors and researchers)	3 (advisors, of which 2 female); 1 (research)

Notes: Actor categories are adapted from Gava *et al.* (2025).
*Farmers are also wine producers, including within their representing organisation.

with information already available from related research activities within the project (McDermott, 2023):

- Integrative information to characterise GS, A, and I was extracted from (i) governance evaluation, using social network analysis to identify key actors and relationships (Vanni *et al*., 2019); and (ii) identification of key supporting market and policy instruments and governance challenges using a mixed-methods approach based on multi-criteria assessment (Galioto *et al*., 2021)
- Integrative information across all subsystems was extracted from the evaluation of the environmental, economic, and social performance of agroecological farming systems, and identification of sustainability trade-offs, synergies, and transition pathways (Landert *et al*., 2019).

The discussion of barriers and enabling strategies is based on findings from a related task within the same project, in which the respondents identified barriers and collaboratively developed strategies to overcome them through cooperation, knowledge sharing, and governance innovation (Schwarz *et al*., 2021a).

The two researchers participated in all interviews (60-90 minutes each) and acted as facilitators and co-producers throughout the process, drawing on insights from related project activities and MAP workshops to support reflection; to coordinate asynchronous exchanges; and to document the interviews through notes, recordings, and meeting summaries. Structured deductive coding was conducted jointly by the two researchers to reach a consensus, using a coding matrix to ensure consistency across data sources (see the Supplementary Materials, which also includes the final dataset).

3.2. Case study

The Chianti Biodistrict (Tuscany, Italy) was formally[1] established in 2016 through a bottom-up initiative led by organic producers with the support of local municipalities. Its mission is to promote organic farming and food chains, crop diversification, sustainable landscape and forest management, research and extension on organic/agroecology, and sustainable tourism. It covers seven municipalities across 887 km^2 and is characterised by a strong landscape identity, high diffusion of organic viticulture in the 'Chianti Classico' Protected Denomination of Origin (PDO) zone, and active civic engagement (Regione Toscana, 2015).

The resource system includes approximately 10,000 ha of vineyards and 5,000 ha of olive groves, which are the dominant land uses. Over 30% of the utilised agricultural area is organic. Productivity is constrained by PDO regulations for *Chianti Classico* wine (and *Chianti Classico* oil), which set strict yield and quality standards, and by the physical configuration of the landscape (terraces, dry-stone walls, and hedgerows) that shape both ecological dynamics and production costs. In a context of increasing biophysical pressures, land-use dynamics such as the expansion of vineyards coupled with the long-term reduction of arable and pasture areas have contributed to rising soil erosion and declining agrobiodiversity. This trend has been further exacerbated by climate-related shocks, as producers seek to secure predictable wine yields to maintain competitiveness in an export-oriented market. Wine accounts for more than 90% of farm net value added and benefits from strong branding through PDO certification and an export-oriented market. Olive oil and other minor products (e.g., cheese, meat, and honey) remain marginal and are primarily marketed locally, although PDO olive oil enjoys

[1] In Italy, biodistricts may or may not have formal institutional recognition. Recognised biodistricts comply with National Law no. 205/2017 and its implementing Ministerial Decree (2022), which define their governance requirements, objectives, and eligibility for public support. In Tuscany, Regional Law no. 51/2019 further regulates their establishment, specifying criteria for recognition and embedding them within the regional rural development and territorial governance framework. Biodistricts without formal recognition are voluntary, self-organised initiatives created by local actors without a legal mandate, generally operating through associative structures such as organic farming organisations.

broader recognition due to its geographic indication. Labour demand is highly seasonal – particularly for pruning and harvesting – and is often met by temporary skilled workers (Regione Toscana, 2015). Diversification efforts, such as livestock reintroduction and the cultivation of grains or legumes on marginal land, are emerging, supported by agritourism, the high-end restaurant sector, and participatory initiatives such as living labs.

In January 2023, the Chianti Biodistrict was officially recognised by the Region of Tuscany and entered into the National Registry of Organic Districts, consolidating its institutional role in steering an agroecology transition. Its parity-based assembly includes seven representatives from organic farms and seven from municipal administrations; the presidency is held by a producer, reinforcing its bottom-up nature. Strategic planning is coordinated through a multi-year plan (*Progetto Economico Territoriale Integrato* – Integrated Territorial-Economic Plan), implemented via a helpdesk (*Sportello Biologico* – Organic Helpdesk), thematic working groups (e.g., biodiversity, agroecological practices, and social farming), and district assemblies that underpin participatory deliberation and accountability (Biodistretto del Chianti, 2022). These mechanisms and decision spaces, alongside the influence on normative change (e.g., municipal herbicide bans), position the Chianti Biodistrict as a territorial governance instrument that formalises multi-actor cooperation to amplify agroecology at territorial scale through participatory planning, diversified actor coalitions, and transdisciplinary knowledge flows (Gava *et al*., 2025).

The Chianti 'region' is internationally renowned for its winescape, a coupled SES shaped by vineyards, wineries, rural architecture, cultural heritage, and tourism. This long-standing tradition of quality wine production attracts hundreds of thousands of visitors annually and underpins the local economy (Brunori, Rossi, 2007). However, the strong specialisation in viticulture has displaced olives and other traditional activities (e.g., semi-extensive livestock and arable cropping), creating risks such as soil degradation, biodiversity loss, water pollution, depopulation of remote areas, and real-estate pressures within the SES and related ecosystems. These challenges prompted collective action on land and landscape management, supported by civic engagement and regional instruments (e.g., rural districts and biodistricts) to promote diversification and local food systems (Simoncini, 2011). The Chianti Biodistrict addresses these systemic risks by seeking to rebalance economic competitiveness with ecological stewardship through coordinated redesign of farming practices and governance arrangements. While actor networks and governance structures have created enabling conditions for agroecological practices, persistent barriers – such as limited advisory capacity and structural lock-ins linked to wine dependence – have constrained the uptake of more advanced practices. In response, Chianti Biodistrict actors have progressively agreed on targeted strategies (e.g., machinery rings, shared composting facilities, and policy adjustments) that triggered feedback loops, where ecological improvements reinforced collective norms, fostering iterative adaptation essential for sustaining the transition.

4. RESULTS

Figure 1 shows how the SES framework was operationalised in practice through the characterisation of subsystems, by highlighting the systemic interdependencies underpinning the ability of the Chianti Biodistrict to foster agroecology transitions. Table A.1 provides a summary of the findings by subsystem.

The analysis presented in this section focuses on actor-mediated dynamics across the SES, in line with the four propositions presented in Section 2.2. Table A.2 supports this analysis by systematising how different SES subsystems contribute to focal action situations, the interactions they enable, and the resulting outcomes, including key feedback loops, drivers, barriers, and resolution strategies at subsystem level. This section is organised around the four theoretical propositions, using the SES framework to examine how context-specific empirical patterns in the Chianti Biodistrict operationalise and substantiate these propositions.

4.1. Who mobilise the SES (P1)?

Under the SES perspective, actors and governance systems enter action situations as inputs and are themselves reshaped by outcomes, through feedback (Hinkel *et al*., 2015; McGinnis, Ostrom, 2014). In the Chianti Biodistrict, three actor groups (Table A.1) repeatedly activated and coordinated cross-subsystem interactions (A ↔ GS → I → O, with feedback to A and GS), thereby operationalising the conditions (P1) whereby stable cross-scale actor coalitions reshape rules-in-use and redistribute coordination capacity across the SES (Table A.2).

- Civic leadership (the Chianti Biodistrict Association) functioned as a focal node convening organic and conventional farmers, municipalities, advisory services, and associations (environmental, organic farming, and consumer). It translated a diffuse concern towards the protection of the traditional winescape into col-

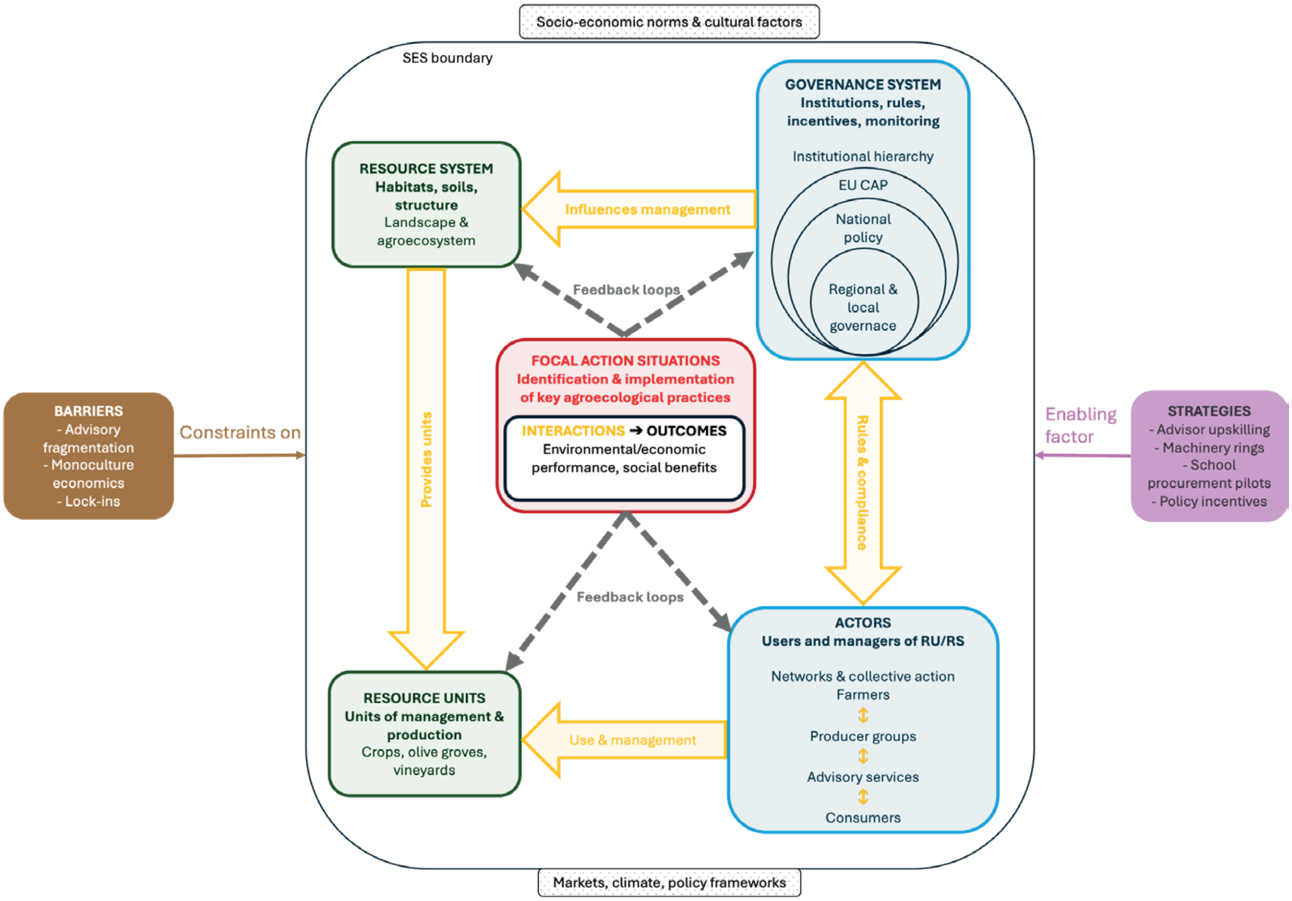

Figure 1. Socio-ecological system dynamics within the Chianti Biodistrict (Tuscany, Italy).

lective decision-making (the Integrated Territorial-Economic Plan, the Organic Helpdesk, thematic working groups, and district assemblies), thus structuring deliberation, information sharing, self-organisation, and networking within focal action situations. Civic actors contributed to shifts in collective norms and coordination rules, by structuring deliberative arenas across focal action situations. These findings align with comparable territorial coalitions and civic coordination initiatives (Amblard, 2019; Blanco, 2011).

– Public brokers (Tuscany region and municipalities) reduced coordination costs by aligning local initiatives with regional instruments (district plans and forestry rules) and by recognising the Chianti Biodistrict (2023), thereby institutionalising rules-in-use at collective/constitutional levels to support agroecology at territorial scale, in line with GS characteristics (Table A.1). These actors aligned incentives and formal recognition, modifying constitutional-level rules, reducing transaction costs and enabling new interaction patterns. This mirrors cases where multi-level governance couples incentives and rules for ecosystem services (Bennett, Gosnell, 2015).

– Advisory and knowledge actors (local advisory service and experimental station, universities) acted as boundary spanners by integrating scientific evidence and local know-how to operationalise agroecological practices (e.g., inter-row cover, threshold-based pest control, and compost protocols), while mediating conflict and risk perceptions across heterogeneous interests (e.g., organic vs conventional farmers), similar to related research (e.g., beekeeping systems; Patel *et al.*, 2020). The boundary-spanning role of these actors transformed actor perceptions and reduced conflict, enabling rule adoption and behavioural change across heterogeneous groups.

4.2. What changes in practice (P2)?

Focal action situations are structured towards the identification and implementation of key agroecological practices. Each focal action situation below exemplifies how governance and actor agency reconfigured RS-RU-A-GS linkages (building on subsystem characteristics; Table A.1) through iterative experimentation and coordinated adjustment, to produce outcomes and feedback (distinguishing provisioning [i.e., creating/maintaining collective goods] and appropriation [i.e., activities that subtract from a stock]; Table A.2) (Hinkel *et al*., 2015).

- Inter-row cover and soil protection (centred on provisioning: RS ↔ A, with appropriation-linked co-benefits): Advisory-led demonstration and peer learning enabled site-specific grass mixes and mowing/rolling regimes, provisioning soil functions (erosion control and water retention) as a collective good at field and landscape scales. Short-term yield reductions were offset by quality gains and lower external inputs; visible ecological improvements reinforced norms and lowered perceived risk (O → A feedback), as observed for broader land-use/ecosystem services/well-being linkages (Schneider *et al*., 2020). Repeated cycles of demonstration and peer learning supported changes in actor mental models, which were translated into revised operational rules and reinforced practice adoption through positive ecological feedback;
- Collective pest monitoring and decision support (GS ↔ A ↔ RU): Shared weather stations, harmonised field observations, and epidemiological bulletins replaced calendar spraying with threshold-based decisions. The local governance contributed, by co-financing infrastructure, harmonising protocols, ensuring homogeneous data processing across micro-climates, thereby enabling a reduction of pesticide pressure without compromising quality and generated a learning loop from observed efficacy to broader adoption (O → GS feedback), as shown in similar research to improve ecosystem-service governance (Bennett, Gosnell, 2015). Standardised protocols and co-financed infrastructure generated rule convergence (GS → A), enabling a shift from individual to coordinated decision rules.
- Composting and nutrient circularity (A ↔ GS ↔ RS): Key barriers to the widespread adoption of agroecological practices (e.g., lack of composting 'starters', high machinery costs, and difficult labour scheduling) were addressed via machinery rings, shared composting hubs (oil-mill residues and urban green biomass), and targeted training, thereby closing nutrient loops, increasing soil carbon, reducing burning and chemical inputs, and reducing the workload for individual workers. The developed organisational arrangements and routines supported durable cooperation as shown in related research (Vallejo-Rojas *et al*., 2016). Shared infrastructure reduced individual costs, enabling joint assets to restructure sourcing and provisioning behaviours.
- Recovery of olive groves and re-entry of arable/vegetable systems (GS ↔ RS/RU): Restoration costs on terraces were partially mitigated via district plans and non-productive investments. Additionally, demand-side actors created alliances with local producers, especially restaurant chefs, local caterers, school procurement pilots. This action situation intertwines RS/RU (characterised by long-term vineyard dominance and land-use simplification; Table A.1) with transformation/exchange activities (processing, school canteens, and retail), endogenising value-chain processes into agri-food-systems (Marshall, 2015) and aligns with research calling to govern cross-sectoral transformations at landscape scale (Wohlfahrt *et al*., 2019) and to have tourism-led collective action (Blanco, 2011). Cross-sector alliances linked value-chain incentives to land-use decisions, creating new feedback between market signals, rule adjustments, and agroecological practices.

4.3. How do actors and coalitions produce desired outcomes (P3)?

The following findings show how in the Chianti Biodistrict case study, positive ecological and institutional outcomes feed back into actor perceptions and governance arrangements through actor coalitions and rule configurations, thereby reinforcing systemic change (Table A.2).

- Improved ecological performance: Farms adopting a broader set of agroecological practices demonstrate markedly superior environmental performance compared with those implementing only a few sustainable measures or conventional systems. In particular, they exhibit lower greenhouse gas emissions, higher soil carbon stocks, reduced toxicity, and improved soil quality. These outcomes reinforce the credibility of advisory recommendations and reduce uncertainty for more risk-averse farmers (O → A: learning feedback) (Landert *et al*., 2020). Positive environmental outcomes were associated with reduced perceived risks, reinforcing commitment to redesigned practices and supporting broader adoption (O → A → GS).
- Economic/market effects: Wine, particularly PDO-labelled, continues to dominate value added, reflecting the specialised RU configuration and market structure (Table A.1). At the same time, the recovery of olive groves and the introduction of niche crops, supported by alliances with restaurant chefs, agritour-

ism, and local farmers' markets, have mobilised local demand (including from tourists), improved diversification margins, and justified non-productive investments. Diversification benefits and demand creation modified incentive structure, strengthening governance support for diversified systems (O → GS). These dynamics reinforce evidence on the importance of coupling governance reforms with targeted incentives and market coordination to sustain agroecology transitions (Bennett, Gosnell, 2015; Marshall, 2015).
- Social/institutional effects: The Chianti Biodistrict assembly, the Organic Helpdesk, and thematic working groups played a central role in stabilising cooperation by codifying roles and routines, a process later reinforced by the establishment of a living lab. Regional recognition of the Chianti Biodistrict further strengthened its identity within the GS (Table A.1), unlocked access to policy instruments, and clarified its position relative to PDO wine and oil consortia as well as pre-existing territorial arrangements (e.g., the rural district). Codified roles and routines generated institutional stability, producing feedback where strengthened rules reinforced cooperation and collective agency. These findings underscore the importance of civic-public-advisory coalitions in addressing state capacity gaps and sustaining farmer-led pathways to agroecology transition (Seghezzo *et al.*, 2020).

4.4. What has prevented redesign and how it has been addressed (P4)?

The agroecology transition in Chianti has made significant progress; however, structural and functional barriers rooted in SES subsystems (Table A.1) highlight the persistence of lock-ins despite the creation of the Chianti Biodistrict. These barriers indicate transition dynamics remain constrained, while the observed responses show how interventions contribute to realign rules, actor interactions and feedback (Table A.2).

- Reduced diffusion of advisory capacity and fragmentation: Despite the presence of some advanced and long-established advisory services, expertise in agroecology, particularly for diversified systems, remains insufficient. Moreover, the uneven distribution of advisory services across the Chianti territory, much of which is remote, has slowed the uptake of redesigned agroecological practices. Targeted measures under the CAP Rural Development Programme (2014-2020), such as advice and training schemes, together with advisor upskilling (including facilitation skills), have been helpful so far. However, a coordination backbone to connect research and experimentation with monitoring and advisory services is still missing and strongly needed. Fragmented advisory systems weaken information-sharing rules), reducing feedback strength and slowing systemic change (A → weak I → suboptimal O; enhancing coordination recovers these pathways (GS → stronger I → improved O → feedback to GS: norms). Overcoming fragmentation also requires strengthening operational, collective, and constitutional rules-in-use and enhancing network structures and boundary-spanning roles to foster more integrated and effective knowledge flows (McGinnis, Ostrom, 2014; Patel *et al.*, 2020);
- Monoculture economics and path dependence: The strong branding and export orientation of Chianti PDO wine continues to bias investments towards vineyards, reinforcing economic lock-ins, associated with the specialised production and value-chain (Table A.1). To date, countermeasures primarily driven by locally based initiatives have combined demand creation (e.g., school procurement pilots, alliances with restaurant chefs, and tourism narratives) with supply-side cooperation (e.g., machinery rings and shared composting facilities) to reduce risk and transaction costs associated with diversification. Economic lock-ins reinforce existing rules and actor dependencies (RS/RU → A), but demand-side initiatives and shared infrastructures create new incentives that reconfigure subsystem interactions (A ↔ RS/RU ↔ GS). These strategies have contributed to reconfiguring interactions among actors, resource systems and units, and governance arrangements, supporting the emergence of new value chains, as documented in related studies (Schneider *et al.*, 2020; Wohlfahrt *et al.*, 2019).

5. DISCUSSION

5.1. Implications

The SES analysis of the Chianti Biodistrict reveals how agroecology transitions can be embedded within territorial governance frameworks through a dynamic interplay of ecological, institutional, and social mechanisms. The empirical findings are consistent with established research directions (Ewert *et al.*, 2023; Teixeira *et al.*, 2018; Tittonell *et al.*, 2020) and align with mechanisms observed in broader applications – for example, water governance and ecosystem services (Prost *et al.*, 2023; Sachet *et al.*, 2021; Sivini, Vitale, 2023). The transition was shaped by a systemic configuration of practices and relationships. In the Chianti Biodistrict case study, ecological strategies (e.g., interrow cover management to reduce erosion and improve soil moisture, composting hubs for oil mill residues and urban biomass to close nutrient loops, and shared pest monitoring systems that replaced calendar spraying with threshold-based decisions) were supported by inclusive decision-making processes institutionalised through tools like the Integrated Territorial-Economic Plan, thematic working groups, and the Organic Helpdesk. These mechanisms enabled coordination among farmers, municipalities, and advisory services, fostering a governance environment conducive to experimentation and learning. Food processing and exchange activities (e.g., school procurement pilots, collaborations with restaurant chefs, and agritourism) were integrated into the territorial food system, stimulating demand for diversified products and encouraging non-productive investments. Together, these mechanisms generated reinforcing feedback loops that strengthened ecological outcomes and governance adaptation. The underlying coordination and feedback logic, rather than the specific instruments, offers a replicable model for territorial agroecology.

The findings contribute to governance research in agroecology transitions by showing how and under which conditions models of civic leadership and bottom-up governance can be formalised and scaled within territorial frameworks. The Chianti Biodistrict association played a catalytic role in convening diverse stakeholders and structuring deliberative spaces that enabled inclusive planning and iterative learning (Dumont *et al.*, 2021; van der Ploeg, 2021).

In the Chianti Biodistrict case study, public brokers, including the Region of Tuscany and local municipalities, were instrumental in embedding agroecological practices within multilevel governance structures, by institutionalising rules-in-use and aligning local initiatives with regional strategies. This exemplifies how agroecology transitions can be supported by policy coherence and administrative integration (Gliessman, 2020; Pimbert, 2025). Knowledge and advisory actors acted as boundary spanners, translating scientific evidence into actionable practices, mediating conflicts, and facilitating innovation uptake, emphasising the importance of distributed agency in SES governance (Goodrich *et al.*, 2020; Vilas-Boas *et al.*, 2022).

This case study advances knowledge on amplification dynamics in agroecology by empirically illustrating how governance networks can serve as engines of systemic change (Gava *et al.*, 2025). The evolution of the system was actively shaped by actor diversity, collective agency, and the iterative adaptation of governance rules (Schiller *et al.*, 2020; Wezel *et al.*, 2018). Focal action situations, where actors converge to address specific resource or coordination challenges, enabled the progressive reconfiguration of subsystem variables (Williams *et al.*, 2024).

This case study also highlights the role of feedback loops in sustaining transitions. Ecological improvements (e.g., enhanced soil conservation, pest management, and composting) reinforced social norms and reduced perceived risks, thereby influencing actor behaviour and governance adjustments (Kelinsky-Jones *et al.*, 2023; Montenegro de Wit, 2022). These dynamics suggest that agroecology transitions are not linear but adaptive, shaped by reciprocal interactions between ecological outcomes and institutional responses across territorial contexts.

5.2. Recommendations

From a research perspective, this study reinforces the importance of methodological pluralism in assessing agroecological systems. Analysing trade-offs across environmental, social, and economic dimensions requires interdisciplinary and transdisciplinary approaches that integrate ecological science with social inquiry, especially by implementing participatory evaluation methods that promote social learning and stakeholder inclusion (Cruz *et al.*, 2023; Rega *et al.*, 2022; Schwarz *et al.*, 2021b).

Capacity building from individual farmers to institutional frameworks emerges as a condition for sustaining agroecology transitions, to ensure that innovations are demand-driven, context-sensitive, and socially embedded. Strengthening advisory services, enhancing facilitation skills, and bridging the gap between research and practice are pivotal for overcoming fragmentation and addressing systemic lock-ins (Gutiérrez Cano *et al.*, 2023; Helenius *et al.*, 2020).

From a policy perspective, the Chianti Biodistrict experience underscores the need for public frameworks that can actively catalyse and amplify agroecology transitions. This involves better reorienting of public spending towards public goods, including advisory services, rural infrastructure, and participatory research (Fiore *et al.*, 2024). Flexible, stakeholder-driven policy frameworks are essential to support adaptive management and the co-evolution of practices and institutions, particularly in contexts marked by uncertainty and diverse actor interests (Conway, 2023). The findings of this study support previous research by emphasising how targeted incentives; strategic planning; and coalitions among civic, public, and advisory actors can compensate for state capacity limitations and foster transitions that are both inclusive and resilient (Runhaar, 2021; Schoonhoven, Runhaar, 2018). This case study further highlights that procurement reforms, strengthened advisory systems, and cooperation-based investments (e.g., machinery rings, composting hubs, and shared monitoring infrastructures) can play an important role in addressing structural lock-ins. Enhancing coordination between policy instruments, local governance bodies, and producer organisations is critical for aligning incentives with ecological objectives. Territorial-level policy frameworks that bridge public-private initiatives, reduce administrative burdens, and encourage diversified value chains emerge as essential levers for accelerating agroecology transition in similar contexts.

5.3. Theoretical and critical assessment

This research supports analytical generalisation along four theoretical propositions and clarifies the conditions under which the biodistrict model can work in other territorial agroecology contexts:

- P1 – Stable civic-public-advisory coalitions can act as mobilisation structures shaping rules-in-use and coordinating collective action.
- P2 – Focal action situations exist that allow actors to redesign RS-RU-A-GS linkages through experimentation and shared learning.
- P3 – Ecological and institutional feedback is visible enough to reinforce norms, lower perceived risks, and stabilise adoption.
- P4 – Efforts to overcome structural lock-ins combine strengthened knowledge systems with territorial economic incentives.

Together, these conditions highlight when the mechanisms observed in the Chianti 'region' are transferable, thus transforming the case study into a generalisable theoretical contribution on SES-mediated agroecology transitions.

In this study, the qualitative application of the SES framework offers contextual depth and a nuanced understanding of governance dynamics within a single case study. Theoretical grounding supports the generation of insights that are broadly relevant for research and policy; however, this design may limit straightforward generalisation beyond the Chianti Biodistrict. Although focusing only on this biodistrict enables an in-depth exploration of underlying mechanisms, this approach limits the examination of variability across contexts and the identification of amplification dynamics under different socio-ecological conditions. Addressing these limitations would require comparative designs, such as multiple case studies or counterfactual analysis with similar agroecological territories.

The use of the SES framework as both an analytical lens and a boundary object proved effective, but its applicability is not universal. In Chianti, actors were already accustomed to co-creation practices and collaborative research, which facilitated shared understanding and participatory engagement. In less-prepared contexts, additional capacity building would likely be necessary to implement a similar research design and participatory strategy effectively.

Reliance on purposive sampling and expert interviews (through the MAP), while suitable for capturing diverse perspectives, may introduce potential biases related to actor positionality, differential visibility or influence within governance networks, and uneven knowledge distribution across SES subsystems. To mitigate these risks, the respondents were invited to contribute only on variables matching their expertise and were given time to consult documentation. The research team systematically triangulated perspectives emerging from participatory activities with independent data sources generated within the same project, helping to balance dominant narratives and cross-check interpretations. Asynchronous refinement further aimed at reducing recall bias and ensuring accuracy. Despite these mitigation strategies, some degree of perspective bias cannot be fully excluded.

While the sample includes both male and female respondents, this study did not explicitly incorporate gender aspects within the SES framework, with potential gendered dynamics influencing actor agency, governance interactions, or the co-production of agroecological practices remaining outside the scope of the analysis. Recent research has shown that gender equity is a key element in agroecology transitions and that women can play strategic roles in initiating and sustaining territorial innovations (Vizuete *et al.*, 2025). Future (SES-based) research on agroecology transitions would benefit from integrating gendered perspectives to capture how differentiated roles and power relations shape governance and co-creation dynamics, and from comparative analyses of territories where women and other vulnerable groups hold varying degrees of agency to better understand their influence on transition trajectories.

6. CONCLUSIONS

This study advances the theoretical understanding of agroecology transitions by operationalising the SES framework within a specialised, market-oriented viticultural system. The analysis identifies four interconnected mechanisms linked to theoretical propositions underpinning systemic change: (i) the mobilisation of civic-public-advisory coalitions that activate and reshape rules-in-use (P1); (ii) the reconfiguration of RS-RU-A-GS linkages through focal action situations that structure practice redesign (P2); (iii) reinforcing ecological, behavioural, and institutional feedback loops that stabilise emerging trajectories (P3); and (iv) the mitigation of structural lock-ins through combined improvements in knowledge systems, coordination capacity and territorial incentives (P4). These mechanisms support analytically generalisable insights suggesting when territorial agroecology transitions, sustained by biodistrict-like initiatives, are likely to succeed. Transferability depends on the presence of stable multi-actor coalitions, institutional spaces for coordinated redesign, visible ecological feedback that can lower perceived risks, and governance capacity to mitigate structural lock-ins. Under these enabling conditions, biodistrict-like governance models can act as institutional innovations capable of orchestrating social-ecological reconfiguration beyond their original context. The findings also clarify how territorially anchored governance innovations can concretely support the Farm to Fork ambition by enabling the amplification of agroecology across the European Union. Finally, this study aligns with and contributes to advancing the European Strategic Research and Innovation Agenda for Agroecology by providing a real-world, scalable and place-based illustration of systemic transformation grounded in socio-ecological mechanisms and enabling conditions.

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The two authors Oriana Gava (OG) and Francesco Vanni contributed equally to this work.

REFERENCES

Aguilera E., Díaz-Gaona C., García-Laureano R., Reyes-Palomo C., Guzmán G.I., Ortolani L., Sánchez-Rodríguez M., Rodríguez-Estévez V. (2020). Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agricultural Systems*, 181: 102809. DOI: https://doi.org/10.1016/j.agsy.2020.102809.

Alarcon M., Marty P., Prévot A.C. (2020). Caring for vineyards: transforming farmer–vine relations and practices in viticulture French farms. *Journal of Rural Studies*, 80: 160-170. DOI: https://doi.org/10.1016/j.jrurstud.2020.08.029.

Amblard L. (2019). Collective action for water quality management in agriculture: the case of drinking water source protection in France. *Global Environmental Change*, 58: 101970. DOI: https://doi.org/10.1016/j.gloenvcha.2019.101970.

Angeon V., Casagrande M., Navarrete M., Sabatier R. (2024). A conceptual framework linking ecosystem services, socio-ecological systems and socio-technical systems to understand the relational and spatial dynamics of the reduction of pesticide use in agrifood systems. *Agricultural Systems*, 213: 103810. DOI: https://doi.org/10.1016/j.agsy.2023.103810.

Assiri M., Barone V., Silvestri F., Tassinari M. (2021). Planning sustainable development of local productive systems: a methodological approach for the analytical identification of ecoregions. *Journal of Cleaner Production*, 287: 125006. DOI: https://doi.org/10.1016/j.jclepro.2020.125006.

Basurto X., Gelcich S., Ostrom E. (2013). The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change*, 23(6): 1366-1380. DOI: https://doi.org/10.1016/j.gloenvcha.2013.08.001.

Bellon S., Ollivier G. (2018). Institutionalizing agroecology in France: social circulation changes the meaning of an idea. *Sustainability*, 10(5): 1380. DOI: https://doi.org/10.3390/su10051380.

Bennett D.E., Gosnell H. (2015). Integrating multiple perspectives on payments for ecosystem services through a social–ecological systems framework. *Ecological Economics*, 116: 172-181. DOI: https://doi.org/10.1016/j.ecolecon.2015.04.019.

Biodistretto del Chianti (2022). *Distretto Biologico del Chianti*, Biodistretto del Chianti, Chianti. https://www.biodistrettodelchianti.it/wp-content/uploads/2025/08/DistrettoBiologicoChianti_13122022.pdf.

Blanco E. (2011). A social-ecological approach to voluntary environmental initiatives: the case of nature-based tourism. *Policy Sciences*, 44(1): 35-52. DOI: https://doi.org/10.1007/s11077-010-9121-3.

Blesh J., Mehrabi Z., Wittman H., James D., Madsen S., Smith O.M., Snapp S., Stratton A.E., Bakarr M., Bicksler A.J., Galt R., Garibaldi L.A., Gemmill-Herren B., Grass I., Isaac M.E., John I., Jones S.K., Kennedy C.M., Kremen C. (2023). Against the odds: network and institutional pathways enabling agricultural diversification. *One Earth*, 6(5): 479-491. DOI: https://doi.org/10.1016/j.oneear.2023.03.004.

Brunori G., Rossi A. (2007). Differentiating countryside: social representations and governance patterns in rural areas with high social density: the case of Chianti, Italy. *Journal of Rural Studies*, 23(2): 183-205. DOI: https://doi.org/10.1016/j.jrurstud.2006.10.001.

Campbell B.M., Beare D.J., Bennett E.M., Hall-Spencer J.M., Ingram J.S.I., Jaramillo F., Ortiz R., Ramankutty N., Sayer J.A., Shindell D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, 22(4). DOI: https://doi.org/10.5751/ES-09595-220408.

Conway T.M. (2023). An agroecological turn in intermediating sustainability transitions with continuous living cover. *Frontiers in Sustainable Food Systems*, 7. DOI: https://doi.org/10.3389/fsufs.2023.1009195.

Cruz J.L., Hewitt R.J., Hernández-Jiménez V. (2023). Can public food procurement drive agroecological transitions? Pathways and barriers to sustainable food procurement in higher education institutions in Spain. *Agroecology and Sustainable Food Systems*, 47(10): 1488-1511. DOI: https://doi.org/10.1080/21683565.2023.2248917.

Dara Guccione G., Vigano L., Sturla A., Vaccaro A., Colombo L., Pirelli T., Varia F. (2024). Insights into the agroecological transition: the case of two Italian bio-districts. *Italian Review of Agricultural Economics*, 79(1): 97-111. DOI: https://doi.org/10.36253/rea-14241.

Dax T., Schroll K., Machold I., Derszniak-Noirjean M., Schuh B., Gaupp-Berghausen M. (2021). Land abandonment in mountain areas of the EU: an inevitable side effect of farming modernization and neglected threat to sustainable land use. *Land*, 10(6): 591. DOI: https://doi.org/10.3390/land10060591.

Debolini M., Marraccini E., Dubeuf J.P., Geijzendorffer I.R., Guerra C., Simon M., Targetti S., Napoléone C. (2018). Land and farming system dynamics and their drivers in the Mediterranean Basin. *Land Use Policy*, 75: 702-710. DOI: https://doi.org/10.1016/j.landusepol.2017.07.010.

Dias R.S., Costa D.V.T.A., Correia H.E., Costa C.A. (2021). Building bio-districts or eco-regions: participative processes supported by focal groups. *Agriculture*, 11(6): 511. DOI: https://doi.org/10.3390/agriculture11060511.

Doblas-Miranda E., Alonso R., Arnan X., Bermejo V., Brotons L., de las Heras. J., Estiarte M., Hódar J.A., Llorens P., Lloret F., López-Serrano F.R., Martínez-Vilalta J., Moya D., Peñuelas J., Pino J., Rodrigo A., Roura-Pascual N., Valladares F., Vilà M., Retana J. (2017). A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean region: beyond drought effects. *Global and Planetary Change*, 148: 42-54. DOI: https://doi.org/10.1016/j.gloplacha.2016.11.012.

Dumont A.M., Wartenberg A.C., Baret P.V. (2021). Bridging the gap between the agroecological ideal and its implementation into practice. A review. *Agronomy for Sustainable Development*, 41(3): 32. DOI: https://doi.org/10.1007/s13593-021-00666-3.

Eelderink M., Vervoort J., van Laerhoven F. (2020). Using participatory action research to operationalize critical systems thinking in social-ecological systems. *Ecology and Society*, 25(1). DOI: https://doi.org/10.5751/ES-11369-250116.

El Bilali H. (2019). Research on agro-food sustainability transitions: a systematic review of research themes and an analysis of research gaps. *Journal of Cleaner Production*, 221: 353-364. DOI: https://doi.org/10.1016/j.jclepro.2019.02.232.

Ewert F., Baatz R., Finger R. (2023). Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption. *Annual Review of Resource Economics*, 15(15): 351-381. DOI: https://doi.org/10.1146/annurev-resource-102422-090105.

FAO (2017). *The experience of bio-districts in Italy*, Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/agroecology/database/detail/en/c/1027958/.

FAO (2018). *The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems*, Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/i9037en/I9037EN.pdf.

Fiore V., Borrello M., Carlucci D., Giannoccaro G., Russo S., Stempfle S., Roselli L. (2024). The socio-economic issues of agroecology: a scoping review. *Agricultural and Food Economics*, 12(1): 16. DOI: https://doi.org/10.1186/s40100-024-00311-z.

Gaba S., Bretagnolle V. (2020). Social–ecological experiments to foster agroecological transition. *People and*

Nature, 2(2): 317-327. DOI: https://doi.org/10.1002/pan3.10078.

Galioto F., Gava O., Povellato A., Vanni F. (2021). *Innovative market and policy instruments to promote the agro-ecological transition strategies*, UNISECO Deliverable 5.4. DOI: https://doi.org/10.5281/zenodo.5578065.

Gava O., Vanni F., Schwarz G., Guisepelli E., Vincent A., Prazan J., Weisshaidinger R., Frick R., Hrabalová A., Carolus J., Yoldi U.I., Pyysiäinen J., Smyrniotopoulou A., Vlahos G., Balázs K., Szilágyi A.J., Jegelevičius G., Mikšytė E., Zilans A., Povellato A. (2025). Governance networks for agroecology transitions in rural Europe. *Journal of Rural Studies*, 114: 103482. DOI: https://doi.org/10.1016/j.jrurstud.2024.103482.

Gliessman S.R. (2020). Transforming food and agriculture systems with agroecology. *Agriculture and Human Values*, 37(3): 547-548. DOI: https://doi.org/10.1007/s10460-020-10058-0.

Goodrich K.A., Sjostrom K.D., Vaughan C., Bednarek A., Lemos M.C. (2020). Who are boundary spanners and how can we support them in making knowledge more actionable in sustainability fields? *Current Opinion in Environmental Sustainability*, 42: 45-51. DOI: https://doi.org/10.1016/j.cosust.2020.01.001.

Guareschi M., Maccari M., Sciurano J.P., Arfini F., Pronti A. (2020). A methodological approach to upscale toward an agroecology system in EU-LAFSs: the case of the Parma bio-district. *Sustainability*, 12(13): 5398. DOI: https://doi.org/10.3390/su12135398.

Guisepelli E., Fleury P., Vincent A., Aalders I., Prazan J., Vanni F. (2018). *Adapted SES framework for AEFS and guidelines for assessing sustainability of agricultural systems in Europe*, UNISECO Deliverable D2.1. DOI: https://doi.org/10.5281/zenodo.4568477.

Gutiérrez Cano L.F., Zartha Sossa J.W., Orozco Mendoza G.L., Suárez Guzmán L.M., Agudelo Tapasco D.A., Quintero Saavedra J.I. (2023). Agricultural innovation system: analysis from the subsystems of R&D, training, extension, and sustainability. *Frontiers in Sustainable Food Systems*, 7. DOI: https://doi.org/10.3389/fsufs.2023.1176366.

Helenius J., Hagolani-Albov S.E., Koppelmäki K. (2020). Co-creating agroecological symbioses (AES) for sustainable food system networks. *Frontiers in Sustainable Food Systems*, 4. DOI: https://doi.org/10.3389/fsufs.2020.588715.

Hertz T., Schlüter M. (2015). The SES-framework as boundary object to address theory orientation in social–ecological system research: the SES-TheOr approach. *Ecological Economics*, 116: 12-24. DOI: https://doi.org/10.1016/j.ecolecon.2015.03.022.

Hinkel J., Cox M., Schlüter M., Binder C., Falk T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*, 20(1). DOI: https://doi.org/10.5751/ES-07023-200132.

Hoegh-Guldberg O., Jacob D., Taylor M., Bindi M., Brown S., Camilloni I., Diedhiou A., Djalante R., Ebi K.L., Engelbrecht F., Guiot J., Hijioka Y., Mehrotra S., Payne A., Seneviratne S.I., Thomas A., Warren R., Zhou G. (2018). Impacts of 1.5°C global warming on natural and human systems. In Masson-Delmotte V., Zhai P., Pörtner H.O., Roberts D., Skea J., Shukla P.R., Pirani A., Moufouma-Okia W., Péan C., Pidcock R., Connors S., Matthews J.B.R., Chen Y., Zhou X., Gomis M.I., Lonnoy E., Maycock T., Tignor M., Waterfield T. (eds.) *Global Warming of 1.5°C*. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty IPCC, Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175-312. DOI: https://doi.org/10.1017/9781009157940.005.

Horlings L.G., Marsden T.K. (2011). Towards the real green revolution? exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. *Global Environmental Change*, 21(2): 441-452. DOI: https://doi.org/10.1016/j.gloenvcha.2011.01.004.

Ingram J. (2017). Perspective: look beyond production. *Nature*, 544(7651): S17. DOI: https://doi.org/10.1038/544S17a.

IN.N.E.R. (2021). *Brochure INNER English*, International Network of Eco Regions, Ceraso. https://www.ecoregion.info/research/.

Jia X. (2021). Agro-food innovation and sustainability transition: a conceptual synthesis. *Sustainability*, 13(12): 6897. DOI: https://doi.org/10.3390/su13126897.

Kelinsky-Jones L.R., Niewolny K.L., Stephenson M.O. (2023). Building agroecological traction: engaging discourse, the imaginary, and critical praxis for food system transformation. *Frontiers in Sustainable Food Systems*, 7. DOI: https://doi.org/10.3389/fsufs.2023.1128430.

Lachman D.A. (2013). A survey and review of approaches to study transitions. *Energy Policy*, 58: 269-276. DOI: https://doi.org/10.1016/j.enpol.2013.03.013.

Laforge J.M.L., Dale B., Levkoe C.Z., Ahmed F. (2021). The future of agroecology in Canada: embracing the politics of food sovereignty. *Journal of Rural Studies*, 81: 194-202. DOI: https://doi.org/10.1016/j.jrurstud.2020.10.025.

Lamine C., Pugliese P., Barataud F., Berti G., Rossi A. (2023). Italian biodistricts and French territorial food projects: How science-policy-experience interplays shape the framings of transitions towards sustainable territorial food systems. *Frontiers in Sustainable Food Systems*, 7. DOI: https://doi.org/10.3389/fsufs.2023.1223270.

Landert J., Pfeifer C., Carolus J., Albanito F., Müller A., Baumgart L., Blockeel J., Schwarz G., Weisshaidinger R., Bartel-Kratochvil R., Hollaus A., Hrabalová A., Helin J., Aakkula J., Svels K., Guisepelli E., Fleury P., Vincent A., Smyrniotopoulou A., Vlahos G., Iordanidis Y., Szilágyi A., Podmaniczky L., Balázs K., Galioto F., Longhitano D., Rossignolo L., Povellato A., Zīlāns A., Jegelevičius G., Frățilă M., Iragui Yoldi U., Astrain Massa C., Bienzobas Adrian J., Resare Sahlin KRöös E., Frick R., Bircher R., Aalders I., Irvine K., Kyle C., Miller D., Sanders J., Smith P. (2019). *Report on Environmental, Economic and Social Performance of Current AEFS, and Comparison to Conventional Baseline*, UNISECO Deliverable D3.1. DOI: https://doi.org/10.5281/zenodo.3625681.

Landert J., Pfeifer C., Carolus J.F. (2020). Assessing agroecological practices using a combination of three sustainability assessment tools. *Landbauforschung: Journal of Sustainable and Organic Agricultural Systems*, 70(2): 129-144. DOI: https://doi.org/10.3220/LBF1612794225000.

Loconto A., Poisot A.S., Santacoloma P. (2017). Sustainable practices, sustainable markets? Institutional innovations in agri-food system. In Elzen B., Augustyn A.M., Barbier M., van Mierlo B. (eds.) *AgroEcological Transitions: Changes and Breakthroughs in the Making*, p.176-191. Wageningen University & Research, Wageningen. DOI: https://doi.org/10.18174/407609.

Long T.B., Blok V., Coninx I. (2016). Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: Evidence from the Netherlands, France, Switzerland and Italy. *Journal of Cleaner Production*, 112: 9-21. DOI: https://doi.org/10.1016/j.jclepro.2015.06.044.

Loorbach D., Frantzeskaki N., Avelino F. (2017). Sustainability transitions research: transforming science and practice for societal change. *Annual Review of Environment and Resources*, 42(1): 599-626. DOI: https://doi.org/10.1146/annurev-environ-102014-021340.

Madureira L., Torre A. (2019). Innovation processes in rural areas. *Regional Science Policy & Practice*, 11(2): 213-218. DOI: https://doi.org/10.1111/rsp3.12215.

Marshall G.R. (2015). A social-ecological systems framework for food systems research: Accommodating transformation systems and their products. *International Journal of the Commons*, 9(2): 881. DOI: https://doi.org/10.18352/ijc.587.

McDermott R. (2023). On the scientific study of small samples: Challenges confronting quantitative and qualitative methodologies. *The Leadership Quarterly*, 34(3): 101675. DOI: https://doi.org/10.1016/j.leaqua.2023.101675.

McGinnis M.D., Ostrom E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*, 19(2): art30. DOI: https://doi.org/10.5751/ES-06387-190230.

Méndez V.E., Bacon C.M., Cohen R., Gliessman S.R. (eds) (2016). *Agroecology: A Transdisciplinary, Participatory and Action-Oriented Approach*. CRC Press, Baco Raton, FL.

Montenegro de Wit M. (2022). Can agroecology and CRISPR mix? The politics of complementarity and moving toward technology sovereignty. *Agriculture and Human Values*, 39(2): 733-755. DOI: https://doi.org/10.1007/s10460-021-10284-0.

Mrabet R., Savé R., Toreti A., Caiola N., Chentouf M., Llasat M.C., Mohamed A.A.A., Santeramo F.G., Sanz-Cobena A., Tsikliras A. (2020). Food. In Cramer W., Guiot J., Marini K. (eds) *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future*. First Mediterranean Assessment Report (pp. 237-264). Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France. ISBN 978-2-9577416-0-1.

Ollivier G., Magda D., Mazé A., Plumecocq G., Lamine C. (2018). Agroecological transitions: What can sustainability transition frameworks teach us? An ontological and empirical analysis. *Ecology and Society*, 23(2): art5. DOI: https://doi.org/10.5751/ES-09952-230205.

Ostrom E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939): 419-422. DOI: https://doi.org/10.1126/science.1172133.

Ostrom E. (2011). Background on the institutional analysis and development framework. *Policy Studies Journal*, 39(1): 7-27. DOI: https://doi.org/10.1111/j.1541-0072.2010.00394.x.

Padró R., Tello E., Marco I., Olarieta J.R., Grasa M.M., Font C. (2020). Modelling the scaling up of sustainable farming into agroecology territories: potentials and bottlenecks at the landscape level in a Mediterranean case study. *Journal of Cleaner Production*, 275: 124043. DOI: https://doi.org/10.1016/j.jclepro.2020.124043.

Partelow S. (2018). A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecology and Society*, 23(4): art36. DOI: https://doi.org/10.5751/ES-10594-230436.

Patel V., Biggs E., Pauli N., Boruff B. (2020). Using a social-ecological system approach to enhance understanding of structural interconnectivities within the beekeeping industry for sustainable decision making. *Ecology and Society*, 25(2): art24. DOI: https://doi.org/10.5751/ES-11639-250224.

Pimbert M.P. (2025). Financing agroecological transformations for territorial agri-food systems: Beyond the myth of financial scarcity. *Elementa: Science of the Anthropocene*, 13(1): 00026. DOI: https://doi.org/10.1525/elementa.2025.00026.

Pomponi T., Carillo F., Henke R., Sturla A., Del Giudice T., Sorrentino A. (2026). Biodistricts as social innovation: territorial implications in Italy. *Journal of Rural Studies*, 121: 103926. DOI: https://doi.org/10.1016/j.jrurstud.2025.103926.

Poponi S., Arcese G., Mosconi E.M., Pacchera F., Martucci O., Elmo G.C. (2021). Multi-actor governance for a circular economy in the agri-food sector: Biodistricts. *Sustainability*, 13(9): 4718. DOI: https://doi.org/10.3390/su13094718.

Prost L., Martin G., Ballot R., Benoit M., Bergez J.E., Bockstaller C., Cerf M., Deytieux V., Hossard L., Jeuffroy M.H., Leclère M., Le Bail M., Le Gal P.Y., Loyce C., Merot A., Meynard J.M., Mignolet C., Munier-Jolain N., Novak S., Parnaudeau V., Poux X., Sabatier R., Salembier C., Scopel E., Simon S., Tchamitchian M., Toffolini Q., van der Werf H. (2023). Key research challenges to supporting farm transitions to agroecology in advanced economies. A review. *Agronomy for Sustainable Development*, 43(1): 11. DOI: https://doi.org/10.1007/s13593-022-00855-8.

Rega C., Thompson B., Niedermayr A., Desjeux Y., Kantelhardt J., D'Alberto R., Gouta P., Konstantidelli V., Schaller L., Latruffe L., Paracchini M.L. (2022). Uptake of ecological farming practices by EU farms: a pan-European typology. *EuroChoices*, 21(3): 64-71. DOI: https://doi.org/10.1111/1746-692X.12368.

Regione Toscana (2015). *PIT - Piano di indirizzo territoriale con valenza di piano paesaggistico - Scheda ambito di paesaggio - Ambito 10: Chianti*. Regione Toscana, Florence. https://www.regione.toscana.it/documents/10180/12604324/10_Chianti.pdf/d1bd9db6-c777-4627-8dc8-42b93ad193b8.

Ruggieri F., Coulon-Leroy C., Mazé A. (2023). How can collective action support the agroecological transition in geographical indication vineyards? Insights from the Loire Valley wine area. *Sustainability*, 15(12): 9371. DOI: https://doi.org/10.3390/su15129371.

Ruggieri F., Mazé A., Coulon-Leroy C. (2025). A social–ecological approach to analyse systemic changes toward agroecological practices in vineyards under geographical indications: a case study of ground cover management in the Anjou-Saumur wine area (France). *OENO One*, 59(4): 9295. DOI: https://doi.org/10.20870/oeno-one.2025.59.4.9295.

Runhaar H. (2021). Four critical conditions for agroecological transitions in Europe. *International Journal of Agricultural Sustainability*, 19(3-4): 227-233. DOI: https://doi.org/10.1080/14735903.2021.1906055.

Sachet E., Mertz O., Le Coq J.F., Cruz-Garcia G.S., Francesconi W., Bonin M., Quintero M. (2021). Agroecological transitions: A systematic review of research approaches and prospects for participatory action methods. *Frontiers in Sustainable Food Systems*, 5. DOI: https://doi.org/10.3389/fsufs.2021.709401.

Schermer M. (2006). Regional rural development: the formation of ecoregions in Austria. In Holt G.C., Reed M. (eds) *Sociological Perspectives of Organic agriculture: From Pioneer to Policy* (pp. 227-242). CABI Publishing, Wallingford. DOI: https://doi.org/10.1079/9781845930387.0227.

Schiller K., Godek W., Klerkx L., Poortvliet P.M. (2020). Nicaragua's agroecological transition: Transformation or reconfiguration of the agri-food regime? *Agroecology and Sustainable Food Systems*, 44(5): 611-628. DOI: https://doi.org/10.1080/21683565.2019.1667939.

Schneider F., Feurer M., Lundsgaard-Hansen L.M., Nydegger K., Oberlack C., Zähringer J.G., Messerli P. (2020). Sustainable development under competing claims on land: three pathways between land-use changes, ecosystem services and human well-being. *The European Journal of Development Research*, 32(2): 316-337. DOI: https://doi.org/10.1057/s41287-020-00268-x.

Schoonhoven Y., Runhaar H. (2018). Conditions for the adoption of agro-ecological farming practices: a holistic framework illustrated with the case of almond farming in Andalusia. *International Journal of Agricultural Sustainability*, 16(6): 442-454. DOI: https://doi.org/10.1080/14735903.2018.1537664.

Schut M., Klerkx L., Sartas M., Lamers D., Campbell M.M., Ogbonna I., Kaushik P., Atta-Krah K., Leeuwis C. (2016). Innovation platforms: experiences with their institutional embedding in agricultural research for development. *Experimental Agriculture*, 52(4): 537-561. DOI: https://doi.org/10.1017/S001447971500023X.

Schwarz G., Prazan J., Landert J., Miller D., Vanni F., Carolus J., Weisshaidinger R., Bartel-Kratochvil R., Mayer A., Frick R., Hrabalová A., Linares Quero A., Iragui U., Astrain Massa C., Helin J., Huismann D., Guisepelli E., Fleury P., Vincent A., Smyrniotopoulou A., Vlahos G., Balázs K., Szilágyi A., Podmaniczky L., Gava O., Povellato A., Galioto F., Zīlāns A., Veidemane K., Gulbinas J., Jegelevičius G., Myškyté E., Frățilă M., Cazacu M., Resare Sahlin K., Röös E., Pia C., Kyle C., Irvine K., Albanito F., Smith P. (2021a). *Report on key barriers of agro-ecological farming systems in Europe and co-constructed strategies*, UNISECO Deliverable 3.4. DOI: https://doi.org/10.5281/zenodo.5549542.

Schwarz G., Vanni F., Miller D. (2021b). The role of transdisciplinary research in the transformation of food systems. *Agricultural and Food Economics*, 9(1): 35. DOI: https://doi.org/10.1186/s40100-021-00207-2.

Schwarz G., Vanni F., Miller D., Helin J., Pražan J., Albanito F., Fratila M., Galioto F., Gava O., Irvine K., Landert J., Quero A.L., Mayer A., Monteleone D., Muller A., Röös E., Smyrniotopoulou A., Vincent A., Vlahos G., Zīlāns A. (2022). Exploring sustainability implications of transitions to agroecology: A transdisciplinary perspective. *EuroChoices*, 21(3): 37-47. DOI: https://doi.org/10.1111/1746-692X.12377.

Seghezzo L., Huaranca L.L., Vega M.L., Jeckeln G.V., Avalos M.A., Iribarnegaray M.A., Volante J.N., Serrano F.H.M., Mastrangelo M., Sun Z., Müller D. (2020). Sustainable farmers, deficient State? Self-reported agricultural sustainability in the Argentine Chaco region. *International Journal of Agricultural Sustainability*, 18(6): 473-491. DOI: https://doi.org/10.1080/14735903.2020.1793645.

Sherwood S., Van Bommel S., Paredes M. (2016). Self-organization and the bypass: Re-imagining institutions for more sustainable development in agriculture and food. *Agriculture*, 6(4): 66. DOI: https://doi.org/10.3390/agriculture6040066.

Simoncini R. (2011). Governance objectives and instruments, ecosystem management and biodiversity conservation: The Chianti case study. *Regional Environmental Change*, 11(1): 29-44. DOI: https://doi.org/10.1007/s10113-010-0112-x.

Sivini S., Vitale A. (2023). Multifunctional and agroecological agriculture as pathways of generational renewal in Italian rural areas. *Sustainability*, 15(7): 5990. DOI: https://doi.org/10.3390/su15075990.

Stotten R., Bui S., Pugliese P., Schermer M., Lamine C. (2018). Organic values-based supply chains as a tool for territorial development: A comparative analysis of three European organic regions. *The International Journal of Sociology of Agriculture and Food*, 24(1). DOI: https://doi.org/10.48416/IJSAF.V24I1.120.

Sturla A (2021). *Esperienze europee*. In Approccio agroecologico e biodistretti. Analisi di due casi di studio. Rete Rurale Nazionale, Rete Rurale Nazionale e Ministero delle politiche agricole alimentari e forestali, Roma, Italy. ISBN 9788833851273.

Suwannadi T., Dechruksa W., Panpakdee C. (2026). Quantifying the effects of pest pressure and peer networks on pesticide purchasing decisions among Thai farmers. *Sustainable Futures*, 11: 101731. DOI: https://doi.org/10.1016/j.sftr.2026.101731.

Teixeira H.M., Van den Berg L., Cardoso I.M., Vermue A.J., Bianchi F.J.J.A., Peña-Claros M., Tittonell P. (2018). Understanding Farm Diversity to Promote Agroecological Transitions. Sustainability, 10(12): Article 12. DOI: https://doi.org/10.3390/su10124337.

Teschner N., Orenstein D.E. (2021). A transdisciplinary study of agroecological niches: Understanding sustainability transitions in vineyards. *Agriculture and Human Values*, 39: 33-45. DOI: https://doi.org/10.1007/s10460-021-10220-2.

Tittonell P. (2014). Ecological intensification of agriculture—Sustainable by nature. *Current Opinion in Environmental Sustainability*, 8: 53-61. DOI: https://doi.org/10.1016/j.cosust.2014.08.006.

Tittonell P., Piñeiro G., Garibaldi L.A., Dogliotti S., Olff H., Jobbagy E.G. (2020). Agroecology in large scale farming—a research agenda. *Frontiers in Sustainable Food Systems*, 4. DOI: https://doi.org/10.3389/fsufs.2020.584605.

Vallejo-Rojas V., Ravera F., Rivera-Ferre M.G. (2016). Developing an integrated framework to assess agri-food systems and its application in the Ecuadorian Andes. *Regional Environmental Change*, 16(8): 2171-2185. DOI: https://doi.org/10.1007/s10113-015-0887-x.

van der Ploeg J.D. (2021). The political economy of agroecology. *The Journal of Peasant Studies*, 48(2): 274-297. DOI: https://doi.org/10.1080/03066150.2020.1725489.

Vanni F., Gava O., Povellato A., Guisepelli E., Fleury P., Vincent A., Prazan J., Schwarz G., Bartel-Kratochvil R., Hollaus A., Weisshaidinger R., Frick R., Hrabalová A., Carolus J., Iragui Yoldi U., Elía Hurtado S., Pyysiäinen J., Aakkula J., Helin J., Rikkonen P., Smyrniotopoulou A., Vlahos G., Balázs K., Szilágyi A., Jegelevičius G., Mikšytė E., Zilans A., Veidemane K., Frățilă M., Röös E., Resare Sahlin K., Miller D., Kyle C., Irvine K.N., Aalders I. (2019). *Governance networks supporting agro-ecological farming sys-*

tems, UNISECO Deliverable 5.4. DOI: https://doi.org/10.5281/zenodo.4568422.
Vilas-Boas J., Klerkx L., Lie R. (2022). Connecting science, policy, and practice in agri-food system transformation: The role of boundary infrastructures in the evolution of Brazilian pig production. *Journal of Rural Studies*, 89: 171-185. DOI: https://doi.org/10.1016/j.jrurstud.2021.11.025.
Vizuete B., García-Llorente M., Pérez-Ramírez I., Oteros-Rozas E. (2025). Gender equity as a key element for agroecological transitions: Neo-rural women as managers of agroecological initiatives. *People and Nature*, 7(2): 449-462. DOI: https://doi.org/10.1002/pan3.10761.
Wezel A., Brives H., Casagrande M., Clément C., Dufour A., Vandenbroucke P. (2016). Agroecology territories: Places for sustainable agricultural and food systems and biodiversity conservation. *Agroecology and Sustainable Food Systems*, 40(2): 132-144. DOI: https://doi.org/10.1080/21683565.2015.1115799.
Wezel A., Goris M., Bruil J., Félix G., Peeters A., Bàrberi P., Bellon S., Migliorini P. (2018). Challenges and action points to amplify agroecology in Europe. *Sustainability*, 10(5): 1598. DOI: https://doi.org/10.3390/su10051598.
Wezel A., Herren B.G., Kerr R.B., Barrios E., Gonçalves A.L.R., Sinclair F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, 40(6): 40. DOI: https://doi.org/10.1007/s13593-020-00646-z.
Williams T.G., Bürgi M., Debonne N., Diogo V., Helfenstein J., Levers C., Mohr F., Stratton A.E., Verburg P.H. (2024). Mapping lock-ins and enabling environments for agri-food sustainability transitions in Europe. *Sustainability Science*, 19(4): 1221-1242. DOI: https://doi.org/10.1007/s11625-024-01480-y.
Wohlfahrt J., Ferchaud F., Gabrielle B., Godard C., Kurek B., Loyce C., Therond O. (2019). Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. *Journal of Cleaner Production*, 232: 898-909. DOI: https://doi.org/10.1016/j.jclepro.2019.05.385.
Zanasi C., Basile S., Paoletti F., Pugliese P., Rota C. (2020). Design of a monitoring tool for eco-regions. *Frontiers in Sustainable Food Systems*, 4. DOI: https://doi.org/10.3389/fsufs.2020.536392.
Zawalińska K., Smyrniotopoulou A., Balazs K., Böhm M., Chitea M., Florian V., Fratila M., Gradziuk P., Henderson S., Irvine K., Konstantidelli V., Krupin V., Latruffe L., Mikšytė E., Miller D., Monteleone D., Polaschegg M., Schwarz G., Tzanopoulos J., Tzouramani I., Vlahos G., Wojciechowska A. (2022). Advancing the contributions of European stakeholders in farming systems to transitions to agroecology. *EuroChoices*, 21(3): 50-63. DOI: https://doi.org/10.1111/1746-692X.12378.

APPENDIX

Table A.1. Summary of the characterised subsystems.

Subsystems (code)	Summary	Key indicators
Resource system (RS)	Highly specialised wine-olive system embedded in a winescape; clear boundaries (seven municipalities), large RS with vineyard dominance; strong influence of human-built structures (terraces, hedges, and fences); productivity largely shaped by PDO rules rather than farming method; long-term equilibrium marked by loss of arable/pasture, soil degradation, and predictable continuation of vineyard expansion; inputs trending down (fertilisers, pesticides)	• Total RS ≈ 71,800 ha (≈ 28,000 ha agri-food) • Vineyards ≈ 10,000 ha; olive groves ≈ 5,000 ha • >30% organic UAA • Durum wheat yields 1-2 t/ha (vs 3-4 Tuscany average) • Vineyard yields 5-7 t/ha; olive 1-1.5 t/ha • N input conv. 35-50 kg/ha; organic ≈ 30% less
Resource units (RU)	RU dominated by high-value PDO wine, with olive oil and niche crops as minor; RU competition: vineyards replace other uses; small revival of grains and semi-extensive livestock; economic value heavily asymmetric (wine >90% of NVA); spatial/temporal patterns strongly seasonal; marketing channels export-oriented for wine, local for minor chains	• Wine accounts for >90% of farm net value added • Grain revival <100 ha • Real estate prices >€5,000/m2 (tourism pressure) • RU labour strongly seasonal (pruning/harvest)
Governance system (GS)	Polycentric multi-level system (EU-region-municipalities-consortia-biodistrict); strong bottom-up governance from organic actors; rules-in-use include PDO constraints, GPP, herbicide/plastic bans, and evidence-based pest monitoring; high social capital but municipal implementation uneven; governance vision links agroecology and sustainable tourism; network needs expansion to tourism and consumer actors; recent formalisation of the biodistrict strengthens institutional mandate	• 7 municipalities, ≈ 57,000 residents • >2,000 farms (≈140 organic; ≈1,800 conventional) • Wine consortium covers ~96% of DOCG producers • Organic UAA ≈ 30%, rising • Institutional milestones: 2016 biodistrict, 2017 rural district
Actors (A)	Fourteen actor groups spanning farmers, municipalities, region, NGOs, consortia, advisors, and research; strong leadership by the Biodistrict Committee, winegrowers' association, consortium, and consultants; high dependence on wine (economic dominance); mental models converging around observation-based AE (monitoring, nutrient loops) but tensions persist (precision vs diversification); missing: consumers and tourism operators	• Organic farmers ≈ 140; conventional ≈ 1,800 • Largest AE adopters ≈ 96 ha average size • Wine = >90% of income; agritourism ≈ 10%
Interactions (I)	Strong farmer-driven redesign: inter-row cover, composting, terraces, livestock reintegration; dense knowledge-sharing through advisory networks, assemblies, producer labs; conflicts between ICT-driven vs AE-driven pathways; investment in public procurement pilots, compost hubs, machinery rings; self-organisation central (biodistrict creation); monitoring innovations drive evidence-based pest management; lobbying by biodistrict and consortium influences regional decisions.	• 6-7 municipalities engaged; multiple MAP meetings over 4 years (UNISECO) • AE adopters reduce GHG from ~2054 → ~794 kg CO2e/ha • Beneficial invertebrates 25% → 34% with AE adoption
Outcomes (O)	Ecological: reduced pesticides, lower GHG, better soil carbon and nutrient cycling, and moderate biodiversity gains Social: labour shortages, high education levels, and housing pressure due to tourism Institutional: strengthened cooperation and identity via biodistrict, assemblies, and living lab Economic: diversification emerging but wine still dominant, and local chains developing	• GHG: 2054 → 794 kg CO2e/ha along AE gradient • Carbon sequestration: -272 → -1828 kg CO2e/ha • Biodiversity (SMART): ~59%-60% • Tourism >700,000 visitors/year
Social, economic, and political settings	Economy strongly dependent on wine tourism; agriculture unusually important (11.5% employment vs 4% for Tuscany); demographic decline in remote areas; cultural identity centred on wine landscape; stable political context; markets dominated by wine brand; infrastructure adequate but uneven; territorial history stable except for recent biodistrict/rural district regulation	• Agriculture = 11.5% of local employment • Per capita GDP ≈ €23,400 • Population: 62,324 (1951) → 58,896 (2011) • Tourism supports 350+ firms
Related ecosystems (RE)	Climate change: higher temperatures (+1.4°C in summer 2019), drought, pest pressure (olive fly); pollution from agriculture, industry, and tourism; wildlife (boar, wolves) increasing crop/livestock damage; hydrology affected by abandonment and woody encroachment; cross-boundary flows of emissions and wildlife create regional-scale pressures	• Summer 2019: +1.4°C, -10% rainfall • High wildlife pressure (boar → wolf presence) • allow land up to 48% in conventional farms

Table A.2. Socio-ecological system contribution to agroecology transition in the Chianti Biodistrict.

Subsystems (code)	Contribution to focal action situations	Actor-mediated interactions	Outcomes	Feedback loops	Barriers/Drivers	Resolution strategies
Actors (A)	Initiate and coordinate transition actions, enabling participatory planning and knowledge co-creation	Farmers, advisors, and civic groups co-create strategies, share knowledge, and build trust networks	Adoption of agroecological practices, increased capacity, peer learning, and reduced risk	Actor networks reinforce norms, enabling collective agency and long-term commitment	Poor advisory capacity and fragmented actor engagement hinder transitions; civic engagement fosters change	Strengthened advisory services, peer learning platforms, and inclusive governance via the biodistrict
Governance system (GS)	Shape and support focal actions through enabling policies and institutional frameworks	Public institutions and civic associations co-design policies and coordinate multi-actor actions	Formal agreements, participatory planning, policy alignment, and institutional innovation	Governance adapts to actor agency, reinforcing enabling environments and responsiveness	Fragmented implementation and lack of coordination; regional law and civic leadership foster integration	Strategic planning, regional support, and formalisation of the biodistrict as an agroecology territory
Resource system (RS)	RS dynamics are central to redesign actions focused on land recovery and diversification	Actors influence land use and resource management through collective strategies and policy tools	Diversified cropping, reduced erosion, recovery of marginal land, and improved ecology	Landscape identity and economic incentives reinforce sustainable practices	Vineyard monoculture and land abandonment hinder diversification; local demand and procurement foster recovery	Diversified value chains, recovery of olive groves, and integration of agroecology into territorial planning
Resource units (RU)	Targeted in focal actions like inter-row cover and composting to enhance ecological outcomes	Farmers manage specific crops and livestock units with ecological practices and input substitution	Improved soil fertility, pest control, and organic production quality	Feedback from ecological performance informs farm-level decisions and practice refinement	Climate stress and pest outbreaks challenge unit-level sustainability; organic demand supports innovation	Pest monitoring, composting, and organic certification promoted through advisory and policy support

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Research article

Structural and informational absences in irrigation data: a Bayesian zero-inflated approach applied to Minas Gerais, Brazil

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Abstract. Minas Gerais is Brazil's second-largest state in terms of irrigated area, with expansion potential exceeding 1 million hectares. Yet 16% of municipalities reported no irrigation in 2019, revealing a paradox between potential and local absence. This study investigates the determinants of irrigation absence using a Bayesian zero-inflated model with a truncated Student's t-distribution. The results indicate that the baseline probability of a structural zero is approximately 12%, but this probability decreases to 4% in municipalities located in the São Francisco Basin or those with potential irrigable area. In contrast, municipalities with agricultural gross value added below the state average show substantially higher probabilities of structural zeros (around 38%). In the extended specification, the interaction between basin location and potential irrigable area reduces the probability of structural zeros to about 1%, indicating a strong combined mitigating effect. By distinguishing structural from informational constraints, this study provides actionable insights for targeted policy interventions aimed at promoting sustainable and efficient irrigation expansion.

Keywords: irrigation, governance, allocation, institutional barriers.
JEL codes: Q18, C11, R58.

HIGHLIGHTS

- Applies a Bayesian zero-inflated model to distinguish structural from informational irrigation zeros.
- Identifies that nearly half of zero-irrigation municipalities reflect informational gaps rather than structural constraints.
- Finds that irrigable area and the São Francisco river basin location markedly lower the likelihood of structural zeros, with cross-basin hydrological implications.
- Delivers evidence to strengthen basin-level water governance.

1. INTRODUCTION

Despite recognition of irrigation as an essential element of agricultural productivity and resilience to climate shocks, many regions worldwide remain far below their irrigable potential (Altchenko, Villholth, 2015; Smilovic *et al*., 2015; Desta, 2024). Understanding regional structures is important for improving water governance and policy design (Playán *et al*., 2018; Fritsch, Benson, 2024). Such gaps may arise from structural barriers, such as water scarcity, or from informational constraints, where irrigation areas are not integrated into management systems.

While the determinants of irrigation expansion have been extensively studied, highlighting the role of infrastructure investment, productivity gains, technologies, or policy incentives (Cremades *et al*., 2015; Abou Zaki *et al*., 2022; Gautam *et al*., 2024; Asfaw, Mekonen, 2024), few studies have examined why irrigable areas remain underutilised in emerging economies, where institutional and informational barriers may differ substantially (Playán *et al*., 2018; Nhamo *et al*., 2024). Brazil exemplifies this gap: although an estimated 13.7 million hectares are considered suitable for irrigation (Agência Nacional de Águas e Saneamento Básico [ANA], 2021), large portions of potentially irrigable land, such as in the state of Minas Gerais, remain unexplored.

According to the Irrigation Atlas (ANA, 2021), 1,247 of Brazil's 5,570 municipalities report no irrigated area. In 2019[1], irrigated agriculture accounted for an estimated 965 m^3/s of water use, concentrated primarily in flood-irrigated rice (38%). This combination of high national water demand and widespread zero-records underscores the need to explicitly model the 'zero mechanism' when examining irrigation dynamics in regions such as Minas Gerais. This issue is particularly relevant because irrigable potential areas coexist with regional disparities and productivity differentials between irrigated and rainfed areas which in turn translate into distinct labour market dynamics and income levels (Ferrarini *et al*., 2019, 2020).

Brazilian agriculture plays a central role in global food supply, ranking among the world's largest producers and exporters of water-intensive crops (Da Silva *et al*., 2016; Visentin *et al*., 2019). Brazil's rapid structural transformation has positioned it as a pivotal contributor to international markets for soybeans, coffee, sugar, meat, and other commodities (Barros *et al*., 2019; Machado, da Cruz, 2022; Dhoubhadel *et al*., 2023). Within this national context, Minas Gerais combines irrigation potential with spatial heterogeneity in agricultural development and access to technical assistance. According to the Irrigation Atlas (ANA, 2021), the irrigated area in the state was 1,144,428 hectares in 2019 (20.33% of cropped area and 14% of Brazil's total), while 1,180,524 hectares remain available for irrigation expansion, a potential 103% increase. The state also encompasses part of the São Francisco river basin, a critical water source for the semi-arid Northeast, highlighting potential trade-offs in water allocation (Ferrarini *et al*., 2020).

The focus on Minas Gerais is justified not only by its extensive irrigated area but also by its importance in national and global food production systems. The state is an important producer of soybean (34% of cultivated area), sugarcane (17%), and coffee (16%), and it accounts for 56% of the total coffee-planted area in Brazil. In this context, the presence of municipalities with irrigable potential but no irrigated area emerges as a relevant gap. The Irrigation Atlas (ANA, 2021) reports that 139 municipalities in Minas Gerais (16.18%) had no irrigation in 2019, in contrast to the 51 municipalities (6%) recorded in the 2017 Agricultural Census (Instituto Brasileiro de Geografia e Estatística [IBGE], 2019). These differences reflect variations in data collection approaches. The Agricultural Census is based on self-reported information collected from farmers during a specific reference period, whereas the Irrigation Atlas integrates multiple data sources, including remote sensing and administrative records.

Understanding whether the absence of irrigation arises from hydrological constraints, governance failures, or informational gaps is fundamental for basin-level water allocation, compliance monitoring, and long-term planning under increasing climatic variability (Nguyen *et al*., 2020; Multsch *et al*., 2020; Ortiz-Bobea, 2021). Studies using Bayesian zero-inflated (ZIP) models have been applied in different contexts within agricultural economics. Nohamba *et al.* (2022) applied ZIP regression and found that citrus producers lose 4.1% of their production, with sprinkler irrigation increasing exposure to losses by 5.3 times, while regular agricultural extension services reduce such losses. Ng'ombe *et al.* (2022), in turn, employed a Bayesian zero-one inflated beta model to analyse milk sales by smallholder farmers in Zambia, showing that married farmers sell 26% more and payment delays reduce the proportion sold by 16.5%.

In this study, structural zeros refer to municipalities where irrigation is not feasible due to inherent constraints, such as water scarcity. In contrast, informational zeros arise from measurement issues, lack of reporting, or limited access to technical assistance and institutional support. This discrepancy raises the

[1] The latest available information.

research question for this study: which factors explain the absence of irrigation in municipalities with irrigable potential, and to what extent does such absence reflect structural hydrological constraints versus informational or governance limitations relevant to water allocation? The main objective is to identify the determinants of irrigation absence in municipalities with irrigable potential, distinguishing between structural and informational mechanisms. Specifically, the following hypotheses are tested:

> H1 – Structural factors, such as hydrological constraints and geographic location, increase the probability of structural zeros.
> H2 – Institutional and economic factors, such as access to technical assistance and productive capacity, are associated with the presence of irrigation and reduce the likelihood of informational zeros.

To this end, this study employs a Bayesian ZIP model, which decomposes the probability of absence into structural zeros (Lambert, 1992), implemented through a zero-inflated Student's t specification adapted from Agarwal *et al.* (2002). This study is structured into five sections. Section 1 introduces the topic. Section 2 presents the database and methodological framework. Section 3 reports the results, followed by Section 4, which discusses the main findings. Finally, Section 5 concludes the study.

2. DATABASE AND METHODOLOGY

2.1. Case study area

Brazil comprises 26 states and the Federal District, and its hydrological system is organised into major river basins, including the São Francisco river basin, which plays a central role in water availability for agricultural activities. Minas Gerais, located in the Southeast region, is one of the largest states in the country, covering approximately 586,500 km² and comprising 853 municipalities. Figure 1 situates the spatial context of the state within Brazil and displays the distribution of irrigated area in 2019 using a quantile classification.

In 2019, water withdrawal in Brazil was distributed across livestock (8.4%), irrigation (49.8%), mining (1.7%), industry (9.7%), thermoelectric generation (4.5%), rural households (1.6%), and urban consumption (24.3%). Brazil's irrigated area expanded from 4.5 million hectares in 2006 to 6.9 million hectares in 2017 and 8.2 million hectares in 2019. In Minas Gerais, the irrigated area increased from roughly 530,000 hectares in 2006 to about 1.12 million hectares in 2017 and 2019.

The Atlas of Irrigation (ANA, 2021) reports a national potential of 13.69 million hectares for additional irrigated agriculture, of which Minas Gerais accounts for approximately 8%, or nearly 1.14 million hectares. The state's hydrological network comprises 17 federal river basins (Governo de Minas Gerais, 2020).

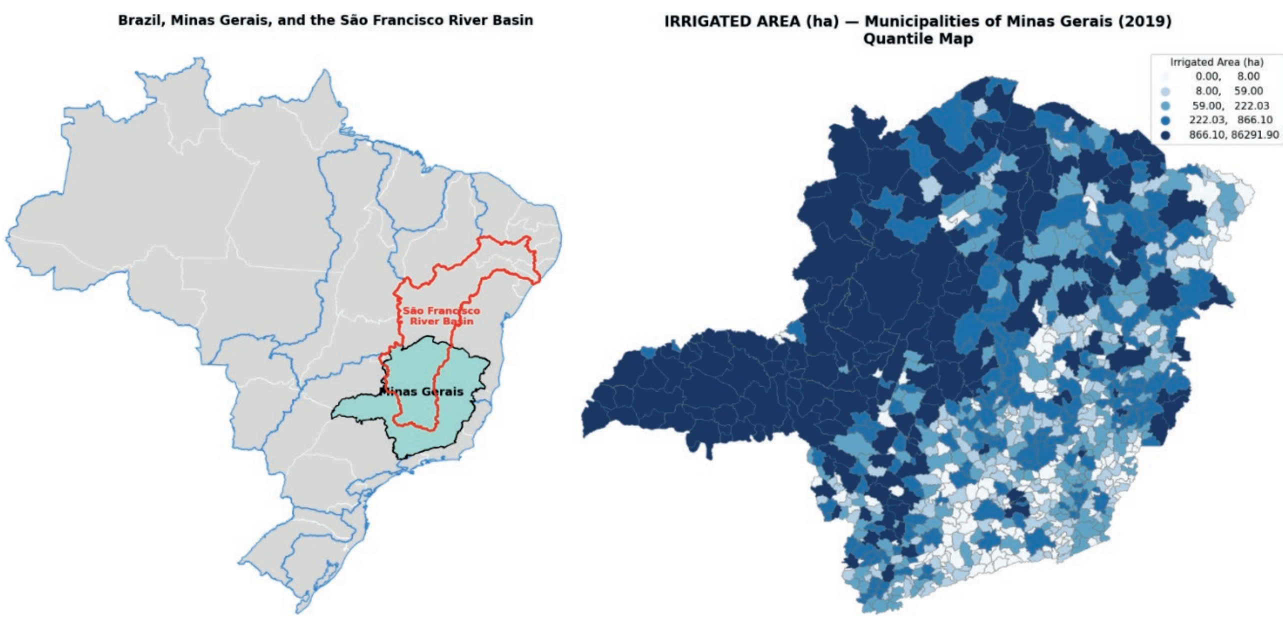

Figure 1. Geographical context of Brazil and the irrigated areas in Minas Gerais (2019). *Source:* Prepared by the author based on the official geographic mesh provided by IBGE (2025) and irrigated area data from the Atlas of Irrigation (ANA, 2021).

Among them, the São Francisco river basin is the third-largest hydrographic basin in Brazil. Within Minas Gerais, it covers approximately 234,557 km², encompassing 282 municipalities and serving an estimated 12.37 million inhabitants. Given this spatial heterogeneity and the inconsistencies in available data, a modelling strategy capable of distinguishing structural from informational zeros.

2.2. Database

The database employed in this study brings together information from the National Water and Basic Sanitation Agency (ANA) through the Irrigation Atlas (ANA, 2021), with a focus on irrigated area and potentially irrigable area in municipalities of Minas Gerais for the year 2019. Complementarily, data from the 2017 Agricultural Census, made available by the Brazilian Institute of Geography and Statistics (IBGE), were used to provide the rural numbers associated with cooperatives/associations per municipality.

For temporal consistency, it is assumed that data from the 2017 Agricultural Census remained constant in 2019[2]. The selection of variables is guided by the literature highlighting the positive role of rural extension in improving productivity and rural development (Birkhaeuser *et al*., 1991; Da Silva, 2001). Municipal economic capacity, measured through agricultural gross value added (GVA), is included to capture the availability of economic resources. In addition, the inclusion of municipalities located within the São Francisco river basin reflects the expansion of irrigated areas in this region (Baiardi, Ribeiro, 2023).

To enhance data transparency and reproducibility, detailed data provenance is provided in Table 1, including the original data sources with specific table references. All variables were harmonised at the municipal level. Continuous covariates were standardised prior to estimation, and the dependent variable was log-transformed for positive observations. No missing values were identified in the original datasets, and the harmonisation process (including numeric conversion and standardisation) did not introduce additional missing observations[3].

Each covariate is included based on its expected role in distinguishing structural from informational mechanisms. In the inflation component, $SF_{\_Dummy}$ and $Area\__{Pot}$ capture geographical and hydrological feasibility, as municipalities located in the São Francisco river basin or with irrigable potential are less likely to face structural constraints to irrigation. The variable $VAB_{\_AD}$, defined as a dummy equal to 1 if agricultural GVA is below the state average, is used as a proxy for low economic capacity, associated with a higher likelihood of structural constraints to irrigation. In the continuous component, assoc_coop and receb_tec reflect access to information and technical support, respectively, which facilitate irrigation adoption conditional. Finally, $VAB_{\_Agro}$ and Part_VAB capture the scale and economic relevance of agricultural activity, respectively, which are expected to be positively associated with irrigated area among municipalities with irrigation. Table 2 presents the descriptive statistics of the continuous variables employed in the model. High skewness and kurtosis indicate a concentration of low values alongside a few extreme observations, supporting the use of Student's t-distribution.

2.3. Theoretical foundations of a zero-inflated model

Following Agarwal *et al.* (2002), the observed outcome is assumed to arise from a structural-zero component and a sampling distribution for positive observations. For a base distribution $n\left(y|\theta\right)$, the zero-inflated probabilities are:

$$P\left(Y=0|p,\theta\right)=p+(1-p)n\left(0|\theta\right) \tag{1}$$

$$P\left(Y=y>0|p,\theta\right)=(1-p)n\left(y|\theta\right), y>0 \tag{2}$$

where p is the probability of excess zeros, and $(1-p)$ is the fraction following the base distribution. Covariates may influence both components of the model through separate linear predictors, typically via a log link for the continuous/count part and a logit link for the inflation probability.

$$\log\left(\lambda_i\right)=\mathscr{B}_i\beta \tag{3}$$

$$logit\left(p_i\right)=\log\left(\frac{p_i}{1-p_i}\right)=G_i\alpha \tag{4}$$

where $\mathscr{B}_i$ and G_i are vectors of covariates for the count and zero-inflation components, respectively, and β and α are the corresponding parameter vectors. In other words, λ_i represents the expected outcome (e.g., irrigated area) conditional on being in the count process, while p_i represents the probability of a structural zero. The next subsection presents the adaptation of this framework to irrigated agriculture in Minas Gerais.

[2] Given the relatively short time interval and the structural nature of the variables used (e.g., land suitability and institutional factors), this is not expected to affect the main results significantly.

[3] A diagnostic procedure was conducted to check potential inconsistencies arising from data type conversion. No additional missing values were generated after conversion.

Table 1. Summary of the selected variables.

Abbreviated name	General information	Source	Expected relationship	Variable type	Number of observations
area_irrig	Total irrigated area (hectares) per municipality	Irrigation Atlas – 2nd edition, online dataset (ANA, 2021)	Dependent variable	Continuous	853
assoc_coop	Number establishments with cooperatives/ associations per municipality	Agricultural Census (IBGE, 2019), Table 6846	Proxy for access to technology and markets; a positive relationship with irrigated area is expected	Continuous	853
receb_tec	Number of establishments receiving technical assistance per municipality	Agricultural Census (IBGE, 2019), Table 6779	Proxy for human capital structure A positive relationship with irrigated area is expected	Continuous	853
$VAB_{\_Agro}$	Gross agricultural value added (thousand R$), per municipality	IBGE (2021), Table 5938	Proxy for municipal financial capacity	Continuous	853
$Part_{\_VAB}$	Share of agriculture in gross value added [GVA] (i.e., *valor adicionado bruto* [VAB]) per municipality	IBGE (2021), Table 5938	Proxy for the relative importance of agriculture in the local economy	Continuous	853
$VAB_{\_AD}$	Dummy: 1 if agricultural GVA < state average	IBGE (2021), Table 5938	A positive relationship with structural zeros is expected	Binary	1 = 647; 0 = 206
$Area_{\_Pot}$	Dummy: 1 if the municipality has potential irrigable area	Irrigation Atlas (ANA, 2021), 2nd edition, online dataset	A negative relationship is expected, reducing the likelihood of a structural zero	Binary	1 = 529; 0 = 324
$SF_{\_Dummy}$	Dummy: 1 if located in the São Francisco river basin	Comitê da Bacia Hidrográfica do Rio São Francisco (CBHSF, 2025) (online dataset)	A positive relationship is expected, with a higher likelihood of irrigation	Binary	1 = 239; 0 = 614

Table 2. Descriptive statistics of the continuous variables used in the model.

Statistics	area_irrig	assoc_coop	receb_tec	$VAB_{\_Agro}$	$Part_{\_VAB}$
Count	853	853	853	853	853
Mean	1,341	293	186	30,952	13.42
Standard deviation	5,195	381	225	59,577	10.73
Minimum	0	0	1	44	0
25th percentile	20	58	54	5,812	6.06
50th percentile	114	165	114	12,241	10.76
75th percentile	605	376	221	30,330	18.39
Maximum	86,291	2,910	2,131	782,041	62.24
Skewness	9.92	2.95	3.11	5.95	1.44
Kurtosis	130.18	11.91	13.63	51.14	2.54

2.4. A zero-inflated model for irrigated agriculture in Minas Gerais

Let y_i denote the irrigated area (in hectares) for municipality i (I = 1, ..., n), and assume that y_i follows a zero-inflated model:

$$y_i = \begin{cases} 0 withprobability \psi_i, \\ exp\left(\widetilde{Y}_i\right), where \widetilde{Y}_i \text{~} Student - t\,(\mu_i, \sigma, v) withprobability 1 - \psi_i \end{cases} \quad (5)$$

where ψ_i denotes the probability of a structural zero. This specification corresponds to a two-part model, in which the zero outcome and the positive outcomes are modelled separately. The variable $\widetilde{Y}_i = \log(y_i)$ is defined only for municipalities with $y_i > 0$ and is assumed to follow Student's t-distribution with location μ_i, scale $\sigma > 0$, and degrees $v > 0$. The exponential transformation ensures that predictions of irrigated area remain positive. Zero-inflation probability ψ_i is linked to a set of covariates via a logistic regression:

$$\psi_i = logit^{-1}\left(X_i^{infl}\beta^{infl}\right), logit\left(\psi_i\right) = log\left(\frac{\psi_i}{1-\psi_i}\right) = X_i^{infl}\beta^{infl} \quad (6)$$

where X_i^{infl} is a vector of covariates (including an intercept) and β^{infl} is the corresponding coefficients. For municipalities where irrigation is possible ($y_i > 0$), the expected log-irrigated area is modeled as:

$$\mu_i = X_i^{cont}\beta^{cont} \quad (7)$$

where X_i^{cont} representing the standardised continuous covariates, and this component is estimated conditional on $y_i > 0$, implying a truncated likelihood for positive observations.

A Bayesian framework is adopted with weakly informative priors[4]. These priors are calibrated based on two considerations. First, the location parameters reflect the expected direction and approximate magnitude of effects, informed by descriptive statistics and preliminary regressions. In particular, the intercept is centred at a negative value to reflect the relatively low baseline probability of structural zeros. Second, Student's t-distribution provides robustness to misspecification and allows for heavier tails compared with the normal distribution, and avoids sensitivity to extreme municipalities with unusually large, irrigated areas. Therefore, two specifications are simulated. Both models share the same structure defined above but differ in the set of covariates included in the inflation component. The inflation part in Model 1 (equation 8) is formally defined as:

$$logit\left(\psi_i\right) = \beta_0 + \beta_1 SF_{Dummy_i} + \beta_2 VAB_{A_{Di}} + \beta_3 area_{pot} \quad (8)$$

where ψ_i denotes the probability of a structural zero for municipality i, SF_{Dummy_i} indicates whether the municipality belongs to the São Francisco river basin, $VAB_{A_{Di}}$ indicates whether the municipality is below the average of the agricultural GVA (Agricultural), and $area_{pot}$denotes the presence of potential area for irrigation expansion. In Model 2 (equation 9), the inflation component includes an interaction term ($SF_{interaction}$= $SF_{Dummy_i} \times area_{pot}$ which captures the joint marginal effect of being located in the São Francisco river basin and having potential irrigable area ($SF_{interaction} = 1$) defined as:

$$logit\left(\psi_i\right) = \beta_0 + \beta_1 SF_{Dummy_i} + \beta_2 VAB_{A_{Di}} + \beta_3 area_{pot} + \beta_4 SF_{interaction} \quad (9)$$

Model 2 extends Model 1 by including an interaction term between $SF_{\_Dummy}$ and $Area_{\_pot}$, allowing the analysis to capture whether the effect of irrigable potential depends on geographical location within the São Francisco river basin. This specification is intended to test for heterogeneous effects in the probability of structural zeros, particularly in regions where water availability and irrigation infrastructure may condition the role of potential irrigable area. Predicted probabilities in the inflated component are obtained by transforming the linear predictor through the logistic function $p = \frac{1}{1+\exp(-n)}$. Robustness is evaluated through 95% highest posterior density intervals (HDIs) and posterior probabilities of coefficient signs. Convergence is assessed using the $\widehat{R}$ statistic and visual inspection of trace plots, with Monte Carlo standard errors (mcse_mean and mcse_sd) and effective sample sizes (ess_bulk and ess_tail) reported for all parameters[5].

To evaluate the influence of prior choices on posterior inference, a prior sensitivity analysis is conducted by re-estimating the Model 1 under an alternative set of less informative priors. In this specification, Student's t priors originally assigned to the zero-inflation coefficients are replaced by diffuse normal[6] priors centred at zero *N*(0,2), reducing the influence of prior location assumptions. For the continuous component, the coefficient priors are unchanged, while broader priors are adopted for the scale (σ ~ HalfNormal (1)), and ((ν ~ Gamma (2,0.5)) parameters. The model structure and data remain unchanged. In addition to the zero-inflated specification, a baseline model without zero inflation is estimated for comparison purposes. This model assumes that the logarithm of irrigated area follows a normal distribution for all observations, including those with zero values, which are adjusted by a small constant to enable the logarithmic transformation. It serves as a benchmark to assess whether the additional complexity of the zero-inflated model leads to improvements in predictive performance.

Predictive performance and model comparison

Predictive accuracy is evaluated using approximate leave-one-out cross-validation (LOO) and the widely applicable information criterion (WAIC), both computed from posterior samples (Vehtari *et al.*, 2017). These criteria estimate the expected log predictive density (ELPD)

[4] For the inflation component, the coefficients are assigned Student's t priors with 3 degrees of freedom, a location vector (-2.0, -1.0, 1.5, -1.0), and scale parameters (0.5, 0.3, 0.3, 0.3). These values help stabilise estimation, particularly for the intercept and binary covariates, while still allowing sufficient flexibility.

[5] All programming scripts are available from the author upon request.

[6] The alternative normal prior specification was chosen to represent a more diffuse and less informative benchmark.

and provide a measure of how well each model is expected to predict new observations. For the zero-inflated model, the predicted probability of structural zeros is directly obtained from the posterior distribution of ψ_i. For the baseline model, which does not include a zero-generating mechanism, the predicted proportion of zeros is mechanically equal to zero. Comparing predicted and observed zero shares provides a direct test of whether the model captures the structural features of the data.

Finally, to examine heterogeneity in zero outcomes, the average predicted probability of structural zeros across different municipality types is computed, defined by key covariates such as location in the São Francisco river basin, irrigation potential, and agricultural GVA. This allows the assessment of whether zero outcomes are systematically associated with observable structural characteristics.

Spatial dependence assessment

Although the models do not include explicit spatial random effects, residual spatial autocorrelation is assessed to determine whether the included covariates adequately capture spatial patterns. To this end, local Moran's I (a local indicator of spatial association) on the residuals of the continuous component (Anselin, 1995) is used. Local Moran's I for a standardised variable *y*, observed in region *i*, z_i, can be expressed as (Almeida, 2012).

$$I_i = z_i \sum_{j=1}^{n} w_{ij} z_j \tag{10}$$

The calculation of I_i considers only the neighbors of observation i, defined according to the spatial weight's matrix w_{ij}, which in this study is specified using the queen contiguity criterion. Model estimation is performed via Markov chain Monte Carlo (MCMC) using PyMC v5.9.0 (2025), with posterior analyses conducted in ArviZ v0.16.1 for convergence diagnostics and exploratory assessment of the Bayesian results (Patil *et al.*, 2010; Kumar *et al.*, 2019). However, given that the residuals show no evidence of spatial autocorrelation, a parsimonious specification without spatial random effects is adopted.

3. RESULTS

Due to the two-part structure of the zero-inflated model, the likelihood is evaluated using only positive observations in the continuous component. As a result, the number of effective observations differs across model components, preventing direct comparison using standard model ranking procedures. Therefore, LOO and WAIC are interpreted as within-model predictive diagnostics, rather than as strict model selection criteria across specifications (Table 3). The continuous component is estimated using only positive observations ($y_i > 0$), which implies a reduced effective sample size in that component of the likelihood. This feature is intrinsic to hurdle-type models and does not reflect missing data or sample selection.

Table 3 indicates that the zero-inflated model improves predictive performance, particularly in capturing the presence of excess zeros, rather than merely providing a better in-sample fit. The sensitivity analysis indicates that the results depend on prior specification in the zero-inflation component. As discussed by Gelman (2006), priors intended to be noninformative or weakly informative can still exert a substantial influence on posterior inference. Under weakly informative priors, coefficients are well identified and consistent with theoretical expectations, and the model reproduces the observed zero share (≈20% vs 16.2%). In contrast, diffuse priors lead to weak identification, with coefficients shrinking toward zero (posterior mean ≈ 0.02) and wide credible intervals, substantially overestimating the proportion of structural zeros (≈50%). Furthermore, the zero-inflated model reveals substantial heterogeneity in predicted zero probabilities across municipality types. Predicted zero probabilities are higher outside the semi-arid region (26.1% vs 10.3%), in municipalities without irrigation potential (35.1% vs. 13.5%), and among those with lower agricultural value added (26.7% vs. 5.9%).

Table 3. Predictive performance diagnostics and zero-share reproduction across the model specifications.

Model	elpd_loo	p_loo	WAIC	P_waic	Predicted zeros	Observations
Log-normal	-2853.37	4.80	-2853.32	4.75	0.00%	853
Zero-inflated Student's t	-1386.01	8.45	-1385.97	8.41	21.67%	715
Observed	—	—			16.18%	

Note: The ELPD values are not directly comparable across the models due to different likelihood definitions and effective sample sizes.

Convergence diagnostics indicate stable MCMC performance across all specifications, with low Monte Carlo standard errors (≈0.001) and satisfactory mixing in both the central and tail regions of the posterior distributions. The inflation component models the probability of structural zeros via a logit specification, while the continuous component captures the magnitude of irrigated area conditional on positive observations. The parameter estimates for Model 1 and Model 2 are reported in Tables 4 and 5, respectively.

The intercepts provide the baseline reference for each model component. In the inflated part, the intercept of -2.007 corresponds to a baseline probability of 11.9% that a municipality is a structural zero when all predictors are held at their mean values. In the continuous part, the intercept of 5.28 indicates an expected irrigated area of approximately 196.4 hectares, given that irrigation is present.

For the inflated component, the results are presented as predicted probabilities to enhance interpretability. Belonging to the São Francisco river basin ($SF_{\_Dummy}$ = 1) reduces the probability of a structural zero from 11.9% to approximately 4.7%[7], indicating that municipalities in this basin are less likely to lack irrigation. In contrast, municipalities with agricultural GVA below the state average ($VAB_{\_AD}$ = 1) have a higher probability of being structural zeros, increasing from 11.9% to about 37.4%. The presence of irrigable area ($Area_{\_pot}$ = 1) also decreases the structural-zero probability to around 4.7%, reinforcing the importance of land suitability in reducing the likelihood of zero irrigation.

In the continuous component, covariates are standardised (mean = 0, standard deviation = 1), and the results are expressed as percentages to improve comparability across the variables. The variable assoc_coop (0.289) implies that a one-standard-deviation increase in the proportion of farmers associated with cooperatives is associated with an approximate 33%[8] increase in the log-mean irrigated area, highlighting the positive role of corporativism. The coefficient for $VAB_{\_Agro}$ (1.073) corresponds to an increase of about 192% in the expected irrigated area, revealing a strong association between agricultural GVA concentration and irrigation intensity. Finally, receb_tec shows a positive but more uncertain effect: the estimated coefficient (0.121) implies a 12.9% increase, but the posterior interval includes zero, indicating limited statistical certainty about this relationship.

Model 2 (Table 5) introduces an interaction term ($SF_{\_interação}$), identifying 194 municipalities that simultaneously belong to the São Francisco river basin and possess irrigable potential. The interaction coefficient indicates that when both conditions are jointly satisfied (São Francisco river basin and irrigable potential), the interaction term reduces the probability even further, to approximately 1.1% (-0.509), indicating a strong combined protective effect against the absence of irrigation. However, the HDI includes zero, indicating uncertainty in the effect direction in the inflation component.

In the continuous component of Model 2, the results remain consistent with those of Model 1. The presence of more associations and cooperatives is positively associated with larger irrigated areas, and municipalities receiving greater technical support also exhibit a higher irrigated area. The relative participation variable in agricultural GVA shows a positive and statistically significant effect, although smaller than the absolute GVA measure used in Model 1, likely reflecting its lower variability (see Table 1). Additionally, in Model 2, the variable receb_tec becomes statistically significant, indicating improved overall model. The increase in ν = 16 in Model 2 suggests that the interaction term captured part of the extreme variability, resulting in lighter tails compared to Model 1. Table 6 provides a summary of the predicted structural-zero probabilities for both models.

The baseline probability of a structural zero remains around 12%, but this probability drops to approximately 5% in municipalities located in the São Francisco river basin or those with potential irrigable area. In contrast, municipalities with agricultural GVA below the state average exhibit higher probabilities of structural zeros (around 38). In Model 2, the interaction term indicates that municipalities simultaneously located in the São Francisco river basin and endowed with potential irrigable area have the lowest probability of structural zeros (about 1%), suggesting a strong combined mitigating effect.

Figure 2 presents the posterior distributions of the mean probability of structural zeros (ψ_i)across municipalities in Minas Gerais to assess the predicted effects on structural zeros from Models 1 and 2. The distributions show that both models estimate a higher proportion of structural zeros than observed. Some considerations follow: (i) according to the 2017 Agricultural Census, which collected data directly from farmers, only 6% of municipalities reported no irrigation; (ii) Irrigation Atlas estimates are indirect, based on remote sensing, hydro-

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[7] With an intercept of -2.007, the baseline probability of a structural zero is (11.9%). Setting $SF_{\_Dummy}$ = 1 shifts the linear predictor from to -2.007 to -0.996, yielding (4.7%).

[8] Because the explanatory variables were standardised (mean = 0, standard deviation = 1), the interpretation is given in terms of standard deviations. For example, , meaning that an increase of one standard deviation in assoc_coop is associated with a 33.5% higher irrigated area on average. The same calculation applies to the other standardised count variables.

Table 4. Model 1 results.

Component	Variable	Mean	3% hdi	97%hdi	MCSE mean	MCSE sd	ESS bulk	ESS tail	$\widehat{R}$
Inflated part	Intercept	-2.00	-3.47	-0.56	0.013	0.012	6365	3304	1
	$SF_{\_Dummy}$	-0.99	-1.88	-0.17	0.006	0.007	8246	3521	1
	$VAB_{\_AD}$	1.48	0.61	2.37	0.007	0.005	7792	3233	1
	$Area_{\_pot}$	-1.00	-1.82	-0.20	0.005	0.005	9275	3802	1
	Intercept	5.28	5.15	5.39	0.001	0	8897	6202	1
Count part	assoc_coop	0.28	0.16	0.39	0.001	0	7605	6361	1
	$VAB_{\_Agro}$	1.07	0.89	1.25	0.001	0.001	6063	6088	1
	receb_tec	0.12	-0.01	0.25	0.001	0.001	6384	6079	1
	Sigma (σ)	1.46	1.33	1.58	0.001	0.001	5065	5359	1
	Nu (ν)	10.38	4.56	18.73	0.079	0.056	4609	4069	1

Table 5. Model 2 results.

Component	Variable	Mean	3% hdi	97%hdi	MCSE Mean	MCSE sd	ESS bulk	ESS tail	$\widehat{R}$
Inflated Part	Intercept	-1.97	-3.39	-0.468	0.009	0.008	8469	3454	1
	$SF_{\_Dummy}$	-1.00	-1.82	-0.119	0.006	0.006	8805	3681	1
	$VAB_{\_AD}$	1.48	0.63	2.374	0.007	0.005	7538	3547	1
	$Area_{\_pot}$	-0.98	-1.84	-0.063	0.007	0.008	7846	2751	1
	$SF_{\_interação}$	-0.50	-1.93	0.865	0.012	0.018	7146	3234	1
Count Part	Intercept	5.26	5.14	5.385	0.001	0.001	8503	5829	1
	assoc_coop	0.39	0.26	0.516	0.001	0.001	7562	6038	1
	$Part_{\_VAB}$	0.51	0.39	0.639	0.001	0	9162	6305	1
	receb_tec	0.51	0.38	0.657	0.001	0.001	7510	5997	1
	Sigma (σ)	1.64	1.52	1.759	0.001	0.001	6458	6583	1
	Nu (ν)	16.00	5.76	30.918	0.112	0.081	6200	5530	1

Table 6. Marginal effects on the probability scale for dummy variables in both models.

Model 1			Model 2		
Variables	Logit (n)	Predicted probability	Variables	Logit (n)	Predicted probability
Baseline	-2.007	*11.9%*	Baseline	-1.972	*12.2%*
$SF_{\_Dummy}$	-0.996	*4.7%*	$SF_{\_Dummy}$	-2.978	*4.8%*
$VAB_{\_AD}$	1.489	*37.4%*	$VAB_{\_AD}$	1.486	*38.1%*
$Area_{\_pot}$	-1.005	*4.7%*	$Area_{\_pot}$	-2.959	*4.9%*
			$SF_{\_interação}$	-4.474	*1.1%*

logical models, imputations, and other data sources, resulting in 16.8% zeros.

The discrepancy observed in Figure 2 reflects the uncertainty inherent in the 2019 dataset, which may explain why the tested models exhibit a wider posterior distribution centred around a ψ value slightly above 20%. When comparing the two models, the inclusion of the interaction variable in Model 2 results in distributions more concentrated near zero, suggesting evidence that the absence of irrigation in these municipalities is not due to structural barriers, but rather to informational constraints (institutional, policy-related, etc.).

Municipalities classified as informational zeros (low ψ) exhibit a substantially higher irrigated area, agricultural GVA, and access to technical assistance compared to those classified as structural zeros. Spe-

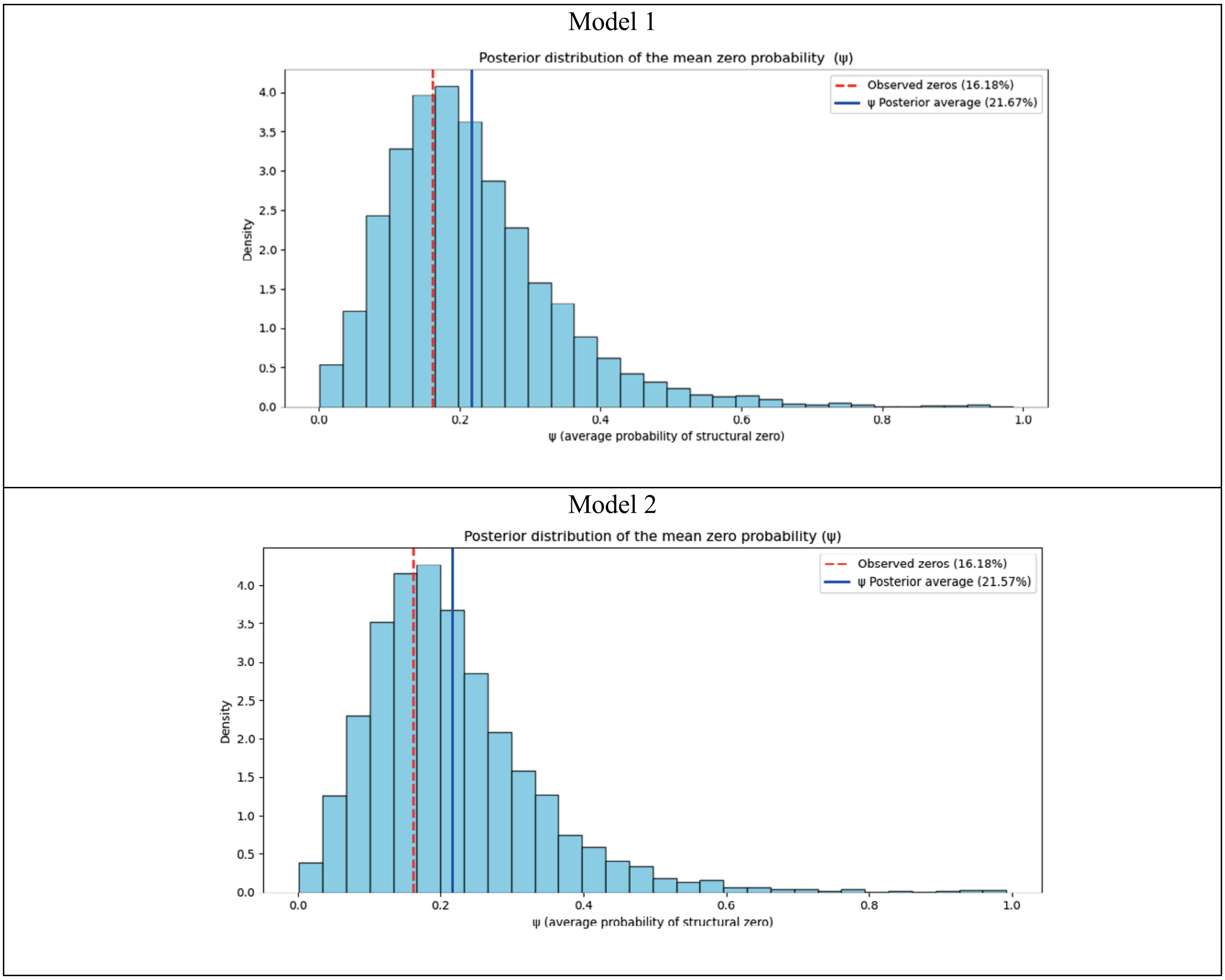


Figure 2. Posterior distribution of the mean zero probability ψ_i.

cifically, average irrigated area in informational municipalities exceeds 3,200 hectares, compared with less than 150 hectares in structurally constrained municipalities (Table 7). Similarly, agricultural value added in informational municipalities is nearly eight times higher than in structural ones.

The differences shown in Table 7 have important distributional implications. Policies targeting municipalities classified as informational zeros may disproportionately benefit regions that are already more economically dynamic and better connected to agricultural services, reinforcing existing inequalities. The results are also evaluated in terms of residual spatial dependence. Moran's I is applied to the continuous part of the model ($y > 0$) to assess whether, within this subset, the inclusion of a spatial structure could directly influence the response variable (irrigated area).

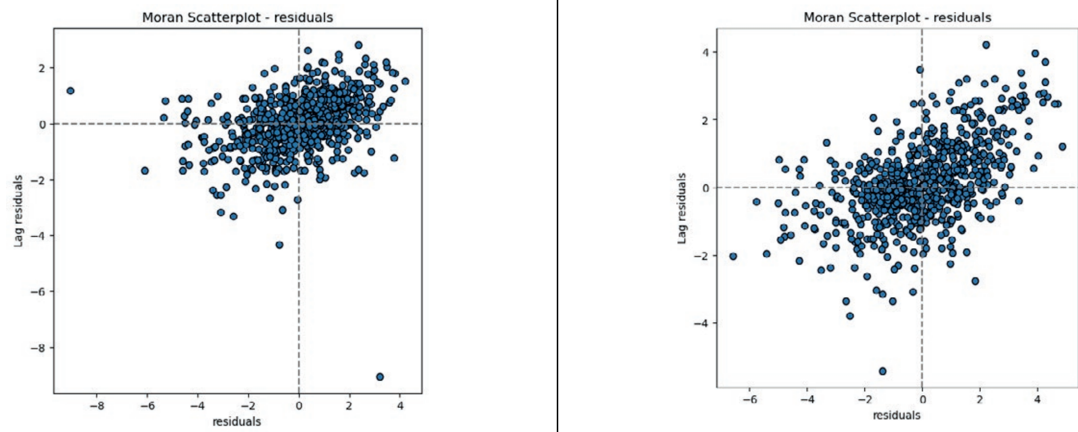
Table 7. Characteristics of municipalities by zero classification.

Zero classification	Irrigated area (hectares)	Agricultural GVA (R$)	Technical assistance (index)
Informational	3,291.68	63,136.78	284.86
Intermediate	293.59	16,184.89	148.00
Structural	146.43	8,501.61	110.38

Note: The values represent group means. Municipalities are classified according to the terciles of the predicted probability of structural zeros (ψ). Informational municipalities correspond to the lowest tercile, while structural municipalities correspond to the highest tercile.

In Model 1, there is no strong evidence of spatial clusters in the residuals, and residual autocorrelation is weak (8.39%). In Model 2, using the relative share of

Model 1	Model 2



Model 1	Model 2
High-high: 60 municipalities (8.39%)	High-high: 91 municipalities (12.73%)
Low-high: 12 municipalities (1.68%)	Low-high: 11 municipalities (1.54%)
Low-low: 43 municipalities (6.01%)	Low-low: 41 municipalities (5.73%)
High-low: 12 municipalities (1.68%)	High-low: 11 municipalities (1.54%)
Not significant: 588 municipalities (82.24%)	Not significant: 561 municipalities (78.46%)

Figure 3. Scatterplots of Moran's I for Model 1 and Model 2.

agricultural GVA instead of the absolute value variable, the results indicate an increase in residual autocorrelation (12.73%), suggesting that the adoption of an alternative regional variable could better capture the observable characteristics in the region and/or the addition of a spatial variable via a conditional autoregressive model could capture some spatial effect.

4. IMPLICATIONS FOR WATER GOVERNANCE

The distinction between structural and informational zeros has direct implications for water governance in Minas Gerais. In Brazil, water governance operates across multiple levels. At the federal level, water resources are regulated through national policies and legal frameworks. The current National Water Resources Plan (PNRH) adopts basin-level water balance assessments as an important premise for constructing management scenarios. Although the second PNRH cycle identifies the expansion of water-use permitting, significant information gaps persist.

At the basin level, watershed committees coordinate allocation and mediate conflicts among users, while at the municipal level, local governments and rural extension services facilitate access to irrigation technologies and technical support. Underestimating irrigated areas leads to systematic biases in the estimation of consumptive water demand, which in turn affects basin-level water allocation and the planning of water-use charges (Wisser *et al*., 2008). Accurate identification of irrigated areas is also essential for understanding regional water budgets and improving allocation efficiency (Kumar *et al*., 2015; Li *et al*., 2018). In basins such as that of the São Francisco River, where agricultural expansion is spatially uneven, inaccurate identification of irrigated areas can lead to systematic over-allocation or under-allocation of water (Maneta *et al*., 2009; Ferrarini *et al*., 2020; Andrade *et al*., 2024), undermining both equity and efficiency in basin governance.

The predictive results indicate that the zero-inflated model improves the representation of observed zero shares and reveals substantial heterogeneity across municipalities. Of the 139 municipalities without recorded irrigation, approximately 80 are associated with structural constraints, while 59 exhibit characteristics consistent with informational or institutional limitations. These results suggest that a non-negligible share of observed zeros reflects informational gaps rather than physical infeasibility.

These findings underscore the importance of policies that map and promote the efficient use of these areas, including financing programmes for converting rainfed agriculture into irrigable productive land, such as the National Sustainable Irrigation Program, launched under the 2025/26 family farming crop plan or with irrigation policies with cooperative support measures, such as targeted credit lines (e.g., Pronaf Cooperativo). The effectiveness of irrigation policies is often constrained by institutional barriers. The complexity of water rights allocation may limit access to water, particularly for smaller producers. This situation can be mitigated through basin-level coordination and simplified allocation procedures.

Regarding the identification of whether zeros reported in the Irrigation Atlas are structural, it is important to consider that irrigation decisions, particularly among smallholders (e.g., timing and crop choice), reflect farmers' flexibility in managing uncertainties to maximise profit and productivity. High-value perennial crops are generally water-limited, whereas decisions on annual crops involve yearly planning depending on water availability (Marques, Howitt, 2005). In Brazil, crops such as soybean, corn, wheat, and beans are often part of rotation systems to reduce costs and enhance productivity (Canalli *et al*., 2020), complicating the accurate measurement of irrigated areas.

Another relevant point is that the agricultural GVA used in this study includes both crop and livestock production, without distinguishing irrigated from rainfed agriculture. Although it is a relevant indicator of rural economic activity, it serves only as a general proxy of local agricultural dynamism and cannot isolate irrigation-specific effects. Consequently, municipalities with high GVA may have productivity concentrated in extensive livestock, which does not necessarily reflect structural irrigation conditions. These findings are consistent with this study's hypotheses. Structural factors are positively associated with the probability of structural zeros, supporting H1. In contrast, institutional and economic variables such as technical assistance and productive capacity are linked to lower probabilities of zero outcomes and characterise municipalities with informational zeros, supporting H2. Therefore, zeros reported in the Irrigation Atlas and related datasets should be interpreted cautiously, as they may indicate temporary or strategic non-use rather than permanent impossibility. Finally, while this analysis focuses on Minas Gerais, the approach and findings may inform irrigation policy design in other emerging economies with heterogeneous agricultural landscapes.

5. CONCLUSION

The results show that structural and informational zeros are associated with differences in agricultural capacity, access to technical assistance, and regional characteristics. In particular, municipalities with lower agricultural GVA and limited technical support are more likely to be classified as structural zeros, as hypothesised. Considering the discrepancy between the empirical zero share (16.8%) and the estimated posterior distribution (20%), the results suggest that the dataset may contain a substantial proportion of informational zeros, with the model compensating for data uncertainty through its statistical structure. This underscores the importance of statistical approaches capable of differentiating between structural and contextual absence of irrigation.

Despite the contributions of this study, some limitations should be acknowledged. First, irrigated area data from the Irrigation Atlas rely on remote sensing and integrated data sources, which may introduce classification uncertainties, particularly in heterogeneous and smallholder-dominated regions. Second, the agricultural GVA used in this study does not distinguish between irrigated and rainfed production, limiting its interpretation as a proxy for irrigation-specific economic performance. Third, the analysis is based on a single cross-section (2019), preventing a dynamic assessment of irrigation expansion. Fourth, the model does not incorporate infrastructure-related variables, such as water withdrawal systems or irrigation technologies, which could further refine the identification of structural constraints. Fifth, the analysis is conducted at the municipal level and does not capture within-municipality heterogeneity. Potentially relevant covariates, such as producer-level characteristics (e.g., education), are not considered in this study, although they may provide additional insights in future research. Finally, the results may be sensitive to prior specification, although robustness checks indicate that the main inferences remain stable under alternative prior choices.

Future research should incorporate additional variables to capture this informational dimension, such as the presence of irrigation projects (public or private), climatic indicators (average temperature, cumulative precipitation), intra-annual water availability, and measures of local governance. This study highlights the relevance of the Irrigation Atlas for improving public datasets and integrating technical information on irrigated agriculture in Brazil. Recognising that many zeros are not definitive allows targeting interventions where they can have the greatest impact, such as in designated irrigation clusters.

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REFERENCES

Abou Zaki N., Kløve B., Torabi Haghighi A. (2022). Expanding the irrigated areas in the MENA and Central Asia: challenges or opportunities? *Water*, 14(16), 2560. DOI: https://doi.org/10.3390/w14162560.

Agarwal D.K., Gelfand A.E., Citron-Pousty S. (2002). Zero-inflated models with application to spatial count data. *Environmental and Ecological Statistics*, 9: 341-355. DOI: https://doi.org/10.1023/A:1020910605990.

Agência Nacional de Águas e Saneamento Básico (ANA) (2021). *Atlas da irrigação: uso da água na agricultura irrigada*, Agência Nacional de Águas e Saneamento Básico, Brasília. https://metadados.snirh.gov.br/geonetwork/srv/api/records/1b19cbb4-10fa-4be4-96db-b3dcd8975db0.

Almeida E. (2012). *Econometria especial aplicada*. Alínea, Campinas-SP.

Altchenko Y., Villholth K.G. (2015). Mapping irrigation potential from renewable groundwater in Africa–a quantitative hydrological approach. *Hydrology and Earth System Sciences*, 19(2): 1055-1067. DOI: https://doi.org/10.5194/hess-19-1055-2015.

Andrade C., de Souza I., da Silva L. (2024). The future sustainability of the São Francisco River Basin in Brazil: a case study. *Sustainability*, 16(13): 5521. DOI: https://doi.org/10.3390/su16135521.

Asfaw Eshetu A., Mekonen A.A. (2024). Determinants of small-scale irrigation adoption in drought-prone areas of northcentral Ethiopia in the context of climate change. *Frontiers in Climate*, 6: 1410527. DOI: https://doi.org/10.3389/fclim.2024.1410527.

Baiardi A., Ribeiro M.C.M. (2023). Eficiência da gestão da agricultura irrigada no Vale do São Francisco: uma análise comparativa no polo regional Petrolina-Juazeiro. *Colóquio – Revista do Desenvolvimento Regional*, 20(3): 28-51. DOI: https://doi.org/10.26767/coloquio.v20i3.2788.

Barros Jr F., Ferreira A.L., Marcondes R.L., Prioste R.R.W. (2019). Coffee exports and industrialization in Brazil. *Applied Economics Letters*, 26(9): 712-716. DOI: https://doi.org/10.1080/13504851.2018.1489498.

Birkhaeuser D., Evenson R.E., Feder G. (1991). The economic impact of agricultural extension: a review. *Economic Development and Cultural Change*, 39(3): 607-650.

Canalli L.B. dos S., Costa G.V., Volsi B., Leocádio A.L.M., Telles T.S. (2020). Production and profitability of crop rotation systems in southern Brazil. *Semina: Ciências Agrárias*, 41(6): 2541-2554. DOI: https://doi.org/10.5433/1679-0359.2020v41n6p2541.

Comitê da Bacia Hidrográfica do Rio São Francisco (CBHSF) (2025). *A bacia: municípios da bacia*, Comitê da Bacia Hidrográfica do Rio São Francisco, Belo Horizonte. https://cbhsaofrancisco.org.br/a-bacia/#municipios-da-bacia.

Cremades R., Wang J., Morris J. (2015). Policies, economic incentives and the adoption of modern irrigation technology in China. *Earth System Dynamics*, 6(2): 399-410. DOI: https://doi.org/10.5194/esd-6-399-2015.

Da Silva H.B.C. (2001). *Agricultural extension and farmer participation in Southern Brazil*, Doctoral dissertation, University College London. https://discovery.ucl.ac.uk/id/eprint/10102551/.

Da Silva V.D.P.R., De Oliveira S.D., Hoekstra A.Y., Dantas Neto J., Campos J.H.B., Braga C.C., De Holanda R.M. (2016). Water footprint and virtual water trade of Brazil. *Water*, 8(11): 517. DOI: https://doi.org/10.3390/w8110517.

Desta H.S. (2024). Modelling land suitability and development potential options for irrigable and rainfed agricultural scenarios in Ethiopia. *Irrigation and Drainage*, 73(3): 1168-1191. DOI: https://doi.org/10.1002/ird.2929.

Dhoubhadel S.P., Ridley W., Devadoss S. (2023). Brazilian soybean expansion, US–China trade war, and US soybean exports. *Journal of the Agricultural and Applied Economics Association*, 2(3): 446-460. DOI: https://doi.org/10.1002/jaa2.71.

Ferrarini A.S.F., Ferreira Filho J.B.S., Cuadra S.V., Victoria D.C., Horridge M. (2019). The expansion of irrigated agriculture in Brazil and potential regional limitations. In Wittwer G. (eds.) *Economy-Wide Modeling of Water at Regional and Global Scales* (pp. 139-157). Singapore: Springer. DOI: https://doi.org/10.1007/978-981-13-6101-2_7.

Ferrarini A.S.F., Ferreira Filho J.B.S., Cuadra S.V., Victoria D.C. (2020). Water demand prospects for irrigation in the São Francisco River: Brazilian public policy. *Water Policy*, 22(3): 449-467. DOI: https://doi.org/10.2166/wp.2020.215.

Fritsch O., Benson D. (2024). Introduction to the handbook on the governance and politics of water resources. In Fritsch O., Benson D. (eds.) *Handbook on the Governance and Politics of Water Resources* (pp. 2-9). Cheltenham, UK: Edward Elgar Publishing. DOI: https://doi.org/10.4337/9781800887909.00008.

Gautam T.K., Paudel K.P., Guidry K.M. (2024). Determinants of irrigation technology adoption and acreage allocation in crop production in Louisiana, USA. *Water*, 16(3): 392. DOI: https://doi.org/10.3390/w16030392.

Gelman A. (2006). Prior distributions for variance parameters in hierarchical models. *Bayesian Analysis*, 1(3): 515-534. DOI: https://doi.org/10.1214/06-BA117A.

Governo de Minas Gerais (2020). *Geografia*, Governo de Minas Gerais, Belo Horizonte. https://www.mg.gov.br/pagina/geografia.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2019). *Censo Agropecuário 2017*, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017/resultados-definitivos.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2021). *Produto Interno Bruto dos Municípios*, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro. https://sidra.ibge.gov.br/pesquisa/pib-munic/tabelas.

Kumar S.V., Peters-Lidard C.D., Santanello J.A., Reichle R.H., Draper C.S., Koster R.D., Nearing G., Jasinski M.F. (2015). Evaluating the utility of satellite soil moisture retrievals over irrigated areas. *Hydrology and Earth System Sciences*, 19(11): 4463-4478. DOI: https://doi.org/10.5194/hess-19-4463-2015.

Kumar R., Carrol C., Hartikainen A., Martin O. (2019). ArviZ: a unified library for exploratory analysis of Bayesian models in Python. *Journal of Open Source Software*, 4(33): 1143. DOI: https://doi.org/10.21105/joss.01143.

Lambert D. (1992). Zero-inflated Poisson regression, with an application to defects in manufacturing. *Technometrics*, 34(1): 1-14. DOI: https://doi.org/10.1080/00401706.1992.10485228.

Li X., Cheng G., Lin H., Cai X., Fang M., Ge Y., Hu X., Chen M., Li W. (2018). Watershed system model: the essentials to model complex human-nature system at the river basin scale. *Journal of Geophysical Research: Atmospheres*, 123: 3019-3034. DOI: https://doi.org/10.1002/2017JD028154.

Machado R.L., da Cruz T.V. (2022). An empirical approach analyzing the socioeconomic sustainability of the international sugarcane trade. *Sustainability*, 14(4): 2198. DOI: https://doi.org/10.3390/su14042198.

Maneta M.P., Torres M., Wallender W.W., Vosti S., Kirby M., Bassoi L.H., Rodrigues L.N. (2009). Water demand and flows in the São Francisco River Basin (Brazil) with increased irrigation. *Agricultural Water Management*, 96(8): 1191-1200. DOI: https://doi.org/10.1016/j.agwat.2009.03.008.

Marques G.F., Lund J.R., Howitt R.E. (2005). Modeling irrigated agricultural production and water use decisions under water supply uncertainty. *Water Resources Research*, 41(8). DOI: https://doi.org/10.1029/2005WR004048.

Multsch S., Krol M.S., Pahlow M., Assunção A.L., Barretto A.G., De Jong van Lier Q., Breuer L. (2020). Assessment of potential implications of agricultural irrigation policy on surface water scarcity in Brazil. *Hydrology and Earth System Sciences*, 24(1): 307-324. DOI: https://doi.org/10.5194/hess-24-307-2020.

Ng'ombe J.N., Kabwela B., Kiwanuka-Lubinda R.N., Addai K.N. (2022). A Bayesian zero-one inflated beta modeling of dairy farmers' decision to sell nothing or some output through contract farming. *Q Open*, 2(1): qoac015. DOI: https://doi.org/10.1093/qopen/qoac015.

Nguyen T.T., Nguyen T.T., Le V.H., Managi S., Grote U. (2020). Reported weather shocks and rural household welfare. *Weather and Climate Extremes*, 30: 100286. DOI: https://doi.org/10.1016/j.wace.2020.100286.

Nhamo L., Mpandeli S., Liphadzi S., Dirwai T.L., Mugiyo H., Senzanje A., Mabhaudhi T. (2024). Why do farmers not irrigate all the areas equipped for irrigation? Lessons from Southern Africa. *Agriculture*, 14(8): 1218. DOI: https://doi.org/10.3390/agriculture14081218.

Nohamba S.O., Musara J.P., Bahta Y.T., Ogundeji A.A. (2022). Drivers of postharvest loss among citrus farmers in Eastern Cape Province of South Africa: a zero-inflated Poisson regression model analysis. *Agriculture*, 12(10): 1651. DOI: https://doi.org/10.3390/agriculture12101651.

Ortiz-Bobea A. (2021). The empirical analysis of climate change impacts and adaptation in agriculture. In Barrett C.B., Just D.R. (eds.) *Handbook of Agricultural Economics*, Vol. 5 (pp. 3981-4073) Amsterdam, Netherlands: North-Holland/Elsevier. DOI: https://doi.org/10.1016/bs.hesagr.2021.10.002.

Patil A., Huard D., Fonnesbeck C.J. (2010). PyMC: Bayesian stochastic modelling in Python. *Journal of Statistical Software*, 35: 1-81. DOI: https://www.jstatsoft.org/article/view/v035i04.

Playán E., Sagardoy J.A., Castillo R. (2018). Irrigation governance in developing countries: current problems and solutions. *Water*, 10(9): 1118. DOI: https://doi.org/10.3390/w10091118.

PyMC (2025). Probabilistic programming library for Python, PyMC Labs, Dublin. https://www.pymc.io/projects/examples/en/latest/spatial/conditional_autoregressive_priors.html.

Smilovic M., Gleeson T., Siebert S. (2015). The limits of increasing food production with irrigation in India. *Food Security*, 7(4): 835-856. DOI: https://doi.org/10.1007/s12571-015-0477-2.

Vehtari A., Gelman A., Gabry J. (2017). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing*, 27: 1413-1432. DOI: https://doi.org/10.1007/s11222-016-9696-4.

Visentin J.C., Guilhoto J.J.M. (2019). The role of inter-regional trade in virtual water on the blue water footprint and the water exploitation index in Brazil. *Review of Regional Studies*. DOI: https://doi.org/10.52324/001c.10168.

Wisser D., Frolking S., Douglas E.M., Fekete B.M., Vörösmarty C.J., Schumann A.H. (2008). Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets. *Geophysical Research Letters*, 35(24). DOI: https://doi.org/10.1029/2008GL035296.

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Research article

Using the Analytic Hierarchy Process to prioritise criteria to enhance AquaCrop from the user perspective

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Abstract. The successful advancement of precision agriculture depends on the availability of agrometeorological and agroclimatic data with high spatiotemporal resolution. However, such data must also be high quality, consistent, and nationally valid, allowing for long-term model calibration and short-term decision support systems. This study explores potential improvements to AquaCrop, a widely used crop water productivity model developed by the Food and Agriculture Organization, by incorporating feedback from interviewees to enhance its applicability and to promote more sustainable water resource use. Interviewees (farmers, researchers, and information technology experts) were surveyed using structured questionnaires, and responses were analysed through the Analytic Hierarchy Process (AHP) using the Super Decisions software. A three-level hierarchical model was developed to assess and prioritise desirable model features. The results demonstrate that the AHP effectively captures user needs and identifies concrete areas for model improvement. Notably, the criterion related to data management (C3) emerged as a key priority, particularly the capability for automatic communication with external Internet of Things platforms. This study emphasises the importance of involving both users (farmers and researchers) and information technology experts in evaluating the technical feasibility of proposed upgrades. The significant preference weights expressed by farmers (0.15) and researchers (0.18) further underscore the importance of aligning model development with real-world operational needs.

Keywords: decision making process, strategic planning, irrigation, crop production models, water management.
JEL codes: Q25, Q54, Q55.

HIGHLIGHTS

- This study is organised into five sections to ensure rigorous implementation of the Analytic Hierarchy Process for the assessment and enhancement of the AquaCrop model.
- User-centred model improvement: this study highlights the importance of user feedback in improving AquaCrop, a widely used crop water productivity model.
- Collaborative approach to software development: collaboration between users, information technology experts and professionals with deep knowledge of software modelling underlines a holistic approach to software development.

1. INTRODUCTION

Crop production simulation models simulate the growth and development of a given crop and estimate its production capacity under different environmental and agronomic conditions. Since the 1990s, these models have become increasingly common in the research sector as well as in agronomic studies (Giardini, 2012). Currently, there are various crop models with different levels of detail, scale, and representativeness, including DSSAT, WOFOST, EPIC, CropSyst, and STICS (Rauff, Bello, 2015; Kasampalis *et al.*, 2018; Chapagain *et al.*, 2022; Garofalo *et al.*, 2025). Among these crop growth simulation models, AquaCrop focuses on water productivity and can be used: (i) to plan irrigation strategies to improve water use and productivity in agricultural production; (ii) to address increasing competition for scarce freshwater resources by optimising consumption; and (iii) to increase profitability by improving the ability of farmers to use water more productively, especially in situations of water scarcity. AquaCrop was launched by the Land and Water Division of the Food and Agriculture Organization (FAO) in 2009 (Steduto *et al.*, 2009). This highly accurate and simple to use model incorporates simulations of crop responses – including yield, biomass accumulation, and water productivity – under different water availability scenarios. These attributes have contributed to its broad acceptance among both researchers and practitioners, who employ it as a decision support tool for the formulation and implementation of efficient water management strategies in routine agricultural practice (Roja *et al.*, 2023). Although there are many advantages to using the AquaCrop model, there are also disadvantages. Indeed, AquaCrop comes as pre-compiled software with an intuitive user interface, but this structure limits customisation, preventing users from directly intervening in the code to adapt the model to specific needs (Vanuytrecht *et al.*, 2014; Foster *et al.*, 2017).

Recent research in crop growth modelling has focused mainly on the calibration steps, defined as the standard practice of estimating crop parameters based on field observations (Seidel *et al.*, 2018; Ahmed, 2020; Winn *et al.*, 2023). Substantial efforts have also been made to collect useful data on different environmental conditions and crop management practices(Steduto *et al.*, 2009). The primary objective of this study is to investigate and enhance the usability of the AquaCrop model, with particular emphasis on its capacity to simulate crop growth and water productivity. To achieve this objective, it was essential to identify potential areas for improvement in the model through a comprehensive analysis of the feedback and preferences provided by researchers, farmers (end-users), and information technology (IT) developers (technical experts).

As highlighted by many studies in the field of soil and water assessment (AbdelRahman *et al.*, 2025; Ali *et al.*, 2025), decision support services in agriculture increasingly rely on multicriteria analysis tools, particularly for identifying and prioritising the spatial data required to develop effective agricultural policies. These approaches enable the management of the inherent complexity of agro-environmental systems by integrating physical, climatic, socio-economic, and land management variables into a coherent and structured decision-making framework. Despite these advances, a methodological gap remains regarding the ability of decision support models to fully address the needs of stakeholders who rely on these tools. Specifically, the literature highlights a lack of alignment between the prioritisation of spatial and environmental data and the operational and strategic requirements of decision-makers in the agricultural sector.

This study contributes to the existing literature through the application of the Analytic Hierarchy Process (AHP) in three ways. First, the results of this study can serve as a suggestion to the various stakeholders, managers and private sector involved in planning crop growth models. Second, the detailed analysis of the barriers identified by the users in the implementation of AquaCrop carried out here contributes to fill the existing gap in the literature and to help the academicians/researchers working in this field. Finally, this study identifies the preferences related to the use of the model and ranks them according to their degree of relevance. The AHP is employed to structure and clarify the relationships and relative importance among key factors influencing the improvement of decision support tools in precision agriculture, as exemplified by the AquaCrop model. Given that the successful advancement of precision agriculture relies heavily on high-quality, consistent, and high-resolution agrometeorological and agroclimatic data, it is essential to systematically evaluate both technical and user-oriented requirements.

This paper is divided into five sections. Section 1 provides the introduction and general overview of crop simulation models. Section 2 presents the key features of AquaCrop and its relevance to policy development. Section 3 outlines the research methodology used to prioritise criteria and sub-criteria. Section 4 discusses data analysis and results. Finally, Section 5 concludes the paper with theoretical and practical implications, as well as the limitations of this study.

2. THE ROLE OF AQUACROP IN POLICY DEVELOPMENT

To clarify the policy implications of this study, it is appropriate to specify which aspects of the new Common Agricultural Policy (CAP) of the European Union this paper aims to support. As described by Knierim, Birke (2023), the CAP for 2023-2027 enhances a key element, the concept of Agricultural Knowledge and Innovation System (AKIS), which refers to the cooperation of actors from extension, research, professional organisations, and other stakeholders in the sector (Labarthe, European Seminar on Extension & Education (26 : 2023 : Toulouse), 2023; Sutherland *et al.*, 2023). Knowledge, innovation, and technical education, including the provision of services to farmers, represents a transversal goal, together with the objective of simpler, more transparent, and effective policy (De Castro *et al.*, 2020). As Van Oost, Vagnozzi (2020) point out, AKIS is a rather complex bundle where research and innovation link with practice and connect with farmers and other operators through the support of farmers' organisations, advisors, private companies, education systems, digital tools, and data and knowledge sharing. Synergies are expected to develop among the different components involved in AKIS, with the ultimate goal of providing the agricultural business system more tools for sustainable economic development (Proietti, Cristiano, 2023; Sutherland *et al.*, 2023). Building on this framework, the goal of this study is reinforced by its focus on providing timely and relevant information to support innovation processes. In particular, it underscores the role of agricultural extension services as essential knowledge providers, with AquaCrop serving as a practical example of how decision support tools can enhance service delivery. To reflect the AKIS approach, this study involves three categories of interviewees: researchers, farmers (users), and IT developers (experts).

AquaCrop is a strategic decision support tool for agricultural and environmental policies addressing water scarcity and climate change. By supporting efficient water allocation, climate adaptation, and sustainable crop management, this model provides policymakers with robust evidence to design resilient and resource-efficient agricultural systems (Figure 1) (García-Vila *et al.*, 2009; Heng *et al.*, 2009; Raes *et al.*, 2009; Steduto *et al.*, 2009; Altobelli, Henke, 2024).

3. RESEARCH METHODOLOGY

This study was conducted in three sequential phases, as illustrated in Figure 2. Phase I involved selection of criteria and sub-criteria through a general survey to establish the hierarchical structure of the AHP. This

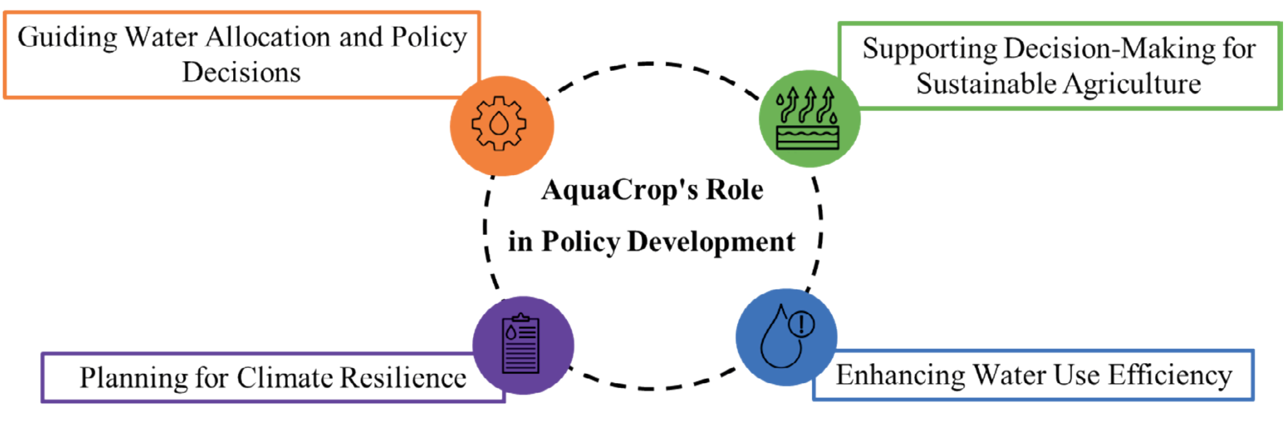

Figure 1. The role of AquaCrop in policy development.

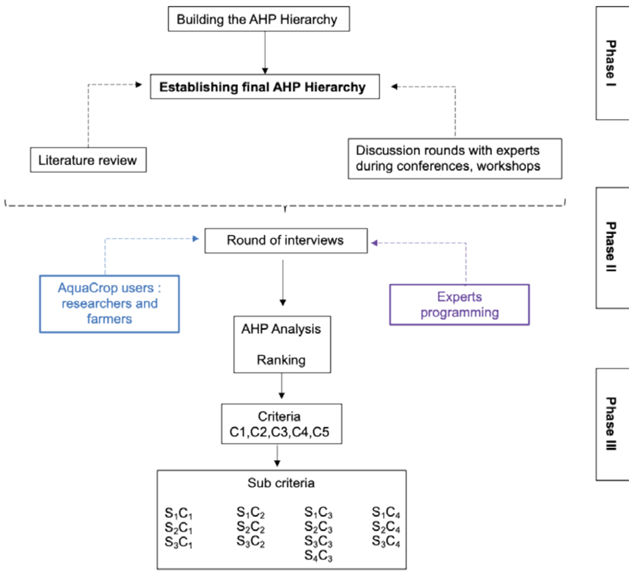

Figure 2. The research methodology summarised in three phases.

preparatory phase had three main objectives: (i) to conceptualise research objectives, (ii) to define AHP criteria and sub-criteria, and (iii) to determine the format of the questions. Phase II comprised the selection and invitation of experts. During four international meetings, experts in agricultural forecasting models presented and discussed their results. Researchers and professors met to discuss future challenges in the sector. By participating in these conferences, frameworks, and meetings, which will be presented later, the authors of this work were able to discuss with respondents from the academic and the research community. Finally, Phase III involved calculation of the weight of each criterion and sub-criterion, by applying the AHP.

According to the literature, to guarantee that the AHP analysis is consistent, it is necessary to ensure proper structuring of the hierarchy and selection of the criteria and sub criteria that are most appropriate to the goal of the hierarchy (Saaty, Vargas, 2012). Phase I was crucial to ensure inappropriate criteria were not selected.

As documented in the literature, the AHP does not require large sample sizes to produce reliable and meaningful results, as it is based on structured pairwise comparisons rather than statistical inference. The robustness of AHP outcomes depends primarily on the expertise of the respondents and the internal consistency of their judgments, rather than on the number of participants involved. Several studies have shown that small panels of well-selected experts are sufficient, and often preferable, when the objective is to elicit informed preferences and priorities in complex decision-making contexts(Cay, Uyan, 2013; Elolu *et al.*, 2025). In this study, the authors decided to involve 10 participants for the stakeholder group to ensure a balance between diversity of perspectives and high consistency of pairwise comparisons, which was confirmed by a consistency ratio below the accepted threshold (< 0.1) for all matrices. This approach is consistent with previous AHP applications in agriculture and natural resource management, where expert samples of similar size have been successfully employed.

3.1. Application of the AHP

The AHP is a method of multi-criteria decision analysis developed by Thomas Saaty in the late 1970s. One of the fundamental determinants to ensure the AHP is used effectively – so that decisions are made under conditions of multi-criteria certainty– is that the decision-maker must have complete information about the decision environment and the consequences of the decision alternatives. The AHP also includes steps for measuring the consistency of judgments called the consistency ratio. A value of 0 means that there is perfect consistency, a value < 0.1 ensures that the judgments are consistent and reliable, and values > 0.1 indicate inconsistency (Benítez *et al.*, 2012; Lane, Verdini, 2007). There are two main sources of inconsistency: the method of structuring the model and criteria considered, and the questionnaire administration method. There is extensive published information on the mathematical foundations of the AHP (Saaty, Ozdemir, 2003; Ishizaka, Lusti, 2006; Ishizaka, Labib, 2009, 2011; Ishizaka *et al.*, 2011, 2012). Therefore, this section provides a brief overview of the steps taken to obtain the weights needed to determine the AquaCrop improvement scenario.

Close collaboration within a well-connected research network significantly accelerated the development of the hierarchical structure of the AHP analysis, enabling rapid consultation with most experts and achieving a high response rate. However, as suggested by (Beiderbeck *et al.*, 2021), research teams should be aware of potential biases and homogeneous thinking within a narrow network. Thus, interaction with experts took place over several rounds during the year and in different contexts. Several researchers were invited to comment on the criteria and subjectivities identified in the next steps of the analysis. In particular, they were first invited to share their experiences of using crop growth models through open-ended questions, focusing on the use of AquaCrop when requested. The first objective of the formulation sessions was not to define the final set of statements that would be required in the second step of the AHP, but rather to collect related information, and to choose the AHP interview format and key questions that led to the definition of the criteria and sub-criteria. The main scientific initiatives that drove the development of this phase of the work are briefly outlined below and summarised in Table 1.

To identify an appropriate structure on which to base the hierarchical structure of the AHP content, the criteria and sub-criteria were selected through a literature review, expert interviews, brainstorming, and group discussions among researchers. In addition, there was extensive consultation with software programmers. Four rounds of expert consultation were conducted through face-to-face brainstorming. This was a fundamental step in collecting the responses, which were then categorised into preferences. Three types of experts, two of them users, were consulted.

- Farmers: the sample consisted of 10 farmers selected from the AquaCrop section workshops. The FAO has published a list spanning from July 2009 to July 2020 (https://www.fao.org/aquacrop/workshops/archive/en/#c668638 accessed on 23 August 2025) of the initiatives it has organised to disseminate knowledge and use of the software among interested parties. International and local partners are involved to train participants in the practical applications of AquaCrop, including strategic management to increase crop water productivity. After completing these courses, participants can train other users in their countries.
- Researchers: a total of 10 researchers were contacted. After each interview, members of the research team reviewed the results to ensure the consistency of the AHP pairwise comparison matrix.
- IT experts: one interview session involved 10 computer scientists. Their expertise in software selection and programming was fundamental to this study. The main objective of the survey was to evaluate the ease of integration of the operations, proposed to the users (researchers and farmers) of the AquaCrop model.

While constructing the hierarchy, the environment surrounding the goal was considered with sufficient relevant detail to fully represent the problem. Assessing the issues and attributes that influence the solution, identifying the stakeholders involved, and incorporating user perspectives in the improvement of AquaCrop constituted the main steps in constructing the hierarchical model. As suggested by Saaty (2004), organising goals, attributes, issues, and actors into a hierarchy serves three primary purposes: it provides a holistic view of the problem, enables decision-makers to compare elements of similar weight or impact, and captures the distribution of influence from the most significant criteria to the least significant. There are several types of hierarchies depending on the arrangement of goals, attributes, and stakeholders in the analysis (Forman, 1993). Hierarchies can be structured as forward or backward planning. This study used a forward planning hierarchy, descend-

Table 1. Network of research activities for the selection of AHP criteria and sub-criteria.

Key events used to construct the hierarchical structure of the AHP and to select participants	
The Global Framework on Water Scarcity in Agriculture (WASAG)	To develop the research question for this study, the authors consulted experts at the 2nd International Forum on Water Scarcity in Agriculture 'Making Agriculture Resilient to Climate Change: Water Scarcity'. The Forum aimed to share relevant knowledge and information on key issues; to network and foster collaboration among partners; and to showcase the latest technologies, practices, and products in agriculture. WASAG brings together key players from all over the world and from different sectors. This partnership is hosted by the FAO and consists of government agencies, international organisations, research institutions, stakeholders, and professional associations to develop and implement policies, strategies and programmes to adapt agriculture to water scarcity on the ground.
Innovation for Drought and Agriculture (FAO – IRI)	Innovation in drought management and agriculture were the key topics discussed during the session. Experts presented participatory and innovative tools, methods, and approaches essential for effective drought management in agriculture. Additionally, they showcased research activities related to the application of agronomic models.
Conference on micrometeorological measurements – Urban microclimate monitoring and agricultural meteorology for climate change (FAIRNESS)	The debate was developed around the exchange of experiences and projects presented by international research centres and universities with the aim of improving the standardisation and integration between databases/sets of micrometeorological measurements, including crop growth prediction models. On this occasion, it was possible to review publications and research activities related to the use of AquaCrop in complex climatic-environment contexts.
The Global Symposium on Soils and Water (GSOWA23)	On this occasion, the most relevant aspects for this manuscript were the technical sessions related to soil and water management, applications of data remote sensing innovations, database for monitoring evapotranspiration, topics on which the functioning of the AquaCrop model is also based.

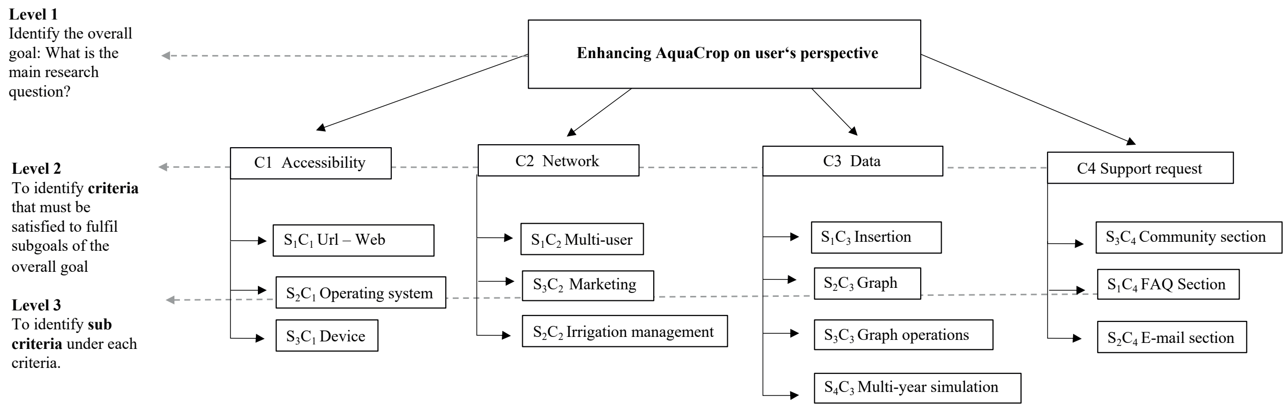

Figure 3. The three levels of the hierarchical structure of the AHP.

ing from the main objective to criteria and sub-criteria. It incorporated exploratory scenarios based on stakeholders' weighted judgments, which guided the optimisation of the AquaCrop model and are discussed in the results section. In this study, questionnaires were distributed to AquaCrop users to achieve the objective outlined above. The AHP was used here solely to assess the relative importance of criteria and sub-criteria, in line with Saaty's approach (Saaty, 1987, 2008). Unlike traditional AHP applications that involve comparing alternatives, this study focused exclusively on structuring and prioritising the criteria and sub-criteria, a methodology also adopted by De Felice, Petrillo (2013).

To improve the performance of the AquaCrop model, a three-level hierarchical network was developed for the selection of features and functions (Figure 3). The first level – focus – has a single objective: to improve the use of AquaCrop to best meet user needs. The second level consists of four criteria (C1-C4) that specify the content and meaning of the focus. The criteria are compared in pairs to determine the criterion with the most relevant weight based on the participants' answers. The third level corresponds to the sub-criteria, which represent the functionalities with the materialised criteria. The relative priorities between the sub-criteria are also established through pairwise comparisons, as for the second level. The criteria and sub-criteria are summarised in Table 2.

4. RESULTS AND DISCUSSION

The AHP was applied to identify and prioritise criteria for improving the usability of the AquaCrop model, to better meet the needs of users. The analysis incorporated judgments from 30 participants, including 20 end users (farmers and researchers) and 10 IT experts. The results are based on pairwise comparisons conducted across all defined criteria and sub-criteria.

Beyond eliciting user preferences, IT experts assessed the operability and technical feasibility of the criteria and sub-criteria identified by users. The resulting hierarchy, referred to as the 'classification of criteria operability', shows a high degree of consistency with the user-derived hierarchies. This alignment indicates that the most critical user requirements are largely achievable from a technical perspective, strengthening the validity of the prioritisation results and supporting their use as a decision-making framework for future AquaCrop development. From a broader perspective, this consistency highlights the central role of AquaCrop as a reference crop model for irrigation planning and assessment of water productivity. The wide adoption of the AquaCrop model in research and operational contexts makes usability, accessibility, and data management key conditions to maximise its impact as a decision support tool.

The results of the questionnaires were analysed using Excel and the open-source software package Super Decisions (https://www.superdecisions.com/, accessed on 20 October 2023). The priority weights of all criteria and sub-criteria were calculated and then combined in each matrix to obtain a global priority vector. Based on the previous experience (Donati *et al.*, 2023), the authors decided to split the sample by dividing the stakeholder group into users (farmers and researchers) and programming experts. In addition, they decided that instead of using a postal survey, they would meet with experts to explain the importance of pairwise comparisons in multi-criteria AHP analysis and to ensure that the participants were fully aware and understood the criteria they had to compare. This procedure reduced the possibility of inconsistent production between the elements of the

Table 2. Description of the criteria and sub-criteria used in the hierarchical structure of the AHP.

Criterion	Description	Sub-criterion	Description
C1	Accessibility	S_1C_1	**URL – Web:** the end user will not be required to install any software on their PC in order to access the service
		S_2C_1	**Operating system compatibility:** installing a model compatible with iOS and Windows on the user's computer
		S_3C_1	**Devices:** implementation of a user interface that facilitates simplified access from smartphones and tablets, such as an app
C2	Network	S_1C_2	**Multi-user:** enables multiple operators to access the same data at the same time
		S_2C_2	**Irrigation management:** sharing information related to the irrigation management conducted by the company with the assistance of AquaCrop
		S_3C_2	**Marketing:** a consultation-only section is proposed for AquaCrop company projects in order to communicate externally the value of sustainable water use achieved
C3	Data	S_1C_3	**Input:** reduction of the amount of data that the user must enter into the model (for crop calibration, irrigation management, and soil characteristics). It is possible to configure the system to communicate automatically with an external Internet of Things platform.
		S_2C_3	**Graph:** the user can obtain at the end of the crop cycle the final production and the total irrigation volume
		S_3C_3	**Graph operations:** it will be possible to carry out five different operations on one graph
		S_4C_3	**Multi-year simulation:** the creation of graphs that can be used to compare different agricultural years and irrigation scenarios
C4	Support request	S_1C_4	**Frequently asked questions (FAQs):** developing a list of questions and answers prepared on the most common problems encountered when using the model, which can be accessed by clicking on the icon
		S_2C_4	**Email section:** reports from users of answers that are not available in FAQs are collected through email support
		S_3C_4	**Community section:** a website equipped with a platform function that allows users to ask and answer questions through registration and active participation.

Table 3. The weights of criteria grouped according to the farmers' judgements.

Goal	Criterion	Weight of the criterion	Final ranking
Enhance the use of AquaCrop to best meet user needs	C1 – accessibility	0.72	1
	C2 – network	0.15	2
	C3 – data	0.07	3
	C4 – support request	0.05	4

pairwise comparison matrix (indicating a degree of randomness in the participants' answers). The consistency ratios for the matrices were < 0.1, indicating consistency in the judgements.

For the farmers, the weights ranged from 0.05 for criterion C4 (support request) to 0.72 for criterion C1 (accessibility) (Table 3). According to the farmers (Figure A.1) from the sub-criteria analysis, sub-criteria S_1C_3 had a priority value of 0.69: to improve the use of AquaCrop, it is necessary to reduce the amount of data that the user must enter into the model (for crop calibration, irrigation management, and soil characteristics). This outcome clearly reflects the dual nature of AquaCrop: on the one hand, its strength lies in process-based simulation of crop-water relationships; on the other hand, its practical adoption is strongly conditioned by the availability, quality, and complexity of required inputs. The high priority attributed to data simplification confirms that enhancing usability is crucial to fully exploit AquaCrop's robustness beyond expert-driven research applications. Sub-criteria S_1C_2 and S_2C_4 each had a priority value of 0.79. This result is consistent with recent AquaCrop-based applications where simplified parameterisation strategies and predefined datasets proved essential to broaden model adoption and to support on-farm irrigation decisions while preserving simulation reliability (Garofalo *et al.*, 2025).

Table 4 shows the weightings for the researchers. According to them, criterion C2 is not as relevant as criterion C1. In general, the farmers' and researchers' were similar, but with a clear difference in the weighting between the most and least important criteria. Nevertheless, data and accessibility are very important for the implementation of the AquaCrop model for both farmers and researchers. On the other hand, the most important

Table 4. The weights of the criteria grouped according to the researchers' judgments.

Goal	Criterion	Weight of the criterion	Final ranking
Enhance the use of AquaCrop to best meet user needs	C1 – accessibility	0.69	1
	C2 – network	0.09	3
	C3 – data	0.18	2
	C4 – support request	0.04	4

Table 5. The weights of the criteria grouped according to the IT experts' judgments.

Goal	Criterion	Weight of the criterion	Final ranking
Classify the operability of the criteria	C1 – accessibility	0.62	1
	C2 – network	0.11	3
	C3 – data	0.20	2
	C4 – support request	0.06	4

Table 6. Summary of stakeholder-assigned weights and priorities for AquaCrop model improvement.

Priority area	Stakeholder(s)	Key criteria/sub-criteria (Weight)	Proposed Action
Streamline input requirements	Farmers	S_1C_3 – input (0.69)	Develop a simplified user interface with default datasets and an assisted setup wizard
Improve accessibility	All groups	C1 – accessibility (0.72 for farmers, 0.69 for researchers, and 0.62 for IT experts);	Improve web interface for low-bandwidth, mobile-friendly, and offline use
Enable multi-user features	Researchers and IT experts	S_1C_2 multi-user (0.55 for researchers and 0.18 for IT experts)	Integrate role-based multi-user access for collaborative use
Enhance graphical outputs and visualisation tools	Researchers	S_2C_3 – graph (0.52)	Expand the dashboard with customisable graphs, real-time simulations, and exportable results
Responsive technical support and user feedback mechanisms	All groups	S_2C_4 – email support (0.79 for IT Experts); C4 – request for support (0.05 for farmers)	Implement updated FAQs and a responsive email/chat support system with issue tracking

sub-criteria are user reports of answers not available in FAQs, collected through email support. At this level of the hierarchy (level 2), there is some difference between the judgements expressed by farmers and researchers. Researchers expressed greater preference for sub-criteria S_1C_2 (0.55) and S_2C_3 (0.52) (Figure A.2). These preferences emphasise the role of AquaCrop as a shared analytical platform, where simulation results are not only generated but also interpreted, compared, and communicated among multiple groups of users. This dimension becomes particularly relevant when AquaCrop outputs are used within integrated evaluation frameworks to assess alternative management strategies.

In this regard, recent multi-objective approaches demonstrated that AquaCrop simulations gain operational value when coupled with decision support layers that can synthesise outputs across objectives and facilitate comparison among scenarios, reinforcing the importance of visualisation tools and collaborative access (Garofalo, Vonella, 2025).

As shown in Table 5, among the IT experts, the highest weight was given to criterion C1, followed by criterion C3. Criterion C4 was given the least importance. The most important sub-criteria for this group are S_1C_1 (0.81), S_1C_2 (0.52), S_2C_4 (0.79) (Figure A.3).

From a technological standpoint, these results suggest that AquaCrop is increasingly perceived not merely as a standalone model, but rather as a component of web-based, scalable decision support infrastructures. Therefore, ensuring accessibility, interoperability, and efficient data handling becomes essential to maintain the relevance of this model and to facilitate its integration into modern digital agriculture platforms.

The analysis of the weights assigned to the criteria and sub-criteria by the various stakeholders enables the development of a scenario aimed at optimising the use of the AquaCrop model. Table 6 summarises the main priorities identified by each group (farmers, researchers, and IT experts), highlighting the proposed improvement scenario.

Overall, the improvement scenario derived from the AHP analysis reinforces the strategic role of AquaCrop as a reference tool for irrigation planning and water productivity assessment. By addressing usability, data handling, and collaborative features, AquaCrop can more effectively bridge the gap between robust biophysical simulation and real-world decision-making, as demonstrated by recent applied and multi-objective implementations (Garofalo *et al.*, 2025; Garofalo, Vonella, 2025).

5. CONCLUSIONS

Pressure on water resources and climate variability make it important to develop reliable and flexible crop simulation models. In this context, this study focused on aspects of AquaCrop that could be improved to increase usability and to meet users' operational needs. Using the AHP, this study sought to translate user feedback into concrete guidelines for the technical and functional development of the model, combining the knowledge of farmers, researchers, and IT experts. The analysis confirmed that the AHP is a robust and transparent approach to capture user preferences and to identify priorities for that can be used to improve the AquaCrop model.

Among the four criteria considered, C3 emerged as one of the most influential for all stakeholder groups. According to the users, criterion C3 is an important feature because the system can be configured to automatically communicate with external Internet of Things platforms. This priority aligns with recent operational applications where AquaCrop integration with spatial databases has enabled automated processing of multiple pedo-climatic scenarios, significantly reducing manual data entry requirements while maintaining model accuracy (Garofalo, Cammerino, 2025). In this regard the improvement scenarios for the AquaCrop tool should consider the significant weights expressed by farmers (0.15) and researchers (0.18). It is also worth highlighting that the sub-criterion related to marketing (S_3C_2) was rated positively by the farmers (0.15). This demonstrates the interest of farmers in using AquaCrop to add the value of predictive, economic, and controlled management of water resources to their production. This interest is particularly relevant considering that recent studies have demonstrated AquaCrop's capacity to support comprehensive environmental assessments when integrated with Carbon and Water Footprint analysis tools, enabling farmers to quantify and communicate the sustainability performance of their water management practices (Garofalo, Cammerino, 2025). As suggested by Altobelli *et al.* (2019, 2021), irrigation advisory services are suitable to promote the adoption of environmental certification systems, such as water footprint, which could improve the sustainability of production processes. Such recognition can increase competitiveness towards the recognition of market value. Moreover, these systems can help provide a very useful and reliable base for the assessment of sustainability in agriculture, also supporting the construction of robust indices for the ongoing switch from the Farm Accounting Data Network to the Farm Sustainability Data Network (Vrolijk, Poppe, 2021).

Triangulation of perspectives allows AquaCrop to be improved in the following ways: (i) simplify data entry with automatic connections to external databases and Internet of Things platforms; (ii) increase accessibility via web and mobile interfaces; (iii) enable multi-user functions for collaborative use; and (iv) strengthen technical support and feedback mechanisms. These results show how the joint participation of users and developers can significantly increase the operational relevance of the model, bridging the gap between scientific modelling and decision-making in the field.

Another aspect worth discussing is that farmers express a particular interest in sharing their experiences on AquaCrop in the form of a network (criterion C2), with a weight of 0.15. In a world where water scarcity defines the conditions for crop growth, AquaCrop is a valuable tool, and its use can be improved and made more efficient by directly involving users. From a public policy perspective, this evidence is fully consistent with the objectives of the CAP for 2023-2027, in particular with the AKIS approach, which promotes cooperation between research, advisory services, and actors in the agricultural sector. The participatory approach adopted in this study is a concrete example of how digital tools such as AquaCrop can be co-developed to become effective elements within AKIS systems, improving knowledge transfer and supporting more sustainable water resource management. Furthermore, by improving the accessibility of the model and user engagement, AquaCrop can contribute to broader sustainability goals, such as reducing inefficiencies in water use, strengthening irrigation advisory services, and developing sustainability indicators.

Taken together, the results highlight that AquaCrop is not merely a crop simulation model; rather, it is a strategic component of modern irrigation decision support systems. The priorities identified through the AHP analysis – particularly data management, accessibility, and user interaction – represent key enabling factors for transforming AquaCrop from a predominantly research-oriented tool into an operational platform capable of supporting farmers, advisors, and policy-driven irrigation strategies. Evidence from recent applied studies confirms that when combined with structured evaluation frameworks, multi-objective optimisation approaches, and environmental assessment tools, AquaCrop can effectively support sustainable water allocation, enhance water productivity, and improve the transparency of irrigation decisions in Mediterranean and other water-limited environments (Garofalo, Cammerino, 2025; Garofalo *et al.*, 2025; Garofalo, Vonella, 2025). These applications demonstrate the model's capacity to bridge the gap between robust biophysical simulation and real-world decision-making contexts, particularly when user-centred improvements enhance its operational accessibility. From this perspective, the improvement pathways identified in the present study represent a concrete step towards strengthening the role of AquaCrop at the interface between scientific modelling, field-level decision making, and agricultural policy objectives. By systematically addressing the needs expressed by farmers, researchers, and IT experts, the proposed enhancements can facilitate AquaCrop's evolution into a more integrated, user-friendly platform that serves both agronomic optimisation and sustainability assessment, which are core elements of the AKIS framework promoted by the CAP.

Future research should focus on operational testing of the proposed improvement scenarios in different agro-climatic contexts, assessing their actual impact on user adoption and decision-making efficiency. Further developments may involve integration with real-time data sources, artificial intelligence, and cloud infrastructure to expand AquaCrop's potential as a decision support tool for precision irrigation and climate-smart agriculture. Ultimately, this study demonstrates that user-centred innovation is not only possible but essential for modelling tools such as AquaCrop to continue to serve as catalysts for more sustainable and resilient agricultural systems.

AUTHOR CONTRIBUTIONS

I.M.D.: Conceptualization, Methodology, Software. P.G., A.P: Data curation, Writing- Original draft preparation. A.M.: Visualization, Investigation. F.A., A.D.M: Supervision. A.K.: Software, Validation: A.M, I.M.D.: Writing- Reviewing and Editing.

REFERENCES

AbdelRahman M.A.E., Yossif T.M.H., Metwaly M.M. (2025). Enhancing land suitability assessment through integration of AHP and GIS-based for efficient agricultural planning in arid regions. *Scientific Reports*, 15(1). DOI: https://doi.org/10.1038/s41598-025-14051-7.

Ahmed M. (2020). Systems Modeling. In *Systems Modeling*. Springer Singapore. DOI: https://doi.org/10.1007/978-981-15-4728-7.

Ali A., Ahmad M., Nawaz M., Sattar F. (2025). Identifying and Prioritizing Spatial Data Required for Effective Agriculture Policymaking: A Comprehensive Analysis Using Analytical Hierarchy Process. *Data Intelligence*, 7(1): 185-220. DOI: https://doi.org/10.3724/2096-7004.di.2024.0054.

Altobelli F., Del Giudice T., Dalla Marta A. (2019). Adopting irrigation advisory services for water footprint estimation to improving biodiversity conservation: a European survey. *Italian Review of Agricultural Economics*, 74(3): 23-28. DOI: https://doi.org/10.13128/rea-11209.

Altobelli F., Henke R. (2024). Economic strategies and policy suggestions of agricultural sustainable food production. *Agriculture*, 14(3). DOI: https://doi.org/10.3390/agriculture14030504.

Altobelli F., Dalla Marta A., Heinen M., Jacobs C., Giampietri E., Mancini M., Cimino O., Trestini S., Kranendonk R., Chanzy A. (2021). Irrigation Advisory Services: Farmers preferences and willingness to pay for innovation. *Outlook on Agriculture*, 50(3): 277-285. DOI: https://doi.org/10.1177/00307270211002848.

Beiderbeck D., Frevel N., von der Gracht H., Schmidt S., Schweitzer V. (2021). Preparing, Conducting, and Analyzing Delphi Surveys: Cross-disciplinary Practices, New Directions, and Advancements. *MethodsX*, 8, 101401. DOI: https://doi.org/10.1016/j.mex.2021.101401.

Benítez J., Delgado-Galván X., Izquierdo J., Pérez-García R. (2012). Improving consistency in AHP decision-making processes. *Applied Mathematics and Computation*, 219(5): 2432-2441. DOI: https://doi.org/10.1016/j.amc.2012.08.079.

Cay T., Uyan M. (2013). Evaluation of reallocation criteria in land consolidation studies using the Analytic Hierarchy Process (AHP). *Land Use Policy*, 30(1): 541-548. DOI: https://doi.org/https://doi.org/10.1016/j.landusepol.2012.04.023.

Chapagain R., Remenyi T.A., Harris R.M.B., Mohammed C.L., Huth N., Wallach D., Rezaei E.E., Ojeda J.J. (2022). Decomposing crop model uncertainty: A systematic review. *Field Crops Research*, 279, 108448. DOI: https://doi.org/10.1016/J.FCR.2022.108448.

De Castro P., Miglietta P.P., Vecchio Y. (2020). The Common Agricultural Policy 2021-2027: a new history for European agriculture. *Italian Review of Agricultural Economics*, 75(3): 5-12. DOI: https://doi.org/10.13128/rea-12703.

De Felice F., Petrillo A. (2013). Absolute measurement with analytic hierarchy process: a case study for Italian racecourse. *International Journal of Applied Decision Sciences*, 6(3): 209-227. DOI: https://doi.org/10.1504/IJADS.2013.054931.

Donati I.I.M., Viaggi D., Srdjevic Z., Srdjevic B., Di Fonzo A., Del Giudice T., Cimino O., Martelli A., Dalla Marta A., Henke R., Altobelli F. (2023). An Analysis of Preference Weights and Setting Priorities by Irrigation Advisory Services Users Based on the Analytic Hierarchy Process. *Agriculture (Switzerland)*, 13(8). DOI: https://doi.org/10.3390/agriculture13081545.

Elolu S., Förster N., Opiyo A.M., Huyskens-Keil S. (2025). Evaporative cold storage for African indigenous vegetables: A SWOT-AHP analysis of stakeholders' perceptions and its impact on the quality of Amaranth and African nightshade. *Journal of Agriculture and Food Research*, 21. DOI: https://doi.org/10.1016/j.jafr.2025.101949.

Forman E.H. (1993). Facts and fictions about the analytic hierarchy process. *Mathematical and Computer Modelling*, 17(4-5): 19-26. DOI: https://doi.org/10.1016/0895-7177(93)90172-U.

Foster T., Brozović N., Butler A.P., Neale C.M.U., Raes D., Steduto P., Fereres E., Hsiao T.C. (2017). AquaCrop-OS: An open source version of FAO's crop water productivity model. *Agricultural Water Management*, 181, 18-22. DOI: https://doi.org/10.1016/j.agwat.2016.11.015.

García-Vila M., Fereres E., Mateos L., Orgaz F., Steduto P. (2009). Deficit irrigation optimization of cotton with aquacrop. *Agronomy Journal*, 101(3): 477-487. DOI: https://doi.org/10.2134/agronj2008.0179s.

Giardini L. (2012). *L'agronomia per conservare il futuro* (Pàtron, Ed.; 6th ed.).

Ishizaka A., Balkenborg D., Kaplan T. (2011). Does AHP help us make a choice? An experimental evaluation. *Journal of the Operational Research Society*, 62(10): 1801-1812. DOI: https://doi.org/10.1057/jors.2010.158.

Ishizaka A., Labib A. (2009). Analytic Hierarchy Process and Expert Choice: Benefits and limitations. *OR Insight*, 22(4): 201-220. DOI: https://doi.org/10.1057/ori.2009.10.

Ishizaka A., Labib A. (2011). Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, 38(11), 14336-14345. DOI: https://doi.org/10.1016/J.ESWA.2011.04.143.

Ishizaka A., Lusti M. (2006). How to derive priorities in AHP: a comparative study. *Central European Journal of Operations Research*, 14(4): 387-400. DOI: https://doi.org/10.1007/s10100-006-0012-9.

Ishizaka A., Pearman C., Nemery P. (2012). AHPSort: An AHP-based method for sorting problems. *International Journal of Production Research*, 50(17): 4767-4784. DOI: https://doi.org/10.1080/00207543.2012.657966.

Ishizaka A., Nemery P. (n.d.). *Multi-criteria decision analysis : methods and software*.

Kasampalis D.A., Alexandridis T.K., Deva C., Challinor A., Moshou D., Zalidis G. (2018). Contribution of remote sensing on crop models: A review. In *Journal of Imaging* (Vol. 4, Number 4). MDPI. DOI: https://doi.org/10.3390/jimaging4040052.

Knierim A., Birke F.M. (2023). Visualised AKIS Diagnosis – an Instrumental Approach to Support AKIS Appraisal. *EuroChoices*, 22(2): 59-70. DOI: https://doi.org/10.1111/1746-692X.12397.

Labarthe P., European Seminar on Extension & Education (26: 2023: Toulouse). (2023). *Sustainability transitions of agriculture and the transformation of education and advisory services: convergence or divergence?* book of abstracts : 26th European Seminar on Extension & Education, Toulouse, 10-13 July 2023. UMR AGIR.

Lane E., Verdini W. (2007). A Consistency Test for AHP Decision Makers. *Decision Sciences*, 20: 575-590. DOI: https://doi.org/10.1111/j.1540-5915.1989.tb01568.x.

O. Rauff K., Bello R. (2015). A Review of Crop Growth Simulation Models as Tools for Agricultural Meteorology. *Agricultural Sciences*, 06(09): 1098-1105. DOI: https://doi.org/10.4236/as.2015.69105.

Proietti P., Cristiano S. (2023). Innovation support services: an evidence-based exploration of their strategic roles in the Italian AKIS. *Journal of Agricultural Education and Extension*, 29(3): 351-371. DOI: https://doi.org/10.1080/1389224X.2022.2069828.

Raes D., Steduto P., Hsiao T.C., Fereres E. (2009). Aquacrop-The FAO crop model to simulate yield response to water: II. main algorithms and software description. *Agronomy Journal*, 101(3): 438-447. DOI: https://doi.org/10.2134/agronj2008.0140s.

Release Note AquaCrop Version 7.1 FAO. (n.d.).

Roja M., Gumma M.K., Reddy M.D. (2023). Crop modelling in agricultural crops. *Review Articles Current Science*, 124(8). DOI: https://doi.org/10.18520/cs/v124/i8/910-920.

Saaty R.W. (1987). The Analytic Hierarchy Process – What it is and how it is used. *Mathematical Modeling*, 9(3-5): 161-176. DOI: https://doi.org/10.1016/0270-0255(87)90473-8.

Saaty T.L. (2004). Decision making – The Analytic Hierarchy and Network Processes (AHP/ANP). *Journal of Systems Science and Systems Engineering*, 13(1): 1-35. DOI: https://doi.org/10.1007/s11518-006-0151-5.

Saaty T.L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services*

Sciences, 1(1): 83-98. DOI: https://doi.org/10.1504/IJSSci.2008.01759.

Saaty T.L., Ozdemir M. (2003). Negative priorities in the Analytic Hierarchy Process. *Mathematical and Computer Modelling*, 37(9-10): 1063-1075. DOI: https://doi.org/10.1016/S0895-7177(03)00118-3.

Saaty T.L., Vargas L.G. (2012). *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. Springer, New York. DOI: https://doi.org/10.1007/978-1-4614-3597-6.

Seidel S.J., Palosuo T., Thorburn P., Wallach D. (2018). Towards improved calibration of crop models – Where are we now and where should we go? *European Journal of Agronomy*, 94, 25-35. DOI: https://doi.org/10.1016/j.eja.2018.01.006.

Steduto P., Hsiao T.C., Raes D., Fereres E. (2009). Aquacrop-the FAO crop model to simulate yield response to water: I. concepts and underlying principles. *Agronomy Journal*, 101(3): 426-437. DOI: https://doi.org/10.2134/agronj2008.0139s.

Steduto P., Raes D., Hsiao T.C., Fereres E., Heng L.K., Howell T.A., Evett S.R., Rojas-Lara B.A., Farahani H.J., Izzi G., Oweis T.Y., Wani S.P., Hoogeveen J., Geerts S. (n.d.). *Concepts and Applications of AquaCrop: The FAO Crop Water Productivity Model.*

Sutherland L.A., Adamsone-Fiskovica A., Elzen B., Koutsouris A., Laurent C., Stræte E.P., Labarthe P. (2023). Advancing AKIS with assemblage thinking. *Journal of Rural Studies*, 97: 57-69. DOI: https://doi.org/10.1016/j.jrurstud.2022.11.005.

Van Oost I., Vagnozzi A. (2020). Knowledge and innovation, privileged tools of the agro-food system transition towards full sustainability. *Italian Review of Agricultural Economics*, 75(3): 33-37. DOI: https://doi.org/10.13128/rea-12707.

Vanuytrecht E., Raes D., Steduto P., Hsiao T.C., Fereres E., Heng L.K., Garcia Vila M., Mejias Moreno P. (2014). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling and Software*, 62: 351-360. DOI: https://doi.org/10.1016/j.envsoft.2014.08.005.

Vrolijk H., Poppe K. (2021). Article cost of extending the farm accountancy data network to the farm sustainability data network: Empirical evidence. *Sustainability (Switzerland)*, 13(15). DOI: https://doi.org/10.3390/su13158181.

Winn C.A., Archontoulis S., Edwards J. (2023). Calibration of a crop growth model in APSIM for 15 publicly available corn hybrids in North America. *Crop Science*, 63(2): 511-534. DOI: https://doi.org/10.1002/csc2.20857.

APPENDIX

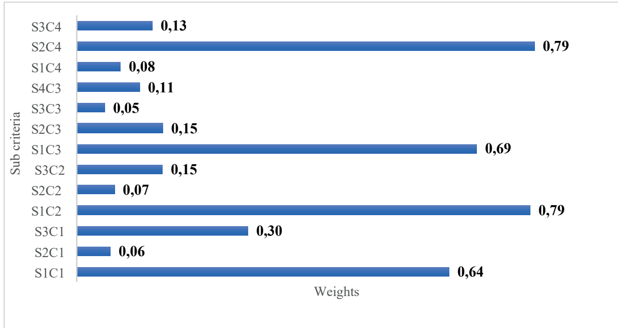

Figure A.1. Ranking and weights of the sub-criteria according to the farmers' judgments.

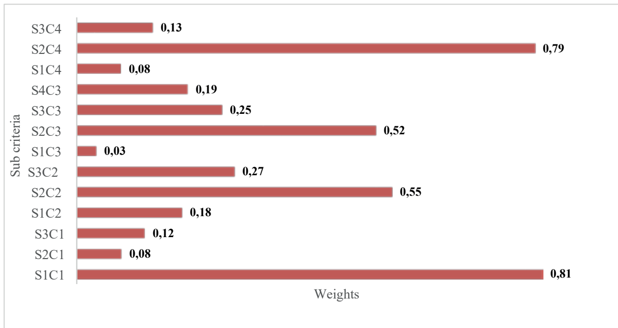

Figure A.2. Ranking and weights of the sub-criteria according to the researchers' judgments.

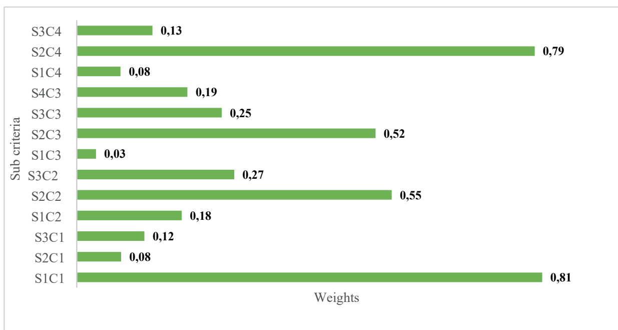

Figure A.3. Ranking and weights of the sub-criteria according to the programmers' judgments.

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