Empowering European agriculture: Policy recommendations to enhance stakeholder engagement for sustainable technology adoption

Discussion Paper prepared for presentation at the 99th Annual Conference of the Agricultural Economics Society, University of Bordeaux, France 14-16 April 2025

Authors: Lisa Parce[1], presenting author; Trevor Donnellan[2], co-author

 *Corresponding Author: Lisa Parce, Teagasc Rural Economy and Development Programme, Athenry, Co. Galway, Ireland. lisa.parce@teagasc.ie

Acknowledgements

We acknowledge funding by Horizon Europe for the QuantiFarm project provided employment for the presenting author through Teagasc and for both authors to serve as co-leaders for a project task (T1.4) and its associated deliverables, D1.3 and D1.4. We are grateful for the comprehensive research conducted by our QuantiFarm project partners, especially TNO researchers responsible for earlier Work Package 1 deliverables which fed into this research. Special thanks to the TNO team of Caroline van der Weerdt, Sabine Verdult, Julia Broderick-Hale, and Dianne van Hemert.

Abstract

This scoping review and multi-tiered qualitative analysis examines data collected through the QuantiFarm project, literature, policies and EU projects to understand the roles of stakeholders in influencing European farmers to adopt Digital Agricultural Technology Solutions (DATSs). The paper adopts a holistic sustainability framework to address economic, social and environmental factors which influence farmers' decision-making about DATSs adoption. Key stakeholders, namely farmers, advisors, technology providers and policymakers, play unique and complementary roles in creating an innovation ecosystem.

During the lifecycle of DATSs adoption, farmers face multiple drivers and barriers. Challenges such as cost, ease of use, data ownership, and interoperability continue to hinder uptake of technologies. Farmers often cite concerns about lack of transparency regarding costs, unclear benefits, and a lack of aftermarket (post-adoption) support. Advisors and technology providers must bridge these gaps by fostering trust, simplifying access to resources and co-developing solutions. Policymakers must ensure that incentives, education, and funding mechanisms are targeted and accessible to farmers of all scales.

This study synthesises diverse perspectives and presents actionable recommendations to enhance stakeholders' roles in the DATSs adoption process, shaping policy frameworks which support sustainable technology adoption. Transparent communication, varied education, reliable advice, tailored farmer-centric technology design and behaviourally driven policies are critical enablers of adoption. Themes resulted from study analysis and are presented as behavioural interventions for embedding in future policy structures. These insights aim to empower policy makers across Europe to support stakeholders in providing farmers with the tools, knowledge and confidence to adopt technologies which improve resilience and sustainability across economic, social and environmental dimensions.

Keywords Agriculture, Farming, Sustainable agriculture, Agricultural technology solutions, Technology adoption

JEL code Agricultural sustainability (Q10) and agricultural technologies and technology adoption (Q16)

Introduction

Agriculture is said to have entered the era of Agriculture 4.0 (Abbasi, Martinez, and Ahmad, 2022), with a rise in availability of smart digital technologies which promise solutions to myriad pressures, such as improving productivity, reducing environmental impacts and enhancing resilience. However, the adoption of DATSs by European farmers remains slower than expected. This lag persists despite increasing pressures, including the need to feed a growing global population, comply with stricter regulations, and adapt to a changing climate.

Farmers face challenges to DATSs adoption such as high investment costs, understanding new technologies, assessing their costs and benefits, and integrating them into existing systems. These determinants impact farmers' decision-making process from first encounter with a technology to investment and use, post-adoption. The slow uptake of digital technologies is explained, in part, by the lack of knowledge about what technological solutions exist and which are right for a particular farmer and farming operation. Insufficient evidence about the costs and sustainability benefits of DATSs adoption under real conditions, and multi-faceted barriers such as cultural attitudes and behavioural determinants further complicate the DATSs adoption process (QuantiFarm consortium, 2022; van der Weerdt et al., 2022). Research shows innovations at farm-level have relevance to farmers where data from the technological solution being presented meets the needs of the farm system, while being economically feasible (Pagliacci et al., 2020).

Effective technology adoption requires collaborative interactions from multiple stakeholders to empower farmers to learn about what technologies are available, which ones are best suited to their needs, and how they can access financial schemes and training supports. Stakeholders - including farmers, advisors, technology providers and policymakers - need the right competencies to navigate this complicated space, balancing the need for farm viability and sustainability so more food is produced with less impact on the environment. Stakeholders must throughout the adoption process, from encounter to post-adoption, to ensure digital tools are accessible to farmers, user-friendly and aligned with sustainability goals. Policy structures aimed at enhancing DATSs adoption should be behaviourally driven to ensure farmers' diverse needs are met. For example, sufficient and appropriate investment funding should be actioned alongside tailored supports for co-design and technical training.

This paper conducts a scoping review and analysis to explore the barriers and enablers of technology adoption. To ensure a balance of perspectives were analysed, the data set was comprised of primary research from the QuantiFarm project, existing literature, and reviews of EU projects and relevant policies. These methodologies support a holistic approach reinforced by analysis of socio-economic factors arising from a Reflective Thematic Analysis (RTA) (Braun and Clarke, 2006, 2021). The RTA identifies five actionable themes (necessary stakeholder competencies) to support sustainable adoption: transparent communication, varied education and training, reliable advice, tailored farmer-centric technology design, and behaviourally driven policy structures. By addressing these areas, this study aims to foster stakeholder collaboration and provide practical recommendations which empower farmers to adopt technologies contributing to economic viability, social equity, and environmental sustainability.

Methodology

This section begins by describing the study's multi-tiered qualitative approach. It then discusses the use of triangulation, highlighting the importance of gaining insights into the phenomena of DATSs adoption through source diversity and varied stakeholder perspectives. A Reflective Thematic Analysis (RTA) method used to identify patterns in data is discussed before the section concludes with explanations of reviews conducted of policies and projects related to technology adoption in agriculture.

This study uses qualitative methodology, combining a scoping review and triangulated analysis to investigate the factors influencing European farmers' adoption of DATSs. The scoping study acts like a map (Arksey and O'Malley, 2005), enabling navigation through diverse materials, including academic literature and deliverables from EU projects that consider farmers' behaviour towards technology adoption (including the QuantiFarm Horizon Europe project [Appendix A] which has motivated this paper). Triangulation is created through integrating these sources to ensure multiple perspectives are examined, presenting a balanced understanding of study phenomena. In addition to source diversity, perspectives of multiple stakeholders (farmers, advisors, DATSs providers, policymakers) are considered to demonstrate the unique and overlapping roles these groups play in technology adoption. Through analysis, materials are synthesised, presenting integrated insights into what policy interventions can be embedded in EU and MS level structures, supporting greater use of appropriate and sustainable technologies.

Reflective Thematic Analysis (RTA) (Braun and Clarke, 2021, 2006) provides a robust strategy for analysing qualitative data, suitable for application to the QuantiFarm dataset and a novel application for socio-economic research. RTA utilises a flexible, but structured approach containing six phases which are 'recursive and iterative' (Byrne, 2022). The six phases of RTA are applied as follows:

Phase 1. Data familiarisation. An iterative review of the data set involved initial scanning of outputs and repeated readings over a period of months to create data familiarisation.
Phase 2. Data organisation. Data were gathered and organised, especially helpful given that other researchers created interview tools and conducted interviews within QuantiFarm.

Phase 3. Coding. This phase used a mixed approach, combining descriptive (understanding salient points) and interpretive coding (interpreting participants' experiences). Data were read repeatedly, key ideas identified, and notations made in a table.

Phase 4. Generating themes. Ongoing movement between the identification of semantic (surface level) and latent (underlying) ideas added insights into more hidden aspects of research content. Themes were reviewed and some were merged, subdivided, or discarded.

Phase 5. Refining and naming themes. Themes were refined by identifying patterns; names were then chosen for accessibility and succinctness. From the RTA, this study translates themes into policy interventions. Grouping like interventions created synthesis with behavioural determinants from primary project research. Ideas were condensed into practical guidelines within five themes.

Phase 6: Producing the write-up. This phase started early and was a gradual process which evolved from a period of synthesising to the reporting of themes.

Supplementing the RTA, a review of existing global, EU and MS level policies related to agricultural and digital technology adoption is undertaken to understand the current policy climate. Analysis explains how effective key policies like UN Sustainable Development Goals (SDGs), the Paris Agreement, and the CAP are functioning in a changing agricultural ecosystem, one that is rapidly evolving in the face of digitalisation. Knowledge of existing policies facilitates appropriate positioning of policy interventions put forth in this study (arising from the QuantiFarm project).

A number of completed and ongoing EU projects are reviewed (a sample appears in Appendix D), seen as a way to learn from the experiences of others, building knowledge to support farmers' DATSs adoption. An initial list of policies was derived from those having a Memo of Understanding (MoU) or Letter of Interest (LoI) with QuantiFarm. Other projects were identified for review through searching for DATSs keywords on the CORDIS repository (a community platform initiative of the European Commission for EU research and projects).

Policy interventions presented in this study offer ways to improve engagement of key stakeholders throughout the lifecycle of DATSs adoption, widening technology adoption and increasing the speed of appropriate uptake by European farmers. The study examines specific barriers to adoption, such as cost, ease of use, data security, and lack of interoperability, as well as enablers, including tailored training programs, transparent communication, and co-created policy initiatives. The analysis triangulates findings to provide a comprehensive view of how DATSs adoption factors interact across the technology lifecycle. This methodological framework ensures a holistic perspective on DATSs adoption, facilitating the development of practical policy recommendations which consider economic, social, and environmental sustainability. Figure 1 illustrates a systemic perspective of sustainability used in this study.

Figure 1: The five sustainable pillars

Source: Schoor et al., 2023

Results

The first half of this section establishes context for the innovation ecosystem, before drivers and barriers to DATSs adoption are discussed from various stakeholders' perspectives. The second part of the section discusses policies and projects relevant to the issue of DATSs adoption. A description is included of how global agreements which the EU has signed, and overarching EU policy aspirations set out in key EU communications, now exert a high level of influence on EU agriculture, particularly in how they shape the objectives of the Common Agricultural Policy (CAP).

This study highlights the continually evolving set of challenges and opportunities European farmers face when adopting digital technology solutions. All stakeholders are under pressure to move towards more sustainable food systems and can benefit from agile behaviours which help farmers manage competitiveness amidst uncertainties of input costs and environmental regulations. Automation, digital or smart solutions, impact almost every aspect of farming life, with varying results (positive, neutral, negative). Having greater knowledge around the costs and benefits of DATSs on commercial farms (an ambition of QuantiFarm), including their perceived use, perceived ease of use, and impact on quality of human and animal life are shown to be linked to transformations in attitudes and actionable behaviours (Pagliacci et al., 2020).

Farmers have always had to be innovative and are constantly adapting to changes and navigating uncertainties, be it weather patterns, market prices, regulations, or consumer demands. Although farmers remain exemplars of innovative practice, many remain hesitant about the suitability of DATSs to their farm. DATSs uptake can be slowed by a lack of transparency around negative impacts and associated risks (McGrath et al., 2023), and fewer than needed assessment tools available for commercial farmers to properly analyse their costs and benefits (Shalloo et al., 2021). Stakeholders across the agricultural innovation ecosystem must communicate to farmers' that their expertise remains vital (Faure et al., 2019). Suggestions to evolve farming practices, including digital technologies and the use of big data, are made to support farmers' innovative solutions for sustainable farming (Garcia-Covarrubias et al., 2023; McGrath et al., 2023), and bolster their knowledge and experiences, not act as replacements (Levy, 2017; O'Brien et al., 2018).

Alignment between stakeholder groups can best support farmers as individuals who are increasingly looking to DATSs to help them "deal with the significant pressure of the effects of climate change, more stringent regulations, insecurity about future prospects, and changing consumer demands" (van der Weerdt et al., 2024, p. 62). Key stakeholder groups' – farmers, advisors, DATSs providers, policymakers – roles in DATSs adoption are discussed next.

Stakeholder groups' roles in DATSs adoption

Farmers

Farmers are at the knife-edge of agri-food challenges on a daily basis. Real-world evidence and feedback from farmers' experiences are essential to understanding individual and universal concerns. Paramount is the need to "involve us [farmers] in the decision" (Detemmerman, 2024). European farmers vary widely across agri-food sectors, biogeographical regions, and behavioural determinants and their decisions to invest in, use, and continue to use DATSs rely on a multiplicity of factors. These dynamics create local, regional, national, and EU-wide variations in personal, external, balancing, decision-influencers, and usage determinants of DATSs adoption (Appendix B; van der Weerdt et al., 2024). Despite sizeable differences, farmers expressed universal concerns about affordability, the real costs versus benefits of technology and uncertainty about long-term usability in the context of climate change and potential regulatory changes (van der Weerdt et al., 2024).

Economics are significant influencers, extrinsic motivators of technology adoption (Coyne et al., 2021; Lechevallier et al., 2018; Leduc et al., 2023). Technologies can be keys to farm efficiency and profitability (European Commission, 2024a) but they are often seen as tools for large scale, industrialised farms (Dedieu et al, 2022). Small and medium sized farmers need capital and often financial supports to enable investment in technologies which provide social and environmental solutions (Dooley et al., 2023). The costs of DATSs range from free, smartphone applications, to those requiring hundreds of thousands of euros in capital outlay, like tractors and milking robots.

In contrast, Manta et al. (2023) showed participant farmers were more influenced in technology adoption decisions by nontangible rewards. Fostering an innovative business culture may go further to influence technology uptake than financial rewards alone (Manta et al., 2023). Concurrently, non-financial factors such as motivation, trust, peer influencers, and technology affinity are drivers of technology use, explained by researchers investigating various behaviour change models – the Technology Adoption Model (McCormack et al., 2021), Theory of Planned Behaviour (Serebrennikov et al., 2020), behavioural change wheel (Michie et al., 2011), Technology Organisational Environment (Piot-Lepetit, et al., 2019), Unified Theory of Acceptance and Use of Technology (Rose et al., 2016), and Means End Chain analysis (Barnes et al., 2022; Leduc et al., 2023).

Barriers to DATSs adoption vary along economic, social, cultural and individual continuums. Farmers reported (van der Werdt et al., 2022, 2024) they are faced with high investment costs, gaps in technical knowledge and skills, and lack clear, demonstrated evidence about how DATSs perform under real conditions. Reasons for adoption resistance are coupled with evidence that uncertain and low government supports, and unreliable or non-existent connectivity for remote and rural areas further hinder the adoption process (Coyne et al., 2021; Ehlers et al., 2021; McGrath et al., 2023; Zampieri, 2024). Farmers have significant concerns about data management, data interoperability constraints, and ethical data policies (Weersink et al., 2018). Issues such as data security and access to technical support post-adoption are also identified as barriers to adoption (Parce and Donnellan, 2025).

Among these complexities to DATSs adoption, labour challenges are high on the list of common concerns faced by European farmers. An example is the difficulty finding workers and rising costs of paying workers with hourly wages for farm workers rising in 2024 (Eurostat, 2024). There is a need to ensure decent working conditions which attract and retain staff (Dedieu et al., 2022; Prause, 2021). DATSs can help address key labour and input cost challenges (Hammersley et al., 2023; Lapple et al., 2017; Piot-Lepetit, et al., 2019; Serebrennikov et al., 2020). However, more needs to be understood about the impact of DATSs on highly skilled seasonal and migratory workers, in terms of pros like learning new technical skills and cons, like workers who feel threatened by higher degrees of monitoring enabled through technology (Prause, 2021).

Age and gender are two other critical factors of DATSs adoption. The agricultural sector as a whole is ageing, with a majority (57.6%) of all farm managers being at least 55 years old and only 11.9% of farm managers (both sexes combined) being young farmers (defined as under 40 years) (Eurostat, 2022). With increasing value placed on work-life balance and mental wellbeing, interest from the next generation in taking over the farm may be improved with the implementation of robots. For instance, dairy DATSs have been shown to impact farmers' and employees' wellbeing by offering increased flexibility, reducing stress (Hansen, 2015), and providing flexibility in daily task scheduling (Garcia-Covarrubias et al., 2023; Hogan et al., 2023). According to the Agricultural Census of 2020, "slightly more than two thirds (68.4%) of farm managers on the EU's 9.1 million holdings were male. Given the numbers of women in farming remains stagnant (van der Weerdt et al., 2022, 2024), they must be more purposefully included in DATSs decision making from being around the table during advisor's visits, included in local discussion groups, and invited to participate in co-design with technology providers (Parce and Donnellan, 2025; van der Weerdt et al., 2024).

Advisors

Public and private advisors regularly interact with farmers and play a critical role in supporting farmers in the DATSs adoption process, helping them balance farm-level compatibility of DATSs with policy objectives (Nettle et al., 2022; Williams, James and Prichard, 2022). Understanding the needs of advisors – their technology affinity, and gaps in technical and soft skills training needed to best serve their farmer clients – is critical to enabling farm level DATSs adoption. Many farmers rely on their advisor for decision making assistance, placing high importance on trust within this relationship (Lechevallier et al., 2018;

Svenson et al., 2023). Advisors who foster a trusting and collaborative environment are better positioned to help farmers get good data from their technologies (IFCN, 2022).

Research (Kelly, 2023) shows that advisors, like farmers, have various levels of technology affinity; some advisors embrace digital technologies, while others lack interest or resources. There is also the reality of time constraints. Advisors cite a lack of capacity to support technology implementation (their own and at farm-level) due to a shift from technological advising to administrative functions (Bull et al., 2022), spending a significant percentage of their time helping farmers fill out scheme paperwork. Roles of advisory service providers are undergoing further changes with, for example, the increased attention on supporting farmers' wellbeing (Hammersley et al., 2023). The recent addition of a Signpost Climate Advisory Programme in Ireland (Teagasc, 2023a) is an example of this shift. Signpost advisors assist farmers in the use of smart phone applications like AgNav, helping farmers gain whole farm life cycle assessment (LCA) data to assist implementing farm-level actions to meet environmental targets (Teagasc, 2023b). Since advisory is a part of CAP and meeting sustainability goals, Parikoglou et al. (2023) argue more is needed to enhance technology education and support of technology adoption through advisory and AKIS.

DATSs providers

DATSs providers perform many roles as they develop, produce, and sell hardware and software components utilised on farms across Europe. The way providers design user interfaces, with and without farmers' input, how their target audiences and marketing materials are created and rolled out, and the level of training and support given to farmers and advisors influence adoption rates. The choices DATSs providers make throughout the lifecycle of the adoption process also influences their bottom line. Market and policy environments can support entrepreneurial efforts in this sector or block innovations. Getting farmers involved with technology design can better meet their needs as the end-users (Bucci et al., 2018). Supporting deep demonstrations (EIT Climate-KIC, 2023), technology providers can increase hands-on learning, an innovation lever. Another potential policy lever is for technology providers to provide additional training, from encounter to post-adoption (O'Brien and de Bhailis, 2021).

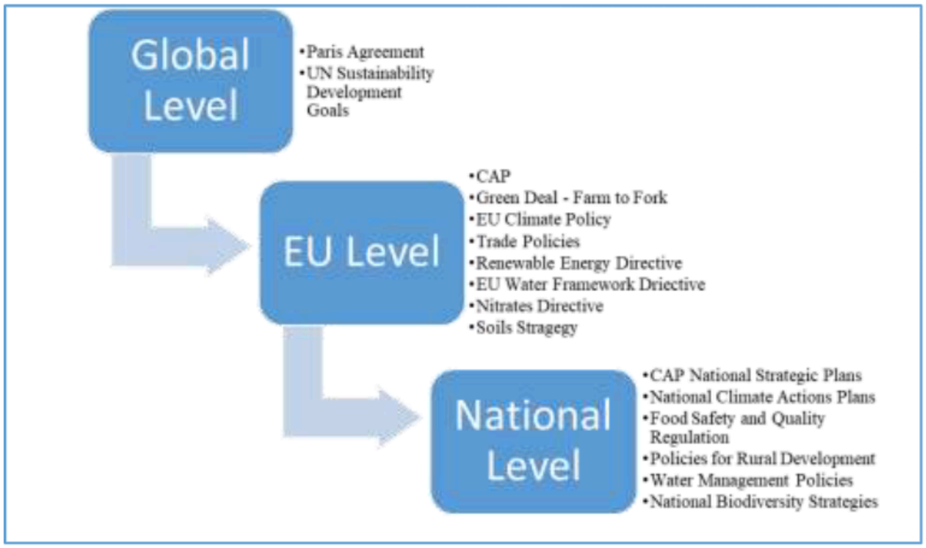
Policymakers

Policymakers are at the sharp end of the regulatory process. They have an important role to play in DATSs adoption as barriers and drivers to technology adoption are topics increasingly dominating EU and MS level policy conversations. Some literature shows policymakers, like researchers, operate at too great a distance from the realities of on-farm decisions (Chindasombatcharoen et al., 2024, Hayden et al., 2021). Like other stakeholder groups, policymakers need to understand the complexities and integrated factors which inform and influence the DATSs adoption process. A needs-driven approach (Shalloo et al., 2021) can overcome mismatches of the promises of what DATSs can deliver and the realities of unique farm conditions. Governmental messages need to be streamlined as farmers can feel 'bamboozled' by the proliferation of technology tools, initiatives, and language around sustainability (Teagasc, 2023c). Farmers face huge challenges to meet environmental goals set out by MS Climate Action Plans, once again they are asked to change farm practices while striving to remain competitive in a changing global market. Financial and nonfinancial incentives can be operationalised through targeted behavioural interventions as part of the agricultural policymaking process.

Policy Context

Existing agricultural policies relevant to DATSs adoption are examined. Global agricultural and environmental policies and programmes such as the UN Sustainability Goals (SDGs) and Paris Agreement have established a benchmark for sustainable agriculture. World Trade Organisation (WTO) agreements govern and streamline agricultural trade. EU level policies, primarily the Common Agricultural Policy (CAP), and supporting guidelines including Farm to Fork and the Green Deal influence farmers' decisions to adopt DATSs. A hierarchy of policies influencing the evolution of EU agriculture appears in Figure 2.

Figure 2: Hierarchy of policies influencing the evolution of EU agriculture



Source: Authors' own analysis

A prioritisation exercise on the UN SDGs was conducted (Appendix C). A partial framework appears in Table 1, containing goals with the highest relevance to farmers and the sector and indicating how DATSs adoption could help meet each SDG goal. Like the Paris Agreement, the UGN SDGs cannot directly influence DATSs adoption but should be seen as a policy influencing other policies more directly relating to EU agriculture.

Table 1: Partial prioritisation framework for UN SDGs and agriculture

SDG	Goal Description	Relevance Level	Commentary
2. Zero Hunger	End hunger, achieve food security	Extremely High	Core mission of agriculture to ensure food security and sustainable production. **Adoption of appropriate DATSs and the data generated can create greater efficiencies for farmers, helping to improve food security.**
12. Responsible Consumption and Production	Ensure sustainable practices	Extremely High	Circular economy principles and efficient resource use are integral to modern agriculture. **Use of appropriate DATSs in farming systems can help farmers do more with existing resources through the optimisation of labour resources, reduction of inputs, reduction of waste, and increased awareness of animal health and crop health indicators.**
13. Climate Action	Combat climate	Extremely High	Farmers are key to GHG reduction, carbon sequestration, and adapting to climate change. **DATSs provide data which can**

	change and impacts		**help create farm-level actions which respond to adverse weather conditions (excess heat, drought, etc.).**

Source: Authors' own analysis

While there are many policy documents at EU level, the CAP remains the main mechanism to steer the EU agricultural sector, given its substantial budget and the extensive administrative, research and advisory mechanisms underpinning CAP objectives developed over many decades. The current CAP (2023-2027) is under revision, offering opportunities to contribute policy interventions for DATSs adoption supports. Small and medium farmers need better supports, simultaneously ensuring all farms who make ecosystem contributions are remunerated (European Commission, 2024; European Union, 2024). Through CAP reform, giving regional policymakers more decision-making capacity may go some way to meet targeted needs of farmers to improve living conditions, attract young farmers to support generational renewal, and tackle gender inequalities. There are competing views on the potential ramifications of moving away from area-based payments, especially amidst global political instabilities. A consensus exists that the cost of inaction is higher than action.

There is a need to come together strategically and systemically to help farmers best manage challenges of the changing climate, food insecurities, shifting consumer expectations, and price fluctuations. Data driven decision making is here. DATSs and the data they produce provide a means to meet farmers' unique needs, helping them to keep doing more with less and realise profits while achieving quality-of-life goals, amid the uncertainties of evolving environmental regulations.

Ongoing and completed EU projects like CODECS, BEATLES, MEF4CAP, BESTMAP, Desira, and SmartAKIS establish context and help to identify current policy work in the DATSs adoption area (Appendix D). An example of intersections between agricultural policy and the digital transformation appears in the BESTMAP project. BESTMAP focuses on creating behavioural, ecological, social, and economic tools for modelling agricultural policy. Data from this project, collected by RISE, showed European Commission policymakers expressed the need to incorporate medium to long-term trends, like digitalisation and precision agriculture, when planning future policies. Research from BESTMAP states there is a drive for 'focused investment in Ag innovation'; transitioning CAP to policy for 'public good' versus 'income support' (Václavík et al., 2022).

CODECS, a sister project of QuantiFarm, is developing tools to provide evidence of sustainable agriculture. In a policy deliverable (Alonso-Roldán and Delgado-Serrano, 2024), the importance of "tailor-made policies" to meet needs arising from agricultural digitalisation was stressed along with requirements these policies "ensure accessibility for all sectors, including small-scale farmers" and "align with broader EU and national strategies... leveraging existing funding channels" (p. 7). The CAP and MS level agricultural public bodies are challenged to "increase their support and be seen as facilitators, not controllers, in advancing digitalisation" (Alonso-Roldán and Delgado-Serrano, 2024, p. 7).

Several areas identified in QuantiFarm research were taken under consideration when drafting policy interventions – farmer autonomy, decision making as a behavioural journey versus a binary, yes/no process, the importance of gender inclusivity, and the need for cross-cultural sensitivity. Five cross-cutting themes were identified as critical to addressing challenges of agricultural digitalisation: 1) Transparent communication, 2) Varied education and training, 3) Reliable advice, 4) Tailored farmer-centric technology design, and 5) Behaviourally driven policy structures. Policy recommendations arising from these five themes will be discussed in the next section.

Discussion

This section integrates knowledge from study results, proposing how the five themes identified through the RTA become a framework for policy interventions. It identifies the CAP as the primary mechanism enabling DATSs adoption and thus the most suitable policy for this study's recommendations.

Rationale for focusing on CAP as the mechanism to deliver DATSs adoption

While not as large a share as in the past, the CAP budget represents a substantial share of the overall EU budget. CAP funding (via Pillar I payments and Pillar II rural development programmes) has broad coverage across much of the agriculture sector. By embedding new support mechanisms within the existing CAP architecture, new administrative structures would not be required to operationalise interventions to support DATSs adoption. There is a need to increase appropriate DATSs adoption to support six CAP objectives in particular: 1) Simplify reporting requirements, 2) Increase competitiveness, 3) Support climate change action, 4) Enable environmental care, 5) Support generational renewal, and 6) Protect food and health quality.

Farmers already have a high level of awareness regarding the CAP and the broad support that it provides. Equally, farm advisory services are structured to provide support and education to farmers in a manner that supports the objectives of the CAP. Policymakers with responsibility for the agriculture sector, are also very familiar with the CAP. At the EU member state level, they have had to become much more actively involved in tailoring the CAP to society's needs while meeting their country's specific needs.

The current CAP, scheduled to run from 2023 to 2027, has introduced the concept of national level CAP Strategic Plans (CSPs), which represents a break from the long-standing common approach to policy design and implementation across the EU Member States. National CSPs allow for more MS level heterogeneity in the design of CAP interventions and present an opportunity to identify and then address specific MS needs through dedicated actions. DATSs adoption could help to achieve various CAP objectives. For example, the latest CAP is supporting smaller farms with better access to precision farming through increased funding and helps in changing agricultural practices. In this way, DATSs are positioned at the intersection to meet dual challenge of balancing the eco-transition with sustainable productivity (Dahm, 2022).

In addition to embedding policy recommendations from this study into CAP structures, interventions can also be embedded into the CAP Rural Network and CAP LEADER payments and programmes, co-financed by the EU MS. Sample policy recommendations from this study and where they fit into the CAP appear below.

Transparent communication (Theme 1)

Transparent communication builds trust by providing clear information on costs and benefits, accurately conveying information about the real implication of DATSs adoption. Fostering trust and accuracy across stakeholder communication can bolster CAP measures through programmes like LEADER, making it easier for farmers to modernise, adapt to new challenges to improve viability and sustainability (Department of Agriculture, Food and the Marine, 2023). Providing this practical information on technology adoption costs and benefits should be prioritised to build farmer confidence. Relationships between farmers and other stakeholders benefit from effective communication skills like listening and using plain language (Serebrennikov et al., 2020).

Varied education and training (Theme 2)

Suggestions to offer more **bespoke and varied education and training** align with knowledge transfer (KT) objectives within the CAP Pillar II, as evidenced by the establishment of the European Skills Agenda. The Skills Agenda is partially actioned through EU CAP Network seminars which occur regularly, providing skills and lifelong learning for agricultural advisory and training service providers. A recent seminar brought 175 EU stakeholders together, covering topics on robotics and AI in farming and forestry (European Union, 2025). To further support the digital transformation, the EU CAP Network recently added 'digitalisation' to the EIP-AGRI website (2025). A report from Nurturing Skills for a Thriving and Sustainable Agricultural Sector (2023) stated more needs to be done with education and training to better equip farmers and advisors in efforts to meet skills shortages within the digital and green transition for economic, environmental, social sustainability.

Education and training initiatives relating to DATSs need to be customised to meet the needs of diverse farm systems and farmer demographics. Learning strategies must combine technical knowledge with soft skills, offering variety to targeted groups, including face-to-face, hands-on demonstrations, and online courses. Social media videos are especially appealing to younger farmers where knowledge is transferred by social media influencers, usually farmers who share their experiences and expertise about technology through bite-sized videos on popular platforms. Across delivery approaches, farmers want to see the impact of using or not using technologies under real conditions (Nyasimi et al., 2017). They are more likely to invest in and use technologies through peer learning, discussion groups, and demonstrations (Levy, 2017; Molina et al., 2021; Palma-Molina et al., 2023).

Reliable advice (Theme 3)

Reliable advice recommendations from this study could be embedded in the CAP under investments in rural development meeting the call to "provide farm advisory services on digital transformation of agriculture and rural areas" (Gemtou et al., 2024, p. 112). Farmers need to know what kinds of technologies are available, where investment funding might be secured, and how those DATSs can help them address their unique but overlapping and complex demands of sustainability under conditions of change and global crises (EU Commission, 2024). Transparent advice about the fine print in goods and service contracts, for example, builds farmers' confidence, giving them tools to make better decisions about how their data is used and which providers best serve their needs. Trust is an intangible but critical aspect within relational learning contexts (Bull et al., 2022; Nettle et al., 2022; Vanclay, 2004). Emphasised by Smart-AKIS guidelines (Iniciativsa-Innovadoras, 2016), trust is critical to farmer-advisor relationships and can be embedded in conversations and social learning discussion groups to positively support decision making.

Advisors can offer practical, farm-specific guidance and involve all decision-makers, while at the same time respecting farmers' desire for autonomy (Cook, Satizabal, and Curnow, 2021; Faure et al., 2019; Kelly, 2023). Tailored, actionable recommendations sensitive to individual farm situations, should involves concerns of all (women, family members, workers) involved in the DATSs decision-making process. "Extension agents are essentially adult educators" (Percy, 2005, p. 127) and would do well to apply a farmer-centric extension model through learning and applying advisory skills including respect, empathy, and collective engagement (Williams et al., 2022).

Tailored farmer-centric technology design (Theme 4)

Recommendations for improved farmer-centric technology design are supported by work in the BEATLES project, outlining other CAP "tools and interventions favouring the adoption of digitalisation" (Gemtou et al., 2024, p. 112). The revised CAP could go further to support investments in digital technologies at any stage of the supply chain and bolster efforts to provide critical infrastructure to support farmers' use of digital tools with investments in broadband connectivity or the installation of digital technologies (Gemtou et al., 2024, p. 112).

Technology providers can prioritise co-creation processes with farmers to ensure solutions are user-friendly, affordable, and aligned with their needs. Policymakers can integrate behavioural incentives and simplify funding mechanisms to make technologies accessible across a diverse farm population. DATSs need to address affordability, interoperability, ease of use, data ownership and data sharing and on-farm relevance. Greater farmer input can enhance usability and acceptance. Getting farmers involved in the design process and post-adoption training helps increase farmer engagement and end-user satisfaction. Writing transparent contracts and teaching farmers how to navigate regulatory requirements are also important responsibilities of technology providers.

Behaviourally driven policy structures (Theme 5)

Behaviourally-driven policy structures consider the multiple and diverse determinants which influence farmers' decisions to adopt DATSs (van der Weerdt et al, 2022, 2024; Parce and Donnellan, 2025). With the CAP coming under increasing influence of wider global objectives, such as the UN SDGs, Paris Agreement on Climate Change, European Green Deal and Farm 2 Fork, its objectives have widened to encompass traditional economic goals with the other sustainability pillars of social and environmental factors. As such, behaviourally focused interventions for DATSs adoption which understand that age, gender, farming location, individual goals, values and motivations, social and cultural determinants complicate policy making. The EU Cohesion Policy promotes balance sustainable development and has progressed beyond historical focus on infrastructure developments to bridge urban and rural divides to driving digital solutions which promote social progress.

Simpler policy communication and co-designed helpful actions can enhance awareness and uptake of DATSs. Policy advice is more likely to be accepted when it brings benefits and reduces costs, such as how spending now can lead to public expenditure savings later. Social benefits of DATSs adoption like labour savings and more task flexibility for better work-life balance are social capital which can be leveraged, leading to stress reduction for mental health improvement. Environmental benefits of improving supports for DATSs include reduced reliance on expensive inputs (feed, chemical fertiliser) and reductions in antibiotic usage due to individualised data about livestock health. These goals for limiting pesticides and antibiotic use, along with other environmental goals (water quality, improved ecosystems and biodiversity) are areas rising in prominence in CAP reform conversations. The EU is under pressure to deliver a CAP that does more for the environment with potentially less money.

Embedding additional financial incentives for technology investments in the new CAP is essential and includes such interventions as MS level tax credits to cover the growing number of available DATSs, free or low-cost trials of new technologies, and incentives for technology cooperatives. Policy amendments can help facilitate more collaborative, culturally sensitive, gender inclusive, farmer-focused approaches within the technology design to postsales process. Funding structures need to go further to help farmers in their difficult decision-making process about DATSs adoption by incorporating a greater variety of technical training to reach vulnerable farming groups – young farmers, older farmers, and women farmers. Increasing the variety and reach of learning methods is essential. Utilising a combination of methods is key to helping farmers accelerate the transition to sustainable, resilient agricultural systems across Europe.

Conclusion

The digital transformation is widely and rapidly impacting farmers and the agricultural ecosystem. An urgency exists for European stakeholders to ensure farmers reduce environmental impacts while balancing competitiveness with social factors like farmer wellbeing. A whole systems approach to developing policy structures which foster resilience through appropriate technology adoption must be sought.

This study has shown that behaviourally driven policy structures which consider the whole farmer and farming system provide greater assurances to farmers by bringing knowledge about and supports for DATSs adoption forward so more farmers know what opportunities exist and how they can access them. Taking a multi-tiered qualitative analysis approach, this study leaned into Reflective Thematic Analysis, a novel methodology for socio-economic research. The primary RTA method of analysis (Braun and Clarke, 2021) was supplemented by a review of policies and projects. Looking for synergies within existing activities uncovered helpful methodologies and provided policy context and insights from related global and EU level policies (UN SDGs, CAP), and EU projects (CODECS, MEF4CAP, BEATLES).

The five cross-cutting themes identified – transparent communication, varied education and training, reliable advice, farmer-centric technology design, behaviourally focused policy structures - offer actionable insights for fostering technology. Incorporating this study's policy insights into frameworks such as the CAP can enhance farmers' ability to navigate DATSs adoption challenges, while making the sector more sustainable. Considering the recent implementation of national level CAP Strategic Plans (CSPs) and the changes within the CAP to give Member States more flexibility and autonomy, it is increasingly important for policy structures to consider local and regional factors impacting DATSs adoption and thus provide opportunities for greater input from national level policymakers.

Transparent communication can build trust by providing clear information on costs and benefits, while education and training programs tailored to different farm types can enhance technical and decision-making capacities. Key stakeholders contribute through promoting technology drivers such as facilitating peer-to-peer learning activities, providing accurate and reliable advice about contracts, and communicating where investment funding might be secured for DATSs adoption.

This study provides a foundation for further dialogue among stakeholders, critical for incentivising farmers operating farms of any size to adopt DATSs most suitable for their circumstances, which serve as partners, not replacements. Keeping younger farmers farming, bringing new entrants into farming, and providing stronger pathways to generational renewal can be helped through more certain and stable regulations management from a policy perspective. Farmers need to know what they can do to meet trifold sustainability markers. There needs to be more funding and behavioural supports for farmers to adopt technology solutions capable of helping them become more economically viable, socially progressive, and environmentally responsible.

References

Abbasi, R., Martinez, P. and Ahmad, R. (2022). The digitization of agricultural industry–a systematic literature review on agriculture 4.0. *Smart Agricultural Technology*, 2, p.100042.

Arksey, H. and O'Malley, L. (2005). Scoping Studies: Towards a Methodological Framework. *International Journal of Social Research Methodology*, 8(1) (February 2005): 19–32. https://doi.org/10.1080/1364557032000119616.

Barnes, A.P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T. and Gómez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. *Land use policy*, 80, pp.163-174.

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2): 77-101.

Braun, V. and Clarke, V. (2021). Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. *Counselling and psychotherapy research*, 21(1): 37-47.

Bucci, G., Bentivoglio, D., & Finco, A. (2018). Precision agriculture as a driver for sustainable farming systems: State of art in literature and research. Calitatea, 19(S1), 114-121.

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality & quantity*, 56(3), pp.1391-1412.

Bull, E.M., Van Der Cruyssen, L., Vágó, S., Király, G., Arbour, T., and Van Dijk, L. (2022). "Designing for Agricultural Digital Knowledge Exchange: Applying a User-Centred Design Approach to Understand the Needs of Users." *The Journal of Agricultural Education and Extension*, (December 5, 2022): 1–26. https://doi.org/10.1080/1389224X.2022.2150663.

Coyne, L., Kendall, H., Hansda, R., Reed, M.S., Williams, D.J.L. (2021). "Identifying Economic and Societal Drivers of Engagement in Agri-environmental Schemes for English Dairy Producers." *Land Use Policy,* 101 (February 1, 2021): 105174.

DAFM. "Ministers McConalogue and Hackett Launch Multi-Species-Sward Measure as Part of Departments 12-Million Support Package." Government. Department of Agriculture, Food and the Marine, March 25, 2022. https://www.gov.ie/en/press-release/87878-ministers-mcconalogue-and-hackett-launch-multi-species-sward-measure-as-part-of-as-part-of-departments-12-million-support-package/#.

Dedieu, B., Contzen, S., Nettle, R., Schiavi, S. M. D. A., & Sraïri, M. T. (2022). The multiple influences on the future of work in agriculture: global perspectives. *Frontiers in Sustainable Food Systems*, 6, 889508.

Detemmerman, V. (2024). Keynote by FarmFluencers [visual graphic]. EU AgriFood Days, Day 1, Session 2, 10 December 2024.

Dooley, S., Lynch, M., Croutear, A., Fitzgerald, J. and Smith, S. (2023). "Voice of the Innovator." Presented at the New Zealand - Ireland Agri-tech Summit Recordings, October 31, 2023. https://agritechnz.org.nz/resources/new-zealandireland-agritech-summit-recordings-2023/

Ehlers, M.-H., Huber, R., and Finger, R. (2021). Agricultural policy in the era of digitalisation. Food Policy, 100, 102019. https://doi.org/10.1016/j.foodpol.2020.102019

European Commission (2024a). The Digitalisation of the European Agricultural Sector. Shaping Europe's Digital Futures, Policies, 8 October 2024. https://digital-strategy.ec.europa.eu/en/node/9570/printable/pdf

European Commission (2024b). Strategic Dialogue on the Future of European Agriculture. EUC, September 2024. Brussels.

European Union. (2024). EU Agri-Food Days [YouTube]. December 12-14, 2024. Brussels. https://www.youtube.com/playlist?list=PLFj-DFMoOMbH2YjpdyykSY-Q5sFPVqH_7

European Union. (2025). EU CAP Network seminar: Robotics and Artificial Intelligence in farming and forestry. February 18-29, 2025, Utrecht, The Netherlands. https://capnetworkireland.eu/event/eu-cap-network-seminar-robotics-and-artificial-intelligence-in-farming-and-forestry/#:~:text=The%20EU%20CAP%20Network%20seminar,sustainability%20in%20farming%20and%20forestry.

European Union. (2023). Nurturing Skills for a Thriving and Sustainable Agricultural Sector. EU CAP Thematic Group 1st meeting [report]: Brussels. https://eu-cap-network.ec.europa.eu/sites/default/files/publications/2024-01/report-1st-meeting-tg-on-skills_0.pdf

Eurostat (2024). *Annual increase in labour costs at 4.6% in euro area*. News: Euro Indicators, Third quarter of 2024, 16 December 2024. European Union. https://ec.europa.eu/eurostat/web/products-euro-indicators/w/3-16122024-ap#inpage-nav-share

Eurostat (2022). *Farmers and the agricultural labour force – statistics*. Statistical themes: Agriculture, fisheries, and forestry: Agriculture, November 2022. European Union. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_and_the_agricultural_labour_force_-_statistics#Data_sources

Faure, G., A. Knierim, A. Koutsouris, H. Ndah, S. Audouin, E. Zarokosta, H.E. Wielinga, B. Triomphe, S. Mathé, and T. Ludovic. (2019). "How to Strengthen Innovation Support Services in European Rural Areas: Lessons Learnt from AgriSpin." European Seminar on Extension and Education, 2017(23). (February 7, 2019). http://www.esee2017.gr/uploads/attachments/82/Faure_et_al..pdf.

Garcia-Covarrubias, L., Lapple, D., Dillon, E., and Thorne, F. (2023). "Automation and Efficiency: A Latent Class Analysis of Irish Dairy Farms." *Q Open* 3(1) (January 25, 2023): qoad015.

Hammersley, C., Richardson, N., Meredith, D., Carroll, P., and McNamara, J.G. (2023). "Supporting Farmer Wellbeing: Exploring a Potential Role for Advisors." *The*

Journal of Agricultural Education and Extension, 29(4). (August 8, 2023): 511–38. https://doi.org/10.1080/1389224X.2022.2082498.

Hansen, B.G. (2015). "Robotic Milking-Farmer Experiences and Adoption Rate in Jæren, Norway." Journal of Rural Studies 41 (October 2015): 109–17.

Helmholtz Centre for Infection Research (HZI). (2022). "One Health - Triad of Environmental, Animal and Human Health." Research, October 2022. https://www.helmholtz-hzi.de/en/news_events/stories/one-health-triad-of-environmental-animal-and-human-health/.

Hoffmann, V., Probst, K. and Christinck, A. (2007). "Farmers and Researchers: How Can Collaborative Advantages Be Created in Participatory Research and Technology Development?" *Agriculture and Human Values,* 24(3). (July 30, 2007): 355–68. https://doi.org/10.1007/s10460-007-9072-2.

Hogan, C., Kinsella, J., Beecher, M. and O'Brien, B. (2023). "The Impact of Work Organisation on the Work Life of People on Pasture-Based Dairy Farms." Animal 17, no. 1 (January 2023): 100686. https://doi.org/10.1016/j.animal.2022.100686.

Hostiou, N., Fagon, J. Chauvat, S., Turlot, A., Kling-Eveillard, F., Boivin, X., and Allain, C. (2017). "Impact of Precision Livestock Farming on Work and Human-Animal Interactions on Dairy Farms. A Review." Biotechnologie Agronomie, Societe Eg Environnement 21, no. 4 (2017): 268–75

Iniciativas-Innovadoras (2016). D3.6. Smart-AKIS Recommendations and Fact-Sheets. EU Horizon 2020 project. Smart-AKIS. Athens: European Commission, March 2016.

Jäger, J., Brutschin, E., Pianta, S., Omann, I., Kammerlander, M., Vishwanathan, S., Vrontisi, Z., MacDonald, J. and Van Ruijven, B. (2023). Stakeholder Engagement and Decarbonization Pathways: Meeting the Challenges of the COVID-19 Pandemic. *Frontiers in Sustainability 3* (January 9, 2023): 1063719. https://doi.org/10.3389/frsus.2022.1063719.

Kelly, T. "Unlocking the Potential of Digital Farming." *Today's Farm*, October 2023.

King, M.T.M., Matson, R.D., and DeVries, T.J. (2021). "Connecting Farmer Mental Health with Cow Health and Welfare on Dairy Farms Using Robotic Milking Systems." Animal Welfare 30, no. 1 (February 2021): 25–38. https://doi.org/10.7120/09627286.30.1.025.

Kling-Eveillard, Florence, Clément Allain, Xavier Boivin, Valérie Courboulay, Pauline Créach, Aurore Philibert, Yannick Ramonet, and Nathalie Hostiou. "Farmers' Representations of the Effects of Precision Livestock Farming on Human-Animal Relationships." Livestock Science 238 (August 2020): 104057. https://doi.org/10.1016/j.livsci.2020.104057.

Läpple, D., Holloway, G., Lacombe, D.J., and O'Donoghue, C. (2017) "Sustainable Technology Adoption: A Spatial Analysis of the Irish Dairy Sector." European Review of Agricultural Economics 44(5): 810–35. https://doi.org/10.1093/erae/jbx015

Lechevallier, E., Stavridou, E., Granell-Ruiz, R., Key, G., & Berckmoes, E. (2018). FERTINNOWA Deliverable No. 3.3 Benchmark report (EU 2020 Project No. 689687; Transfer of INNovative Techniques for Sustainable WAter Use in FERtigated Crops).

Leduc, G., Billaudet, L., Engstrom, E., Hansson, H., and Ryan, M. (2023). "Farmers' Perceived Values in Conventional and Organic Farming: A Comparison between French, Irish, and Swedish Farmers Using the Means-End Chain Approach." Ecological Economics 207 (May 2023): 107767.

Levy, W. "Precision Agriculture: A Smart Farming Approach." *SPORE*, August 2017.

Manta, F., Morrone, D., Toma, P., and Campobasso, F. (2023). "Determining Paths of Innovation: The Role of Culture on the Adoption on Organic Farming Management." Business Strategy and the Environment 32, no. 1 (January 2023): 96–109. https://doi.org/10.1002/bse.3119.

McCormack, M., Buckley, C., and Kelly, E. (2021). "Using a Technology Acceptance Model to Investigate What Factors Influence Farmer Adoption of a Nutrient Management Plan." Irish Journal of Agricultural and Food Research 60, no. 1 (2021): 142–51. https://doi.org/10.15212/ijafr-2020-0134.

McGrath, K., Brown, C., Regan, A., Russell, T. (2023). "Investigating Narratives and Trends in Digital Agriculture: A Scoping Study of Social and Behavioural Science Studies." *Agricultural Systems*, 207 (April 2023): 103616.

Michie, S, Van Stralen, M.M., and West, R. (2011). "The Behaviour Change Wheel: A New Method for Characterising and Designing Behaviour Change Interventions." Implementation Science 6, no. 1 (December 2011): 42. https://doi.org/10.1186/1748-5908-6-42.

Molina, P. P., Hennessy, T., O'Connor, A.H., Onakuse, S., Moran, B., O'Leary, N., and Shalloo, L. (2021). "Adoption of Precision Livestock Farming Technologies in Irish Pasture-based Dairy Systems" in Irish Dairying: Delivering Sustainability, 282-283. Moorepark: Teagasc.

Nettle, R., Major, J., Turner, L., and Harris, J. (2022). "Selecting Methods of Agricultural Extension to Support Diverse Adoption Pathways: A Review and Case Studies." *Animal Production Science*. https://doi.org/10.1071/AN22329.

Nyasimi, M., Kimeli, P., Sayula, G., Radeny, M., Kinyangi, J., and Mungai, C. (2017). "Adoption and Dissemination Pathways for Climate-Smart Agriculture Technologies and Practices for Climate-Resilient Livelihoods in Lushoto, Northeast Tanzania." *Climate,* 5(3). (August 15, 2017): 63. https://doi.org/10.3390/cli5030063.

O'Brien, B. and de Bhailís, D. (2021). Use of digital technology in making precision management decisions on-farm. Teagasc News & Events. 6 August 2021. https://www.teagasc.ie/news--events/daily/farm-business/use-of-digital-technology-in-making-precision-management-decisions-on-farm.php.

O'Brien, B., O'Sullivan, C., and Gowing, P. (2018). "Alternative Milking Technologies - Factors Influencing Preferences" in Moorepark Dairy Levy Research Update International Agricultural Workforce Conference, 60-69. Moorepark: Teagasc.

Pagliacci, F., Defrancesco, E., Mozzato, D., Bortolini, L., Pezzuolo, A., Pirotti, F., Pisani, E. and Gatto, P. (2020). "Drivers of Farmers' Adoption and Continuation of Climate-Smart Agricultural Practices. A Study from Northeastern Italy." Science of The Total Environment 710 (March 2020): https://doi.org/10.1016/j.scitotenv.2019.136345.

Palma-Molina, P., Hennessy, T., O'Connor, A.H., Onakuse, S. O'Leary, N., Moran, B., and Shalloo, L. (2023). "Factors Associated with Intensity of Technology Adoption and with the Adoption of 4 Clusters of Precision Livestock Farming Technologies in Irish Pasture-Based Dairy Systems." Journal of Dairy Science 106, no. 4 (April 2023): 2498–2509. https://doi.org/10.3168/jds.2021-21503.

Parce, L. and Donnellan, T. (2025). D1.3 Behaviour Intervention Recommendations – first version, QuantiFarm, EU Horizon Europe, no. 101059700.

Parikoglou, I., Emvalomatis, G., Thorne, F., & Wallace, M. (2023). Farm Advisory Services and total factor productivity growth in the Irish dairy sector. European Review of Agricultural Economics, 50(2), 655-682.

Piot-Lepetit, I., Florez, M., and Gauche, K. (2019). "Understanding the Determinants of IT Adoption in Agriculture Using an Integrated TAM TOE Model: A Bibliometric Analysis." In *Governance of Food Chains and Consumption Dynamics*: What Are the Impacts on Food Security and Sustainability?, 29. Montpellier, France: Institut National de Recherche Agronomique (INRA).

Prause, L. (2021). Digital Agriculture and Labor: A Few Challenges for Social Sustainability. Sustainability, 13(11), 5980. https://doi.org/10.3390/su13115980

QuantiFarm (2021). Horizon Europe Description of the Action (DoA). European Union Horizon Europe project no. 101059700, QuantiFarm.

QuantiFarm consortium (2022). "Project: 101059700 — QuantiFarm Grant Agreement Amendment." Grant Agreement. European Commission, July 1, 2022. GRANTAGREEMENT_Amendment - AMD-101059700-11.pdf.

Rose, D. C., Sutherland, W. J., Parker, C., Lobley, M., Winter, M., Morris, C. & Dicks, L. V. (2016). Decision support tools for agriculture: Towards effective design and delivery. *Agricultural systems*, 149, 165-174.

Rotz, S., Duncan, E., Small, M. Botschner, J., Dara, R., Mosby, I., Reed, M., and Fraser, E.D.G. (2019). "The Politics of Digital Agricultural Technologies: A Preliminary

Review." *Sociologia Ruralis* 59, no. 2 (April 1, 2019): 203–29. https://doi.org/10.1111/soru.12233.

Schoor M, Arenas-Salazar AP, Torres-Pacheco I, Guevara-González RG, Rico-García E. (2023). A Review of Sustainable Pillars and their Fulfilment in Agriculture, Aquaculture, and Aquaponic Production. Sustainability. 15(9):7638. https://doi.org/10.3390/su15097638

Serebrennikov, D., Thorne, F., Kallas, Z., and McCarthy, S.N. (2020). "Factors Influencing Adoption of Sustainable Farming Practices in Europe: A Systematic Review of Empirical Literature." *Sustainability*, 12(22) (November 21, 2020): 9719.

Shalloo, L., Byrne, T., Leso, L. Starsmore, K., Geofhegan, A., Werner, J., and O'Leary, N. (2021). "A Review of Precision Technologies in Pasture-based Dairying Systems." *Irish Journal of Agricultural and Food* Research, 59(2): 279-91.

Shortall, J., Shalloo, L., Foley, C., Sleator, R.D., and O'Brien, B. (2016). "Investment Appraisal of Automatic Milking and Conventional Milking Technologies in Pasture-based Dairy System." *Journal of Dairy Science*, 99(9) (September 2016): 7700-7713.

Stephens, T. (2021). *One Welfare in Practice: The Role of the Veterinarian.* 1st ed. Boca Raton: CRC Press.

Teagasc (2023a). Environment-Climate Action. "Signpost Advisory Programme." Government. Accessed December 5, 2023. https://www.teagasc.ie/environment/climate-action/signpost-advisory-programme.

Teagasc (2023b). "Introducing AgNav - Putting Climate Action Planning Back in Farmers' Hands." Government. *Teagasc News & Events - Daily - Environment* (blog), May 8, 2023. https://www.teagasc.ie/news--events/daily/environment/introducing-agnav---putting-climate-action-planning-back-in-farmers-hands.php#

Teagasc (2023c). *Pathways to Achieving our Climate Action Targets* [Youtube recording]. Introducing the Teagasc Marginal Abatement Cost Curve (MACC) 2023. July 12, 2023. Teagasc Ashtown, Dublin.

van der Weerdt, Verdult, S., and Broderick –Hale, J. and van Hemert, D. (2024). D1.2: Assessing the impact of digital technology solutions in agriculture in real-life conditions. QuantiFarm report, 29 November 2024. QuantiFarm project consortium. European Union Horizon Europe. https://quantifarm.eu/deliverables.

van der Weerdt, C., Wemmers, S., Verdult, S., and Broderick –Hale, J. (2022). D1.1: Behaviourally Determinants for DATS Adoption – first version. QuantiFarm report, 1 July 2022. QuantiFarm project consortium. European Union Horizon Europe. https://quantifarm.eu/wp-content/uploads/2024/07/QuantiFarm_D1.1-Behavioural-determinants-of-DAT-adoption_v1.pdf

Van Evert, F., Gaitán-Cremaschi, D., Fountas, S., and Kempenaar, C. (2017). "Can Precision Agriculture Increase the Profitability and Sustainability of the Production of Potatoes and Olives?" *Sustainability* 9, no. 10 (October 17, 2017): 1863. https://doi.org/10.3390/su9101863.

Weary, D. M., and Marina A.G. Von Keyserlingk. (2023). "Review: Using Animal Welfare to Frame Discussion on Dairy Farm Technology." *Animal* 17 (August 2023): 100836. https://doi.org/10.1016/j.animal.2023.100836.

Weersink, A., Fraser, E., Pannell, D., Duncan, E., and Rotz, S. (2018). "Opportunities and Challenges for Big Data in Agricultural and Environmental Analysis". *Annual Review of Resource Economics*, 10(1), October 5, 2018: 19:37. https://doi.org/10.1146/annurev-resource-100516-053654.

Williams, A., James, J. and Prichard, P. (2022). "Developing an Extension Model of Practice to Guide and Empower Extension Practitioners." *Rural Extension & Innovation Systems Journal* 17, no. 1: 10–20.

Zampieri, A., Director for Sustainable Resources (2024). Overcoming Hurdles: Unlocking the Potential of Digitalisation in Agriculture (Keynote speech by Director for Sustainable Resources, Joint Research Centre, European Commission). EU AgriFood Days, 12 December 2024. European Union.

Appendix A: The QuantiFarm project, an overview

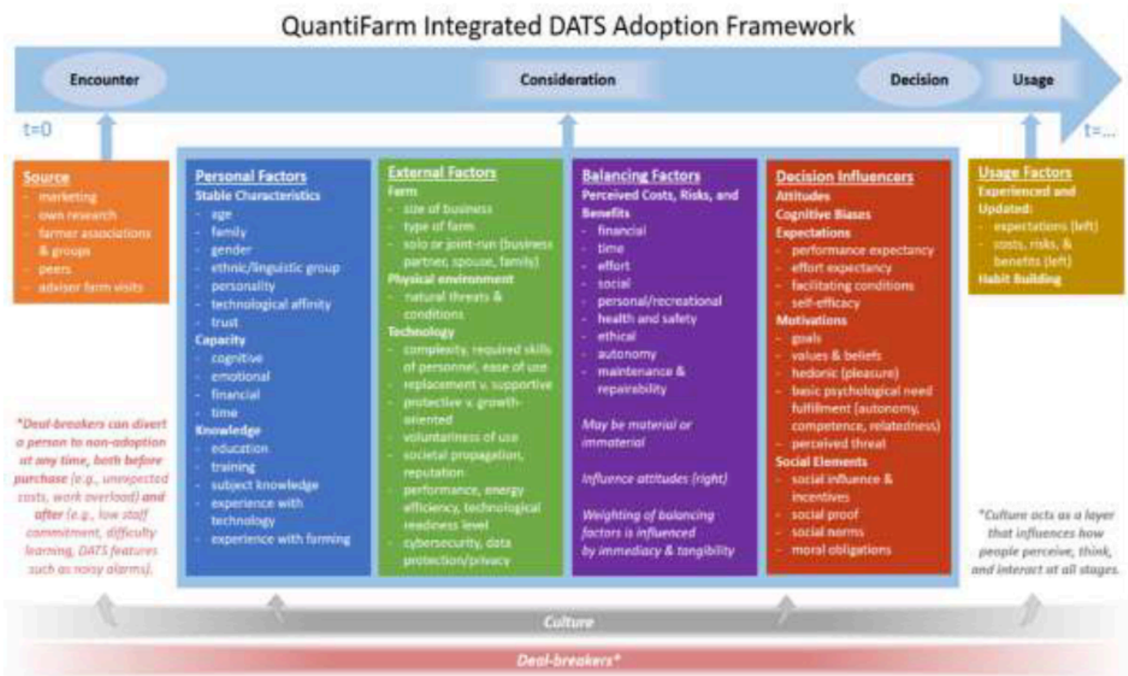
This research draws on the QuantiFarm project, focused on supporting further uptake of digital technologies. QuantiFarm is a Horizon Europe project running from July 2022 to March 2026. DATSs are key factors for improving sustainable performance and competitive, while offering flexibility to ease labour challenges and providing opportunities for greater work-life balance. QuantiFarm aims to deploy innovative and useful tools, services and policy recommendations which are supported by an Assessment Framework. The Framework gathers and qualitatively and quantitatively assesses the multiple costs and benefits of DATSs used across European on diverse small and medium sized commercial farms over three years.

QuantiFarm comprises 32 partners, representing six farmers organisations, eight scientific research institutes and organisations, 10 advisors' organisations and Digital Innovation Hubs (DIHs), eight technology and agri-tech enterprises, one policymaker and three policy influencers, and one certification body. Project activities are built around 30 Test Cases (TCs), spanning 20 countries in 10 (out of the 11) biogeographical regions across Europe, capturing multiple geo-political and financial settings. Over 100 test case farmers, representing 51 farms of different types, sizes, ownership and operating conditions, committed to participate in the project, both directly but also through cooperatives and large umbrella organisations. Each TC consists of at least one type of DATS.

TCs use a variety of technologies across seven agri-food sectors including arable, fruit, vegetables, meat, dairy, apiculture, and aquaculture. In total, there are 38 different DATSs being tested within the project, representing 28 DATSs providers, and 23 categories of DATSs. Technology categories include, satellites, drones, proximal sensors, weather station, robots, instrumented machinery, animal tracking systems, and automatic milking systems. Specific types of DATSs tested include Financial Management Information Systems (FMIS) applications, controlled traffic farming technologies, reacting and variable rate technologies, recording and mapping technologies, robotic systems, and smart machines.

Appendix B

The revised Integrated DATSs Adoption Framework appears in QuantiFarm D1.2 - final version (van der Weerdt et al., 2024).



Appendix C – UN SDGs prioritisation framework

The table below represents the full UN SDG prioritisation framework with commentary on each goals' relevance leading to its designated relevance level in terms of DATSs adoption.

SDG	Goal Description	Relevance Level	Commentary
2. Zero Hunger	End hunger, achieve food security	Extremely High	Core mission of agriculture to ensure food security and sustainable production. Adoption of appropriate DATSs and the data generated can create greater efficiencies for farmers, helping to improve food security.
12. Responsible Consumption and Production	Ensure sustainable practices	Extremely High	Circular economy principles and efficient resource use are integral to modern agriculture. Use of appropriate DATSs in farming systems can help farmers do more with existing resources through the optimisation of labour resources, reduction of inputs, reduction of waste, and increased awareness of animal health and crop health indicators.
13. Climate Action	Combat climate change and impacts	Extremely High	Farmers are key to GHG reduction, carbon sequestration, and adapting to climate change. DATSs provide data which can help create farm-level actions which respond to adverse weather conditions (excess heat, drought, etc.).
6. Clean Water and Sanitation	Ensure sustainable water management	Very High	Agriculture directly impacts water usage and quality through irrigation and runoff. Water-smart DATSs play a key role in promoting sustainable water management. These advanced technologies ease the demand on conventional water sources, boost efficiency in water usage, and decrease water waste from an environmental perspective.
8. Decent Work and Economic Growth	Promote economic growth and employment	Very High	Farming is a cornerstone of rural economies and job creation. DATSs adoption can address labour shortages, attract workers and young farmers with increased affinity for technology, and improve economic stability.
15. Life on Land	Protect ecosystems and biodiversity	Very High	Sustainable land management supports soil health, biodiversity, and ecosystem services. DATSs offer ways to monitor the health of ecosystems. The data produced along with AI tools can provide recommendations for ways to improve soil health and water quality.
1. No Poverty	End poverty in all forms	High	Farm incomes and rural employment are essential to poverty reduction in agricultural areas. Advanced technologies on farm can attract younger farmers into the sector and be a draw for workers with higher technology affinity. DATSs can play an instrumental role in overcoming labour shortages, ensuring rural livelihoods.
3. Good Health and Well-being	Ensure healthy lives	High	Farmers reduce pesticide use and ensure livestock and food safety, promoting public health. DATSs can reduce farmers stress by enabling more flexibility working schedules and reducing animals stress via improved disease detection.
7. Affordable and Clean Energy	Ensure access to clean energy	High	Farms contribute to renewable energy (e.g., bioenergy, solar, wind) while improving efficiency. Alternative energy sources can help power DATSs on farms, reducing the burden on the traditional energy grid.

SDG	Goal Description	Relevance Level	Commentary
9. Industry, Innovation, and Infrastructure	Build resilient infrastructure	High	Technology and infrastructure development improve farm productivity and sustainability. DATSs adoption involves technology providers, R&D, and advisors, all stakeholders who are helping develop a resilient infrastructure for farms and rural development.
14. Life Below Water	Conserve marine resources	High	Reducing runoff and pollution from agriculture protects aquatic ecosystems. Fully automated processes and sensor technology on fish farms can improve production efficiency and increase profits.
17. Partnerships for the Goals	Strengthen global partnerships	High	Collaboration with stakeholders drives innovation and amplifies sustainable initiatives. Increasingly stakeholder engagement within the DATSs adoption process has come to the fore with emphasis on building a trusting environment for more transparent communication and decision making.
4. Quality Education	Ensure inclusive and equitable education	Moderate	Education supports the adoption of sustainable practices and modern technologies. The adoption of DATSs can be improved through experiential education and training which is facilitated by credible experts, peer learning, and the inclusion of technical and soft skills for all stakeholders – farmers, their advisors, technology providers, and policymakers.
5. Gender Equality	Achieve gender equality	Moderate	Empowering women in farming enhances equity and decision-making roles. Including women in the DATSs adoption conversation is critical. Research shows many spouses/partners in male-run farms are involved with administration and decision making, yet aren't included in conversation about DATSs design, use, and policies.
10. Reduced Inequalities	Reduce inequality within and among countries	Moderate	Supporting smallholder farmers and disadvantaged regions is essential. DATSs can support aging farmers by reducing the physical burden of some farm tasks, increasing flexibility in day-to-day tasks for all farmers, and encouraging younger family members, workers, and new farmers to be more involved with small and medium sized enterprises.
11. Sustainable Cities and Communities	Make cities inclusive and resilient	Moderate	Farmers sustain rural communities and connect with urban centres through food systems. Digitalisation of urban and rural farming promotes modernisation, competitiveness, and sustainability by encouraging the adoption of digital technology solutions. Improved interconnectivity and access to broadband and digital tools by farmers and consumers in rural communities and cities bridges the divide and helps bring producers and consumers closer together.
16. Peace, Justice, and Strong Institutions	Promote justice and strong institutions	Moderate	Farmers need fair policies and access to markets and resources for equitable opportunities. Increasingly, policies to enable further digitalisation of farming are receiving considerable attention. Farmers need financial and non-financial supports and incentives to have more equitable and inclusive access to DATSs.

Appendix D

Table 1. Examples of innovation activities closely linked with QuantiFarm.

EU Projects, with QuantiFarm MoUs	Summary	Relevance to QuantiFarm, WP1 D1.3/D1.4
CODECS, Horizon Europe, 2022-2026	CODECS will develop methods, tools, evidence, a vision of "sustainable digitalisation" with the goal of improving the collective capacity to understand, assess and foresee the full range of benefits and costs of farm digitalisation, and to build digital ecosystems that maximise the net benefits of digitalisation.	Sister project. CODECS has a dedicated WP on policy analysis for sustainable digitalization. QuantiFarm can benefit from CODECS outputs as both projects seek to understand and support farmers' motivation and capacity to adopt sustainable practices. Particularly relevant is the overlap around the adoption of digitalisation as an enabler of 'sustainable and transformative change'.
BEATLES, Horizon Europe, 2022-2026	BEATLES aspires to identify individual, systemic and policy lock-ins and levers that influence entire food systems' behavioural change. It seeks to develop transformation pathways of change to accelerate the systemic and systematic transition to climate-smart agriculture and smart farming technologies, fully aligned with the ambitions of the Farm to Fork and Biodiversity Strategies, and the new CAP at regional and EU levels.	QuantiFarm can work alongside and learn from the behavioural framework created from BEATLES' systematic literature review (D1.1), test cases, and policy recommendations to widen DATSs adoption supports and goals of offering practical policy intervention.

Source: Authors' own analysis, with some descriptions adapted from project websites, QuantiFarm's D6.2 (Fotakidis et al., 2023), and the CORDIS repository (European Commission, 2024)

Table 2. Example of further synergies with existing and completed EU projects

Other relevant EU Projects	Summary	Relevance to QuantiFarm, WP1 D1.3/D1.4
NIVA4CAP, H2020, 2019-2022	NIVA4CAP aims to increase the speed of innovation, reduce administrative burdens, sustain broader and deeper collaboration in an innovation ecosystem and provide accepted methods to establish information flows to improve environmental performance. NIVA also promotes reduced administrative burden and involvement of stakeholders. This project's results promote a transparent, simpler administrative process that contributes to a future CAP that increases environmental performance.	QuantiFarm research from WP1 demonstrates administrative burden is a barrier to DATSs adoption. QuantiFarm's WP1 deliverables can build on NIVA4CAP's activities, continuing to promote innovation, reduce administrative burden, and deepen collaborations with stakeholders to improve environmental performance on farms.

Other relevant EU Projects	Summary	Relevance to QuantiFarm, WP1 D1.3/D1.4
Desira, H2020, 2019-2023	The DESIRA project will develop a methodology, and a related online tool, to assess the impact of past, current and future digitalization trends, using the concept of socio-cyber-physical systems, which connect and change data, things, people, plants and animals. Impact analysis will be linked directly to the United Nation's Sustainable Development Goals and will contribute to the promotion of the principles of Responsible Research and Innovation. Involving 25 partners across Europe, the consortium will organise 20 Living Labs and one EU-level Rural Digital Forum, it will ultimately contribute to policy development across the EU.	QuantiFarm's WP1 benefits from Desira's assessment of digitalisation trends. Its linkage to the UNs Sustainability Development Goals can support a SDGs prioritisation exercise in D1.3. Within this project, the Rural Digital Forum can assist QuantiFarm's writing of relevant policy interventions. The identification of three key impact drivers – design access, and complexity – can be added to WP1 research, further shaping policy interventions offered in QuantiFarm D1.3.
SHERPA, H2020, 2019-2023	SHERPA (Sustainable Hub to Engage into Rural Policies with Actors) gathered evidence from across Europe, at multiple levels, regarding digitalisation, showing the directions in which it is most appropriate and feasible to address local needs. SHERPA Multi-Actor Platforms (MAPs) were invited to discuss key topics in relation to their areas: Digitalisation needs; existing policy interventions, with examples of actions taken by local actors addressing these needs; recommendations of policy interventions; ways the EU can support these interventions; knowledge gaps, and areas for further research.	QuantiFarm's WP1 can review SHERPA's MAPs to learn more about digitalisation gaps, existing policy interventions with examples, recommended policy interventions, suggestions for EU support measures, and where knowledge gaps exist. This review can inform policy measures presented in D1.3/D1.4.
MEF4CAP, 2021-2023	MEF4CAP focuses on co-designing the new monitoring and evaluation framework for CAP after 2027. MEF4CAP examines how technology can support data collection for independent monitoring. MEF4CAP will make an inventory of future data needs for M&E, describe the current developments in ICT and data capturing techniques and assess the technological readiness of these solutions. The project will deliver a roadmap for future monitoring, where the needs of different stakeholders are met, and the potential of different approaches is fully and optimally exploited.	QuantiFarm can benefit from MEF4CAP outcomes, building on its technical work for creating solutions for independent monitoring using digital technologies. The MEF4CAP roadmap for monitoring technologies which keeps different stakeholder needs to the fore, can also enhance WP1's understanding of various stakeholder perspectives, ensuring relevant behavioural policy interventions are presented.

Source: Authors' own analysis with some descriptions adapted from project websites, QuantiFarm's D6.2 (Fotakidis et al., 2023), and the CORDIS repository (European Commission, 2024)