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Original Article

Digital Agriculture: A Geographical Study of Smart Farming Practices

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Abstract

This study examines the concept of digital agriculture with a specific focus on smart farming practices from a geographical perspective. Digital agriculture integrates advanced technologies such as information and communication technology (ICT), the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and geospatial tools to enhance agricultural productivity, sustainability, and decision-making. The research explores the spatial dimensions of smart farming, emphasizing how geographical factors such as climate, terrain, infrastructure, and regional development influence the adoption and effectiveness of digital technologies in agriculture. It also analyses core technological components including sensing networks, data management systems, automation, and supply chain integration. By comparing adoption patterns across the Global North, Global South, and emerging regions, the study highlights disparities, challenges, and opportunities in digital transformation. Furthermore, it evaluates the impacts of smart farming on productivity, environmental sustainability, and rural livelihoods, while addressing issues of governance, data security, and digital divides. The findings suggest that although digital agriculture holds significant potential for transforming agricultural systems, its success depends on region-specific conditions, policy support, and equitable access to technology.

Keywords: *Digital Agriculture; Smart Farming; Precision Agriculture; Geospatial Analysis; Internet of Things (IoT); Artificial Intelligence (AI); Big Data; Agricultural Sustainability; Spatial Variability; Rural Development; Agricultural Technology; Data Management; Climate Adaptation; Farm Automation; Digital Infrastructure*

Introduction

The term 'digital agriculture' encompasses a wide variety of practices, advances, and concepts. A commonly used definition, particularly in developing-country contexts, situates it as the modernisation or digitalisation of the agriculture sector at systemic and economy-wide levels, increasingly mediated by digital technologies. It includes the provision of equipment and tools, agricultural extension, weather monitoring, fertiliser, pest and weed management, various market linkages, agromet information, national agricultural censuses, advisory services, and crop and fish production data. Associated descriptors, such as smart farming and other variants, sometimes mark the astuteness of data use or machine learning techniques, algorithmic interventions, and sensor-based data collection and decisions. Experiences elsewhere indicate that emerging digital technologies have greater benefits when existing local systems are already relatively more developed and are able to complement, replicate, or augment corresponding local capabilities in various forms (Nasirahmadi & Hensel, 2022); (Roscher et al., 2023).

Smart farming is characterised as the collection, evaluation, and processing of location-specific information about the environment or production methods to increase production efficiency and sustainability over time. Such information relates to climate, soil, plants, water, pests, and diseases and has been termed location and situation awareness. Both definitions encourage geospatial analysis through the mapping of existing digital agriculture information and the assessment of spatial determinants supporting different applications across societies.

The Conceptual Framework of Digital Agriculture

Grounded in precision agriculture (PA) and agriculture 4.0 (A4.0), digital agriculture employs technologies such as information and communication technology (ICT), the Internet of Things (IoT), big-data analytics, artificial intelligence (AI), and machine learning to enhance food security, food quality, and environmental sustainability amid an increasing population, a growing appetite for higher-quality products, and other pressures on the agricultural system (Kremer Sott et al., 2021).

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Smart farming embodies this technological upgrade of agriculture, encompassing equipment, software, data management, and communication technologies that facilitate the collection of agronomic information for subsequent analysis and decision making. Geospatial operating principles complement this integration: digital infrastructure permits the efficient collection, transmission, storage, and processing of spatially referenced data; a data ecosystem model describes how data is generated, processed, and exchanged for multiple purposes; and governance specifies licensing, access rights, and protocols that help delineate ownership, establish control, and build trust across ever-expanding data networks.

The continuing evolution of the digital revolution has structural implications for the geographies of agriculture. Whereas earlier technico-economic paradigms focused on mechanization, chemicalization, and biotechnology, today's socio-technical systems address the interactive capacity of equipment and living organisms, particularly across the two dimensions of space and time. A historical baseline indicates that spatial variation in the capacity to adopt technological systems is widespread and persistent. The diffusion of telephones, electricity, tractors, computers, and mobile telephony remains differentially distributed yet widely recognizable. Capture of underpinning spatial processes—production intensity, tele-density, roadway density, and trade-connectivity—across equipment, capital, infrastructure, and skills networks clarifies genesis and connectivity, reveals wider linkages and emerging thresholds, and suggests dates of first recognition across countries and first significant adoption within countries (Roscher et al., 2023). The turn of the twenty-first century marks the emergence of digital pathways in tele-sensitive activities, dynamizing space-time relations for both spatial and mix systems of agriculture. Examination of the digital transition in smart farming continues the trajectory of geospatial exploration beyond reviewing equipment and use.

Geographic Dimensions of Smart Farming

Digital agriculture is the use of digital technologies for agricultural production and marketing through the collection, transfer, and data analysis of information (Kremer Sott et al., 2021). These technologies are also called technological solutions. Four technological solutions are regarded as core digital agriculture: (1) digital infrastructure, (2) digital content, (3) digital devices, and (4) digital services. Smart farming, a form of digital agriculture that optimizes agricultural production systems through integrated technology, has recently emerged. Smart farming provides farmers the ability to exploit agricultural data both on-farm and off-farm in one big data cloud.

Digital infrastructure refers to the communication facility and network capability for enabling all kinds of services in agriculture. Communication technology changes periodically, and according to Kremer Sott et al. "the smooth transition of agricultural development depends on the digital infrastructure more than technology adoption." In recent years, space and spatial theories have emerged as an increasing focus of international social science research. Four aspects of digital agriculture can be analysed to contribute to scholarly discussions on agricultural development, technology diffusion, digital divide, and regional gap; these are namely (1) smart farming technological solutions, (2) digital agriculture territorial patterns, (3) development policy frameworks and (4) procedure digitization, eco-circularity and ecological footprint.

1. **Spatial Variability in Agricultural Systems**

Agricultural systems exhibit substantial humanitarian, economic, and ecological variability at different spatial scales across any given region. Agro-ecological factors such as soil type, topography, and climate systems vary extensively within a given area; hence, the concept of space is not only physical but involves human perception. Human-induced processes within specific physical environments give rise to the concept of place, representing the interrelationship of people, society, culture, and territory. These variations exert clear influence across regional innovation systems, including consideration of regional policies, governmental support, skill sets, human capital, investment and entrepreneurship, access to media and financing, collaborating communities, and market access across a big-to-small scale continuum (Kremer Sott et al., 2021). The level of development for any region or country determines the variety of agricultural systems from subsistence, commercial, semi-commercial, and corporate types. Various forms of digital agriculture can also be observed and these forms are classified according to factors such as consumer access to markets, support from local governments, industrial base, and cultural background.

Such spatial variability determines regional differences in the farm types or systems producing food commodities, the different agri-food supply chains or systems, the type or series of digital agricultural practices/technologies/solutions, and configuration of a region-wide smart farming ecosystem. Three observations can be made on the spatial variability of agriculture systems: the type of farming systems, the biophysical environment, and the access to market types. Low-tech agriculture predominates in many areas of Africa, Middle East, Latin America and other regions. By contrast, smart farming as an agriculture 4.0 practice emerges since 2013 in the Global North countries. Such considerations are reflected in the regional maps of smart farming in the subsequent sections.

2. **Access to Digital Infrastructure Across Regions**

While usage of mobile phones remains limited, access to digital infrastructure is expanding through mobile devices, enabling rural community access to agriculture-related ICTs and applications. Connectivity along value chains has become more ubiquitous, with farmers employing mobile phones to procure market and weather information. Public data and information are increasingly accessible and reusable online. Scientists and their collaborators access a variety of applications across digital clouds, facilitating remote collaboration. Tools and knowledge bases are becoming interconnected, sharing information and workflows across disciplines, research cycles, and value chains. Involvement of diverse actors—including farmers

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and traders—in agricultural research and innovation systems is also increasing (G. Ballantyne et al., 2010).

3. **Terrain, Climate, and Resource Gradients**

Terrain, climate, and resource gradients shape the potential for adopting smart-farming practices. Geographical characteristics command significant attention as a major factor influencing diverse digital agriculture approaches. Variations in climate conditions affect the types of crops cultivated, the timing of farming operations, and, consequently, the degree of automation employed in agriculture. Flat terrain facilitates greater mechanization and automation in farming compared to uneven land, and access to supplementary water resources through rainfall or irrigation influences the mix of farming activities undertaken. These geographical gradients also govern the ordinary agricultural situation encountered by farmers, thereby affecting the expected performance and returns of various digitization routes. For instance, a farmer able to cultivate diverse crops across both rainy and dry months is likely to invest in ready-to-market solutions such as yield monitoring or supply-chain tracking rather than non-yield-based options (de Paul Obade & Gaya, 2021). This study links climate and terrain indicators to the smart-farming context in order to outline their influence on the choice of digital technologies, investment priorities, and the anticipated scale of adoption.

Core Technologies in Smart Farming

In most parts of the world, farmers widely adopt a diverse range of technologies, which they integrate with existing systems to attain significant changes in agricultural practices. The pace and extent of such adoption vary with technologies, spatial scales, and agro-ecological, socio-economic, and political factors. To comprehend the modernization of the agricultural sector, it is essential to determine the conspicuous trends of technology adoption, to catalogue core technologies and their contribution to smart farming within an overall agricultural digital transition, and to investigate the underlying influences of spatial variations.

Fundamentally, smart farming relies on a physical infrastructure of equipment, vehicles, facilities, and buildings that service production and supply chains. Sensors, satellites, and drones collectively equip a sensing network capable of monitoring dynamic ecosystems and various production and environmental variables (Guevara et al., 2024). Infrastructure comprises soil, weather, and climate; water resources; pest and disease; product quality; and farming systems. Deployment of these technologies is geographically uneven, resulting in spatially varying technology landscapes and consequently differential smart farming prospects. Technologies not only serve heterogeneous contexts and functions but also interact through the exchange of dynamic data, which influences technology pathways, disciplines, and associated public interventions (Kremer Sott et al., 2021). It is therefore imperative to catalogue core technologies and examine spatial variations.

1. **Sensing and Sensing Networks**

Sensing networks enable the collection of spatially-distributed data via interconnected sensors. They support monitoring of input application, crop growth, animal well-being, environmental quality, and compliance with regulatory requirements. Smart-farming applications cover a broad spectrum; which functions are targeted depends on farmland/enterprise characteristics and user preferences.

A survey of smart-farming adoption identifies four basic technology components: (i) sensing, (ii) data management, (iii) automation, and (iv) supply chain interfacing (Zelalem Bayih et al., 2022). The zero or near-zero adoption of data management, automation, and supply chain functions—dubbed "first-generation" digital agriculture—accords with the idea that early usage concentrates on basic data capture and supply chain linking (Javier Ferrández-Pastor et al., 2016).

2. **Data Management and Analytics**

The revolution of digital agriculture has seen concrete developments of multi-functional data management platforms to tackle data problems in agriculture research and production (Pan et al., 2023). CyVerse is a Google Cloud-based data management solution for big-data applications in agriculture. GARDIAN allows researchers to discover datasets, publications and expertise generated by large agricultural research programs, facilitating collaborative work among different disciplines. GEMS integrates genomic, phenotypic and environmental data and provides a suite of tools to manage, analyze and visualize large agricultural datasets. TERRAREF provides high-resolution sensor data of complex plant growth and environmental conditions, enabling the understanding and modeling of plant-environment interactions. A structured approach for the management and utilization of agricultural remote sensing big data is proposed to enhance productivity in precision agriculture. Data warehousing and decision support systems, like continent-scale crop data warehouses, leverage related, heterogeneous crop data, improving decision-making, operational efficiency and sustainability in agriculture.

Geostatistics is a technique widely utilized to identify soil spatial variability, leading to the collection of more soil data and the mapping of soil heterogeneity (Kremer Sott et al., 2021). Georeferenced analyses help farmers visualize digital agricultural information. Although beneficial, spatial variability analyses often entail high costs, restricting their use among smallholder farmers. Future endeavours should concentrate on reducing spatial variability analysis expenses. The advent of Global Positioning Systems (GPS) represents a pivotal milestone in the establishment of digital agriculture. The use of GPS, combined with Geographical Information Systems (GIS), remote-sensing and variable-rate technology, enhances productivity and reduces operational costs. Hybrid GPS technologies improve the precision of agricultural practices such as seeding, plowing, watering and fertilizing, contributing to the sustainability of agricultural systems.

3. **Automation, robotics, and AI in Farm Operations**

Agriculture is increasingly embracing automation, robotics, and artificial intelligence. Practical examples include aerial imaging drones equipped with multispectral sensors to monitor crop health; automated irrigation systems controlled by wireless sensor networks; and computer vision

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algorithms that count seedlings in greenhouses. Robotic systems for weed management (both autonomous and intra-row methods based on machine vision) are under development. Automated harvesting equipment and artificial intelligence-powered farm management software also show promise (Nagel, 2019). Nevertheless, issues such as cybersecurity vulnerabilities and the high costs of advanced machinery pose obstacles. Overall, agriculture is moving towards full automation of production processes, from sowing to post-harvest, through the combined applications of the Internet of Things, artificial intelligence, and autonomous vehicles.

The world's population has surpassed 7 billion and is projected to reach 9 billion by 2050, necessitating increased agricultural output while conserving resources. Traditional mechanised agriculture relies heavily on petrochemical energy. Smart farming offers access to state-of-the-art technologies that enable a timely response to the varying conditions present within a field through advanced data gathering, processing, and dissemination. Such automation is feasible, yet the need for flexibility in these dynamic environments and the associated infrastructure investments present challenges. Using small intelligent mobile robots that perform specific tasks, for example, can lower production costs by allowing mobility and adaptability (R. Aravind et al., 2017). The introduction of robots into agriculture brings benefits such as sustainability improvements, consistent execution of tasks, and overall cost savings. Various types of agricultural robots are available, including autonomous tractors retrofitted with electronics and communication components, and compact mobile solutions to assist harvesting operations. Multiple robots can communicate with one another, coordinating activities to boost efficiency.

4. **Supply Chain and Market Interfaces**

Production and post-harvesting require planning and coordination along the supply chain. Pricing remains a key factor for farmers when making planning decisions. Planning takes place at various levels, including after-seeding, post-harvest, and tillage planning, and depends not only on prices but also on many other variables such as contracts stipulating delivery schedules and volumes, availability of alternative markets, the potential to acquire other commodities, possible forward contracts, seasonal patterns, and various other technical, regulatory, and machinery constraints. These planning tiers are connected vertically, which means that variables and decisions from one tier may inform planning in the other tiers (Prause et al., 2021).

Case Studies by Region

Digital agriculture is defined as truthful using a geospatial framing only with precision using OECD definitions. Its scope is further narrowed down to smart farming as it is understood within the digital agriculture literature. Geospatial framing is the lens through which geographic issues affecting digital agriculture adoption and practice worldwide are addressed, as the review of the literature suggests a marked gap in the geography of agricultural technology of all sorts. Geospatial development is as relevant to digital agriculture as it ever was because agriculture depends on climate and the demands for it range from region to region, especially in developing countries. Since the early indications of still early literatures on precision agriculture, studies believed, expected, and pondered growing adoption and use of precision agriculture by farmers, yet the situation continues to be far from universal or even close to it, hardly satisfying even the intended uses of the original definitions. Because of it, farmers and policy makers were pointedly interested in understanding the widespread adoption of precision agriculture, the newly emerged peer in precision agriculture hence caught attention as a potential wider cover of the heterogeneity coordinating this issue and the applied case on it is expected to probe the specificity of the digital agriculture being captured; so far the need of finding the relevant digital agriculture class remains pertinent, a broader scope than morning interest in smart farming per se capable of draws ample reply upon first accessing the authors' consequently launch of yet another tier revisiting the scope of digital agriculture again wider than smart farming alone. Depending on which definition of digital agriculture being relied on, sufficiently regional coverage either can or cannot be achieved or can or cannot be checked fairly reasonably still remains an open revisit to the digital agriculture definition fundamentals itself is brought forward again to settle the merely yet early supply attempt.

Classifying digital agriculture as encompassing smart farming and targeting initial accessibility roll out at southern context; Such spatial elements are also captured under greater and greater digital agriculture specification scrutiny.

One class of smart farming emerging was distinguished as recommend running on merely monitoring and complementary to precision farming, necessitating further understanding of such combination and of agricultural information systems collapsing would provide another framing. Yet a pivot of opening barriers appeared as suitable move steering between southern wake and northern catching unit inquiries.

Extent simpler impression but less captured nevertheless fits outline can still be set down for early executes in any area. Foundational works are acknowledged earlier on classifying and structuring the agriculture industry, some hints get extracted out of them on a far wider level on precisely agriculture remaining way open meantime yet reiterated once other some concerns blocking away preservation breeding are broadly taken in scope meanwhile farmer flock south covers naturally.

The further wider positioning passage echoing down on mechanism large backdrop hence pops up more attractiveness under wider stepping framework fit access cover southern outer don't know check further down precisely enough yet hence crop down easier coating pushes nevertheless easy while substantial precisely remains openness for ascertain nor broad surround emphasis gathering still unattended (Kremer Sott et al., 2021).

— 'references': * 'cite_from': "(Carmela Annosi et al., 2019)" 'cite_id': "8084d044-82d6-4b4c-885c-f88282b48803"

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1. **Global North: Adoption Patterns and Policy Environments**

Smart farming practices exhibit geographical patterns that reflect farming systems, connectivity, climate, and terrain (Kremer Sott et al., 2021). Advanced mechanization characterizes large-scale farming systems, with terrain and location posing constraints on adoption. The conventional continuous growing system emerges from crop–livestock land management, with climate conditioning adoption of specific technologies (Carmela Annosi et al., 2019). Access to timely consumption and monitoring of transport and logistics shaping follow-up services and crop delivery trigger various digital tools. For the developed economies of the Global North, the digital agriculture policy environment comprises digital infrastructure, policy mechanisms, and supporting institutions. A comprehensive OECD survey of digital farming covering sixteen member countries reveals that most countries have well-structured policy frameworks to encourage adoptions and they carry out multi-dimensional investments to further develop the foundations of digital farming, including easing burdens on data transfer among the public sector, private sector, academia, start-ups, and overseas partners while a few countries even undertake national digital farming pilot projects to facilitate farmer innovations (Terhorst & Garrard, 2022). Canada, Denmark, the Netherlands, and New Zealand are at the forefront of these initiatives. In addition to traditional agricultural support, Australia, Iceland, and Switzerland are extending practical instruments such as insurance to agribusiness activities toward establishing risk management policies essential for digital farming experiments and specific consulting services concerning processing and packaging are offered to help fledgling start-ups.

2. **Global South: Innovation, Constraints, and Dilemmas**

Innovations in digital agriculture proliferate in the Global South, propelled by startups engaging with unsatisfied needs across Africa, Asia, and Latin America. Countries including Bangladesh, Brazil, China, Ethiopia, India, Kenya, Nigeria, and Thailand experiment with remarkable initiatives, burgeoning platforms, and scalable solutions (Kremer Sott et al., 2021). Diverse innovations arise in varied settings, with distinct arrangements of government, industry, and academia (Lemeilleur et al., 2019). Resource constraints stimulate inventive approaches to construction, and contradictory pressures challenge prioritisation in multifunctional systems. Within the Global South, digital agriculture allows individual countries to select pathways offering high potential and attractiveness, while concurrently pursuing collaborative learning and transfer through South-South cooperation. Nations benefit from awareness of other rural circumstances, possible farm designs, distinct motivation, and partial solutions adaptable to different scenarios.

3. **Emerging Regions: Hybrid Models and Knowledge Transfer**

Various European scholars detected significant geographical differences in the adoption of digital agriculture technologies as well as in policies promoting such technologies. A certain degree of commonality is observed within the EU, where countries are united in their approach to building digital infrastructures and designing common policies (Kremer Sott et al., 2021). In transition countries of Eastern Europe still moving towards Europe and relying on environment-sensitive sectors like agriculture, these regions may evolve towards a knowledge hub. Besides state-of-the-art technologies like big data, cloud computing, IoT, drones, blockchain etc. that are difficult for small farmers to access, countries such as China, Brazil and Mexico are exploring hybrid models that combine traditional and digital solutions.

The hybrid model comprises success stories from different countries reflecting challenges at different stages of agricultural sector development and governance choices on the evolutionary path. The farmer-to-farmer model of knowledge transfer fills the equipment gap of smallholder farmers and facilitates the diffusion of systemic solutions. Traditional agricultural research systems are not sufficient for smallholder farmers. Makerspace, fields observation network and other hybrid models could originate from personal experience of doctoral students or professors in institutes of technology.

Impacts on Productivity, Sustainability, and Rural Livelihoods

This section examines how the adoption of digital technologies and smart farming practices affects three key outcome areas: productivity, sustainability, and rural livelihoods. Impacts on productivity and sustainability are considered first; impacts on livelihoods, including rural labour and networks, are considered subsequently as a distinct dimension.

A growing body of quantitative empirical evidence demonstrates that the adoption of digital technologies and smart farming practices is associated with significant productivity gains, along with reduced reliance on physical inputs and increased yield stability (George Bocean, 2024). Smart-farming technologies facilitate online engagement with suppliers, enable more efficient precision planning, and allow greater yield and soil mapping to determine the best strategies to follow (Steinweg, 2023). The geospatial mapping of food production supports farmers in determining not only what to plant, but also when and how best to grow and harvest, contributing to increased yields (Steinweg, 2023). The spatial pattern of adoption and the characteristics of practices in a region contribute significantly to shaping these gains (Bocean, 2024).

The environmental sustainability of adoption remains ambiguous. Widespread claims circulate that smart farming leads to substantial reductions in physical inputs such as fuel, fertilizer, and water. Although the reality is less clear-cut, some studies confirm that smart-farming practices generally favour greater resource stewardship and adherence to environment-friendly regulations (Bocean, 2024). As a general tendency, the sector-wide assessment of food safety regulations has been found to reinforce a more environmentally sustainable pattern of adoption (Bocean, 2024). Precision technologies lower the risk of oversaturation, improve climate-resilient practices, secure control over physical inputs, and increase selective input usage. Among farmers without access to smart technologies, mitigation measures against climate change include techniques that are highly detrimental to the long-term preservation of the productive capacity of the land (Steinweg, 2023). In another investigation, however, precision agriculture has been associated with measures that elude compliance with implemented schemes (Steinweg, 2023). As a result, significant knowledge gaps persist concerning the specific sustainability outcomes engendered by smart-farming solutions.

Analysis of the influence of spatial factors highlights the distinctive social and economic effects of adoption. The automation of high-skilled decision support systems and agriculture robotics extends the applicability of millennial capital to smaller farms. Significant scope remains for small youth-constrained farms to introduce automatic systems that generate economically viable farm plans in a wide spectrum of contexts (Steinweg, 2023).

1. **Productivity Gains and Resource Efficiency**

The incorporation of digital technologies into agriculture not only changes production methods but also modifies the nature of the agricultural process itself. Although agricultural intensification remains a primary objective in many regions, smart farming can also promote resource efficiency while increasing productivity. Quantitative analyses provide evidence of a broad range of economic benefits derived from the adoption of smart farming technologies.

On a dataset of approximately half a million observations covering 190 countries, a cross-sectional econometric analysis using a global synthetic control method identifies that the use of digital technologies, including farm management information systems, cloud computing, and precision irrigation, significantly enhances total agricultural productivity while increasing agricultural production and profitability (Carillo & Abeni, 2020). Further panel-data regression analysis reveals that smart farming facilitates resource-efficiency improvements by raising the value of total production relative to the investment level. This effect is particularly pronounced in regions and countries with higher levels of infrastructure provision and policy support but is also detectable in settings with limited access to basic infrastructure (Kremer Sott et al., 2021).

2. **Environmental Implications and Climate Adaptation**

Research indicates that smart farming technologies can mitigate environmental pressures, facilitate climate adaptation, and enhance resource stewardship. Three broad impacts emerge: (1) improved water management and reduced runoff; (2) lower greenhouse gas (GHG) emissions; and (3) enhanced crop residues and soil health. The capacity for smarter resource management correlates with infrastructure and climate conditions. Smart farming does not universally bolster climate resilience; for instance, increased mechanization may amplify vulnerability to acute shocks. These observations remain tentative and warrant further investigation in the context of a changing climate.

Smart farming technologies support enhanced water management and runoff reduction by enabling site-specific irrigation, including precise water scheduling and monitoring, as well as automation of irrigation systems. Irrigation is critical for crop production in many regions (Kazimierczuk et al., 2023). Water-saving investments are typically less favourable where economic and climatic conditions are less conducive to digital agriculture (Kremer Sott et al., 2021). Digital technologies further enable GHG emission reductions through precision application of farming inputs, such as sewage sludge, fertilizers, chemicals, and biostimulants. Adoption of DA technologies may also lower nitrous oxide emissions by predicting plant nitrogen responses and adjusting fertilizer rates accordingly.

3. **Social and Economic Effects on Farming Communities**

Digital technologies in agriculture, often called digital agriculture, smart farming or precision agriculture, have a profound influence on the social and economic structures of farming communities. Research emphasizes the need to examine the adoption, use and adaptation of these technologies, how they influence farmer identity, skills and farm work, the way agricultural knowledge and innovation systems develop in relation to them and who participates in this development. Governance of digital agricultural systems has raised concerns about power, ownership, privacy and ethics, as the potential influence of these systems on farmers' livelihoods and wellbeing remains partly unaddressed by the research. Despite the significant implications of digitalisation for economic performance, further exploration is still required regarding the economics and management of digitalised agricultural systems and the power and economic implications these hold for farming communities (Duncan et al., 2021); (Carmela Annosi et al., 2019); (Fleming et al., 2018).

Governance, Policy, and Ethical Considerations

Many digital agricultural systems have an emphasis on the governance of data and technologies in relation to land and infrastructure. This is partly because of the multi-modal nature of the systems and partly because digital technologies are seen as disruptive and powerful (Moschitz & Stolze, 2018). In many cases, interactions arise from an ethical or socio-technical angle, concerned with rights, equity, fairness, participatory governance, transparency, inclusion, and trust.

Data governance regimes describe the policies, actors, and processes associated with data governance, drawing from existing literature. Themes that have emerged from analysis of frameworks across agricultural innovations and other sectors are discussed. These include direct ownership, regional or national sovereignty, collective ownership, multiple rights (e.g., ownership, control, access), trust brokers, the relevance of cross-border governance, and the importance of multiple metadata items, such as provenance and quality.

1. **Regulatory Frameworks and Data Sovereignty**

Smart farming technologies generate a large amount of multimodal data that can affect farm management decisions, product traceability, and supply chain optimization. One of the major challenges related to the digitalisation of agriculture is the governance of data. The ownership of datasets, privacy of the information collected, and practices of data sharing are key issues that require adequate regulatory frameworks. An additional challenge arises when digital agriculture mainly involves the analysis of data collected in regions other than where it is used (Fraser, 2017). Data sovereignty that rests on the physical location of data is tightly connected with questions of regulatory compliance, sharing and ownership (Sanderson et al., 2018). As countries and regions adopt various frameworks for the digitalisation of agricultural practices, the cross-border flow of agricultural data raises a number of questions regarding the evolution of the regulatory and legal contexts (Kotal et al., 2023).

2. **Access, Equity, and Digital Divides**

Having moved from examining agricultural practices to policies, the next topic shifts the focus from the articulation of objectives to implementation. As with the preceding one, the framing affects the content, yet it remains broad. The aim is to identify if potential unequal access to digital agriculture constitutes a barrier to its implementation. Two discourses suggest that access concerns remain: the pervasiveness of a digital divide an advanced country such as Australia (Terhorst & Garrard, 2022); and the pursuit of universal access to these technologies as part of rural revitalization strategies in rapidly developing countries (Kremer Sott et al., 2021). These insights point to access not being an obstacle for agricultural stakeholders in the Global North and globally outside smart farming, and similarly for the Global South to a lesser extent.

As pointed out by the Australian authors, the fundamental preconditions for digital agriculture are in agricultural policies, with few settings letting them influence technology use or locations. Access implies ownership and therefore assistance, which further supports the hypothesis. Rather than being a core driver, access and regional digital divides may constitute an additional facilitating dimension in a much broader process that reshuffles agri-food systems through data and knowledge circulation across geographies.

3. **Privacy, Security, and Trust in Digital Agriculture**

To preserve productive, sustainable, and resilient food systems, actors need confidence that the essential digital systems governing agriculture will collect, store, and use data securely and without jeopardising personal privacy. Trust issues involving data privacy and security loom large for digital agriculture, particularly in systems involving multiple partners, such as data producers (e.g., landowners, farmers), data intermediaries (e.g., cooperatives, consultants), and data users (e.g., processors, retailers). Emerging digital systems introduce new data privacy and security threats. Different partners often lack a shared understanding of digital agriculture systems and concerns regarding privacy, security, and trust; even parties with a similar understanding might weigh these issues differently. Attempting to describe overarching privacy, security, and trust constructs for digital agriculture as a whole instead of developing distinct analyses for different types of systems (spatially, sectorally, and technologically) keeps information too general. Application scenarios vary widely and remain challenging to specify in many rural areas.

Technological advances such as remote sensing, cloud computing, and the Internet of Things facilitate data generation, collection, sharing, and processing, promising more efficient and precise production decisions (Ahmad Awan et al., 2020). Expanding agricultural data infrastructures and ecosystems and the influx of commercial services complicate regulatory compliance across national jurisdictions. The General Data Protection Regulation (GDPR) specifies rights for data subjects regarding collection, processing, and storage, notably including the right to erasure and the right to restrict processing (Kotal et al., 2023). Majorities of farmers and agribusinesses express apprehension regarding data use; a high share of cooperative members remain uncertain about how confidentiality is maintained within supervision platforms. The situation remains simpler in the Digital Pump, a self-maintained data-tracking dashboard for irrigation that utilises no classified data, thus bypassing data privacy issues altogether.

Methodological Approaches for Geographical Inquiry

Smart farming is a worldwide phenomenon being examined in disciplines such as agricultural science, technology studies, geospatial data science and geography. Different regions adopt smart farming at different rates and in different ways, making a geographical approach to studying phenomena like smart farming essential (Kremer Sott et al., 2021). Geographical features, such as the density of farmer cooperatives, are known to influence agricultural technologies like precision agriculture, and thus it is reasonable to assume that smart farming fits a similar pattern of geographical influence (Duncan et al., 2021). A clear understanding of smart farming requires the investigation of its geographical dimensions, mainly through the geographical features of technology adoption, the geographical similarity of farmer cooperative configurations and the geographical insight of supplemental models. Such an inquiry is possible mathematically, using correlation analysis to derive the relationships between the models, patterns, drivers and other concepts of smart farming.

To ensure a comprehensive understanding of the geographical aspects of digital agriculture, a combination of methodologies has been chosen. This study applies spatial analysis, remote sensing and a range of qualitative inquiries. Spatial patterns and interactions are foundational to geographical study; therefore, spatial analytic methods and relevant datasets are preferentially used. The geographical dimension of phenomena can be monitored and assessed using remote-sensing or telemetry technologies; for example, it can reveal biophysical developments, land-use transition and urbanisation of dwelling stocks. The dating of georeferenced photographs and high-resolution satellite imagery, combined with auxiliary information, facilitates the monitoring of smart farming developments in the geographical context of innovation development. Such a combination illuminates the interrelationships between smart farming's spatial patterns, enabling factors, and contextual settings and development trajectories. An understanding of geographical phenomena often requires insight into the local meanings, logics and rules associated with those phenomena, particularly when those phenomena are geographically uneven, culturally clustered or policy dependent. Participatory and qualitative methodologies are engaged to obtain these insights.

1. **Spatial Analysis and GIS Techniques**

Because digital agriculture incorporates various web-connected devices, sensors, satellite imagery, and other spatial technologies, the spatial patterns of adoption and impact are complex. Event data provide the basic framework for understanding these dimensions. By journaling and archiving the temporal sequence of observed signposts at regional and local sites, considerable insight into the geospatial characteristics of digital agriculture is generated.

All dimensions of spatiality—space, place, and spatial processes—have been used to characterize digital agriculture practices and initiatives, including significant evidence about smart farming adoption at the national and regional levels (Sanyasinaidu, 2017). Oasis, in the Western Cape, serves as an indication of what adoption looks like and what is feasible. Most districts are rural, but the significant urban area of Cape Town represents a very different economic geography. Farm sizes, both large and small, are also diverse. Therefore, this spatial analysis framing provides essential information about potential velocities, expectation management, and amplification mechanisms.

2. **Remote Sensing and Telemetry**

Remote sensing and telemetry constitute distinct but complementary approaches for studying and monitoring location-based activities in agriculture through methods such as satellite-acquired images, aerial photographs, and igc networks. Remote sensing and telemetry underpin agricultural monitoring systems implemented in integrated pest management, crop growth monitoring, soil moisture monitoring, and other agricultural applications to reduce agricultural losses, minimize pest damages, and improve crop growth (Kremer Sott et al., 2021). They are also widely adopted by farmers and agricultural companies in many countries including but not limited to the United States and China, where the annual production of remote sensing data in agriculture reaches billions of square kilometers.

3. **Qualitative and Participatory Methods in Spatial Contexts**

Participatory and qualitative approaches offer complementary measures to integrate social constructs within digital agriculture, capturing non-quantifiable aspects fundamental to technology acceptance. The emphasis on context-specific farming systems and sociocultural variances necessitates understanding local meanings and drivers, particularly given adoption disparities stemming from cultural resistance (Marx et al., 2016). Qualitative methodologies thus serve as a valuable supplement in conjunction with spatial analyses of infrastructure and functions, enabling a broader comprehension of diverse technology contexts involved in smart farming. While qualitative data remain often overlooked in the rapid advancements shaping biophysical and socio-technical sciences, the scarcity of theoretical frameworks for their integration attests to their crucial value in enabling thorough comprehension of local settings (Fischer, 2022).

Participation in assembling a representative digital agriculture portfolio elaborates on infrastructural and functional delineation within different geographical and socio-technical frameworks. Distinct regional cases illustrate the interplay of technological infrastructures, environmental features, crop and livestock systems, policy supports, and sociocultural preferences motivating smart farming actors. The formation of spatially endorsed typologies concurrently conveys knowledge on diversified smart farming expressions that deviate from the blueprint standards disseminating through manuals and online resources, permitting users to absorb motivational and anchoring elements stemming from geographical, environmental, and institutional heterogeneities. Such efforts recognize that digital agriculture does not benefit from universal solutions, aligning with the literature stressing the socio-technical and policy-specific nature of the phenomenon; Munoz-Rojas, 2020).

Additional field visits delve into low-tech sensor apparatuses guiding access to dedicated regional exhibitions, commodity supplies, or farmer gatherings pivotal in ongoing digital agriculture awareness. They also characterize the rise of a barely formalized agronomic advising profession responding to frequent farmer requests concerning both the acquisition and operational modalities of connected apparatuses. Heightened apprehension exists among spatial data practitioners surrounding the compatibility of spatio-temporal modelling or standardization frameworks with novel spatial materials perceived as social, dictating prior compilation of user-centric, problem-solving exemplars beforehand (Musy, 2021).

Future Trajectories and Innovations

Digital farming is at the dawn of the fourth industrial revolution (Agriculture 4.0), where information and digital technologies, big data, the Internet of Things (IoT), and artificial intelligence (AI) are integrated within agricultural processes to improve productivity and the overall efficiency to tackle complex and interconnected global issues like population growth, climate change, food security, resource depletion, and economic turmoil (Kojo Gyamfi et al., 2024). An increasing reliance on automation, data-driven decision-making tools, and the collaboration between farmers and robots are observed to assist farmers in producing smarter farming systems (Kremer Sott et al., 2021). More agricultural machinery, operation size, and intensification of farming systems may render scheduling, planning, and forecasting tasks complex and time-consuming. With the rapid development of technologies, the digital farming sector is continuously evolving, and tracking future innovations and trajectories becomes essential to grasp the overall development direction of the sector.

1. **Intelligent Decision Support and Autonomy**

Digital agriculture promises transformative benefits for input efficiency, waste reduction, and enhanced decision-making. Over time, however, increasingly sophisticated equipment and systems pose challenges for trust and complexity. Such systems operate with high autonomy—informing or deciding actions independently of human input, relying on external signals or prior events. Continual and singular autonomy is common. Analysis of autonomy

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shares three axes, continuously automated versus decision support, high autonomy versus supervised action, and operational context on farm versus off-farm. Autonomous systems can still perform high-value tasks beyond routine control. Automated tractor guidance exemplifies progressive digital agriculture, shifting progressively from tractor-mounted manual systems with operator skill to sophisticated guidance systems permitting non-operational time.

2. **Interoperability, Standards, and Open Data**

"Upward trajectories of larger farms are associated with increased digital maturity, which can lead to farm consolidation. Free and 1d326cf7-a54a-4cad-9e02-67c2c64f870e access to data improves equity and provides a counterbalance to this concentration of power." – (Fleming et al., 2018) Open frameworks and standards on data and operations of farm management records, access to reliable off-the-shelf applications, connectivity to sensor data, widespread spatial reference information, and the capacity for archiving, sharing, and public engagement can help to reduce throughputs and leverage scientific datasets for regional priorities. Emerging trends and technologies can be monitored and addressed in an evolving toolbox tailored to local priorities. (Høxbroe Jeppesen et al., 2022) Data and trust are crucial. From a technological vantage, it is possible to identify and assess the degree of 1d326cf7-a54a-4cad-9e02-67c2c64f870eness of datasets across public infrastructure. These dedicated 1d326cf7-a54a-4cad-9e02-67c2c64f870e data infrastructures, including sensor data and catalogue systems, are gradually gathering momentum and can assist planners in publicly monitoring these data streams, rendering matchmaking and knowledge transfer simpler. Data and sensor incompatibility as a result of the spatial and technological fragmentation of agriculture creates barriers that impede widespread adoption. Agriculture spans a multitude of sectors, farming practices, and species, and thus concrete threshold conditions vary significantly both at the local and regional levels. The capabilities for sensor fusion, metadata specification, and 1d326cf7-a54a-4cad-9e02-67c2c64f870e protocols are relatively well established and can promote early deployments. Interoperability challenges related to sensor, protocol, and software 1d326cf7-a54a-4cad-9e02-67c2c64f870e data across the full supply chain are significant. The required technologies and governance systems remain an 1d326cf7-a54a-4cad-9e02-67c2c64f870e domain for experimentation and illustration. Market maturity lies well below envisaged futures, and setups continue to pursue proprietary business models rather than shifting to hybrid models.

Open and geospatial data occupy a central position in the current digital transformation of agriculture. Although their importance is widely acknowledged, the unique spatial dimension of agriculture provides a promising entry point for local and regional actors. Open datasets are beginning to coalesce in the interest of agriculture, and evidence suggests that these activities have positive momentum and that the adoption of modular and public infrastructures is prevalent. Concerns over digital territorialization—the emergence of a patchwork of data ecosystems ruled by a small number of dominant players that consolidate power—are emerging. A variety of data ecosystems are evolving, along with countermeasures that cultivate modular and distributed systems with limited dependency on few specific actors. Resourcing and coverage remain major challenges that have implications for 1d326cf7-a54a-4cad-9e02-67c2c64f870e data uptake, and varying international experiences 1d326cf7-a54a-4cad-9e02-67c2c64f870e avenues for reflection. (Open Data for Agriculture and Nutrition, 2016) The diversity of the agricultural sector in Europe means that no single data framework or approach will suffice for the entire continent. The domain consists of multiple sectors, diverse activities and farming systems, different climatic and biophysical environments, a wide spectrum of value chain structures, and multiple decision-making modes. Very significant technological, social, and institutional changes are anticipated alongside the evolution of digital agriculture.

3. **Resilience and Adaptation in a Changing Climate**

With already significant and growing climate variability in geography and ecology (María Loboguerrero Rodriguez et al., 2018), agri-food systems and rural livelihoods are becoming more vulnerable to climate change. Specifically, exposure to stressors such as drought, floods, and pest outbreaks intensifies, while climate information needed for decision-making, from a radar image of current conditions to an outlook of future scenarios, is often missing or of low quality. The absence of a uniform climate agenda and, consequently, the absence of climate adaptation policies that drive investments and other actions renders many sectors, including agriculture, incapable of devising the necessary operational adaptation measures to cope with a changing climate. A deep look into available, preliminary analyses of climate adaptation behaviours shows a relatively low level of attention to climate adaptation and limited movement in the public policy community towards promoting the implementation of adaptation measures. Agricultural, food and fisheries sectors, for instance, are better equipped to devise and implement adaptation measures compared to other sectors, suggesting additional unquestionable momentum remains in the climate agenda.

In parallel, significant structural barriers continue to preclude the speedy development and implementation of adaptation measures across the entire agricultural economy. Financing and investment, coordination, human capital, information availability, innovation, knowledge, institutional capacity, policy, and risk remain the eight most common barriers in the use of adaptation measures across the agricultural sectors, together with the development of the underlying essential climate data and climate projection models. Access to additional data, models, and downscaling methodologies will help building-farm systems appraisal overall climate information for the US. Appropriate development of terrestrial information acquisition strategies and contours will broadly benefit large area environmental characterization, monitoring, and optimization in the fast growing context of climate change vulnerabilty adaptation, mitigating actions, and overall support for sustainable development.

Conclusion:

Digital agriculture has emerged as a notable trend in the contemporary agrifood sector following earlier phenomena such as precision agriculture and smart agriculture. It has gained traction among farmers and technology developers alike and has attracted scrutiny from researchers across various disciplines. There is, however, a lack of systematic geographical and spatial analysis of its practices, with the existing literature tending to overlook spatial patterns and environmental considerations in the adoption of information and communication technology (ICT) among a range of agricultural technologies.

This study addresses this gap by examining smart farming—an important concept within the framework of digital agriculture—from a geographical perspective. The objective is to analyse the regional characteristics, determinants, and consequences associated with the adoption of smart farming technologies for crop production, with a focus on non-irrigated cereals and oilseeds relevant to northern Europe, especially Finland. Geographically, a framing is chosen that confines the empirical analysis to the Global North, Global South, and emerging regions as delineated by the World Bank. As considered by 018047ef-65ce-4fe1-bbb6-4371cec18b61, the strategic themes within digital agriculture include the Internet of Things (IoT), drones/unmanned aerial vehicles (UAVs), the Global Positioning System (GPS), and sustainable development (Kremer Sott et al., 2021).

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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