4Growth

D3.6 - Future of Digital Agriculture & Forestry- Final

Horizon Scanning Report

Work Package 3 - Digital Agriculture & Forestry Uptake – Forecast & Foresight

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Abbreviations

Abbreviation	Written in full	Explanation
Agritech	Agricultural Technology	The use of technology in agriculture, horticulture, aquaculture as well as forestry to improve yield, efficiency, profitability or sustainability.
AI	Artificial Intelligence	Artificial intelligence (AI) refers to systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals.
CAP	Common Agricultural Policy	The EU's common agricultural policy, introduced in 1962, applies to all member states and is regularly updated. It aims to boost farmers productivity and income, promote sustainable resource management, and support rural areas and economies.
GenAI	Generative AI	The fundamental component of generative AI is its ability to produce new content, including text, images, videos, sounds, and codes, based on deep learning models and extensive data training.
IoT	Internet of Things	IoT refers to a network of physical devices or objects, embedded with sensors, software and network connectivity allowing them to collect and share data.

Executive Summary

The 4Growth project[1], funded by the Horizon Europe programme, examines the adoption of digital and data-driven technologies in European agriculture and forestry. It documents the current landscape of change and maps future developments that are critical for these sectors. Through its Foresight Module, the project explores the evolving conditions of digital transformation in agriculture and forestry using two qualitative foresight methods: horizon scanning and scenario building. This report presents insights from the project's horizon scanning activities[2]. These insights aim to identify a range of current and future changes in the wider environment which are expected to impact on digitalisation in agriculture and forestry in Europe.

Digitalisation in agriculture and forestry is accelerating, shaped by developments in social, technological, economic, environmental, and (geo-)political domains. This report presents the 4Growth trends, – understood as key developments shaping digitalisation in European agriculture and forestry – identified through horizon scanning. Until 2040, these trends are expected to significantly reshape practices in both sectors, fostering or hindering a transition toward data-driven, automated, and resilient systems. The 4Growth trends can be summarised by the developments shaping digitalisation in agriculture and forestry below.

Developments shaping digitalisation in agriculture and forestry:

- **Geopolitical and Economic Pressures:** Rising global tensions, trade restrictions, and resource dependencies are driving Europe toward greater self-sufficiency and domestic production. In response to energy shortages and supply chain vulnerabilities, digital technologies, like precision technologies and decision-support for less input-intensive practices, are becoming more critical. They help improve efficiency, reduce waste, and ensure full traceability from production to market. Since 2023, EU enlargement policies have included plans for Ukraine's post-war integration, creating opportunities to rebuild agriculture and forestry sustainably using modern, tech-enabled approaches.
- **Policy and Regulatory Framework:** The EU's Common Agricultural Policy (CAP) can play a key role in advancing digitalisation by incentivising precision agriculture through eco-schemes and rural development funds, including investments in digital infrastructure in rural regions. Advanced digital monitoring can support the effective enforcement of environmental regulations by ensuring compliance with soil, air, and water standards, enabling performance-based funding for sustainable practices, and reducing administrative reporting burdens. In addition, emerging carbon markets and nature restoration efforts are creating new business models that can be supported by trusted digital tools for monitoring, data collection, and reporting.

[1] This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101134855.

[2] Horizon scanning is a foresight technique of screening (scientific and other) literature, to identify trends, i.e., developments of change. It is a structured bottom-up process, in this case looking at relevant developments documented since 2020. The approach covers a "360-degree" perspective of social, technological, economic, environmental, and (geo-)political spheres, zooming in from more general and global topics to sector-specific topics.

- **Environmental and Climate Pressures:** Climate change, biodiversity loss, high energy prices and resource scarcity are accelerating a shift toward more sustainable and adaptive practices. Technologies such as remote sensing, biosensors, crop simulation models, and digital twins can help to optimize inputs, manage climate-related risks, and support regenerative approaches. Digital systems can play a vital role in addressing soil degradation, water scarcity, and demand for higher yields on limited land; for example, by supporting innovations like strip farming and nature-based solutions. They can also enable effective monitoring, planning, and evaluation of habitat restoration on non-productive land.
- **Market Concentration and Power:** The ongoing consolidation in agri-food and forestry markets can accelerate the adoption of scalable digital solutions, such as remote sensing, automated machinery, and integrated management systems, to help manage large-scale operation. Major agri-tech and supply firms are entering the sector to gain market insights and offer bundled, service-based solutions, further driving digital uptake. Meanwhile, growing influence from wholesalers, retailers, processors, and consumers is increasing demand for quality management systems and supply-chain transparency tools.
- **Societal and Demographic Change:** A generational shift is bringing younger, digitally savvy farmers and forest managers into the sector, with greater openness to adopting new tools, practices, and business models. Increasing involvement of women, who often lead diversified, community-oriented operations, can also reshape digital agriculture and forestry. Cooperative models and shared ownership can further expand access to advanced technologies for smallholders, strengthening trust, data sovereignty, and community support.
- **Workforce Challenges and Skills**: Labour shortages, especially for physically demanding, seasonal work, drive the need for digital solutions that automate or ease tasks such as milking, weeding and harvesting. Augmented Reality can guide untrained workers, for example, by helping distinguish seedlings from weeds or guiding basic machine repairs. As digitalisation advances, large farms and forestry operations require more highly skilled specialists to implement and manage new technologies and train colleagues. Smallholders, in turn, can rely on cooperative models and shared access to specialised machinery and operators when needed.
- **Infrastructure and Cybersecurity Challenges:** Despite growing momentum, digital transformation is slowed by gaps in rural infrastructure—only 60% of EU rural households have high-speed internet. Raising cybersecurity risks, from data breaches to machinery sabotage, underscore the need for resilient (including partly offline) systems and strong governance.

Considering these global developments, the following points outline how digitalisation and technology in agriculture and forestry are responding to these challenges, and indicate future requirements[3]:

Monitoring: Increasing competition, geopolitical tensions, climate, and demand pressure on

[3] Under "future requirements" we mean the criteria that digital tools and data services must meet to address the evolving conditions faced by agricultural and forestry operators.
For details and comparisons with current 4Growth Observatory insights (D4.13) and future market estimations from the 4Growth MMFT (D3.2), see in Chapter 3 and Annex 3.

productive land drive agriculture and forestry operators to **improve their competitiveness, reduce their resource dependencies and explore new business opportunities**. While climate change induced spread of diseases, pests and hazard risks require **better early warning systems** that scan for environmental threats. To address these challenges, multi-scale digital monitoring, combining real-time data with long-term trends, is becoming increasingly essential **for adaptive, sustainable land management and as a tool for carbon farming and biodiversity tracking**.

Future requirements: Effective monitoring will **require robust data infrastructure and skilled interpretation**, integrating multiple data sources, from public and private satellites and drones to local proprietary field data sources, in smart and reliable ways. **Trust will be critical**, as farmers and forestry operators must retain full control over shared data to ensure their autonomy. Those who share proprietary data should also **receive tangible benefits, such as reduced administrative reporting,** when public authorities or supply chain partners use monitoring data to assess production performance or meet compliance requirements.

Simulation and Prediction: Rising trade disruptions and the growth of oligopolistic players tend to **increase market volatility**. While increasing **climate stress calls for innovation** in production practices, more resilient livestock, crops, and plants, as well as new kinds of veterinary drugs, fertilizers, and pesticides. In response, **predictive market models, crop and livestock simulations, and digital twins are emerging**. As these tools develop, they could deliver insights for managing climate risks, extreme weather events, and market volatility. These tools also have the potential to **accelerate research and development through virtual breeding** and AI-powered biodesign, while **predictive maintenance** can contribute to ensuring continuous operation of critical machinery. Digitalisation can improve the resilience of European agriculture and forestry by **better anticipating risks and preparing respective solutions, strategies and innovations**.

Future requirements: Effective simulation and prediction tools need to be able to **integrate and validate increasingly diverse data sources**, overcome remaining data gaps, and learn from historic and comparable use cases, while **tailoring insights to specific local applications**. Digital models need be able to **account for the complexity and variability of natural systems** without excessive computing and time demands. The results must **deliver clear, action-oriented insights** to farmers, forestry operators, research partners, policymakers, and others **to anticipate risks through early warning systems and prepare solutions and strategies** (like introducing climate smart practices and climate adaptive plants and livestock).

Decision Support for the Management of Agricultural and Forestry Systems: Amid growing competition, rising supply risks, increasing influence of supply chain partners, market volatility, and stricter regulatory demands, digital decision support tools can help to drive the competitiveness of agriculture and forestry by **optimising inputs, boosting yields** to ensure a stable supply of calories and wood**, and supporting regulatory compliance**. **Collaborative data sharing**, as an optional feature of decision support systems, can enhance the quality of advice provided by decision-making tools. In addition, digitalisation can **automate documentation and reporting, supporting supply chain transparency**.

Future requirements: Seamless integration of these tools into administrative reporting systems, for both public authorities and supply chain partners, is increasingly essential to reduce administrative burdens. Digital tools should be designed to streamline administrative reporting to public authorities and supply chain partners. This can be achieved by ensuring that **authorities and partners have the necessary means to process and validate this data seamlessly**. Respective **harmonisation and standardisation are required for the interoperability** between different systems and organisations. **European Agricultural Data Spaces** are an instrument to host the data from different domains and actors in the agriculture and forestry sector enabling safe data sharing. Strong European **data regulation builds trust** in data spaces by requiring **regular forward-looking evaluations** to address emerging challenges, risks and opportunities.

Automation and Robotics: Similar to the set of global developments that call for decision support systems (e.g., growing competition, rising supply risks, increasing influence of supply chain partners, market volatility, stricter regulatory demands) plus workforce shortages and skills gaps, are accelerating the adoption of precision technologies, autonomous machinery, and soft robotics. These innovations **help reduce input use, labour dependency, and environmental impact.** Emerging applications like Augmented Reality (AR)-guided tasks, multifunctional land use, and biodiversity-friendly automation are expanding digitalisation beyond industrial-scale farming.

Future requirements: While precision farming and forestry can reduce reliance on resource-intensive inputs from foreign suppliers, the digital devices and server farms themselves depend on various critical raw materials and energy. From an open strategic autonomy perspective, this reliance on a small number of multinational technology providers raises risks that require increased awareness, including cybersecurity threats. To be prepared for the future challenges, automation and robotics need to be able to support resource-efficient, innovative, and re-imagined traditional practices, such as nature-based solutions. Precision agriculture and forestry tools need to help restore and maintain healthy eco-systems, preserving the natural capital of fertile soils and rich biodiversity. To reduce dependency on the small number of solution providers, the European Union and its member states need to support the development of strong European digital provides and empower agriculture and forestry actors to engage with digital tools and data on a level playing field. In addition, it is essential to continuously raise capacities in the race to fight emerging cyberattacks, espionage, disinformation and market manipulation.

Digital Communication and Market Integration: Growing competition and market pressure, changing consumer demands, evolving self-perceptions of agriculture and forestry actors, and supply chain requirements from processors and retailers are driving farmers and forestry operators to **connect directly with consumers and market partners via ICT platforms**.

These platforms are **reshaping producer-consumer relationships** by enabling direct sales, customised production, and collaborative models like community-supported agriculture. Digital integration also **creates new opportunities in carbon markets** and **strengthens ties between agriculture, forestry, and other sectors**.

Future requirements: Care must be taken to avoid marginalising less-digitised smallholders and agroecological models. This can be addressed by **expanding the application fields** of digital tools to cover a **wide-range of specialised tasks**, designing them for **multiple purposes,** and developing **business models that serve low-budget clients**. **Transparent and reliable communication of quality standards** will become increasingly important to meet consumer demands for healthy living and **supply chain transparency, through fraud-proof communication** channels and validation tools. As individualisation grows, a better understanding of **consumer micro-segments** is needed to deliver **customised offers and individualised customer communication**. An overview on results is provided in Figure 1.

This Horizon Scanning report highlights the diverse trends and developments shaping the broader context of the digital transition in agriculture and forestry. It underscores the need for a well-directed, inclusive, and responsive evolution of digital technologies to ensure they effectively support sector-specific needs and long-term sustainability. The learnings and conclusions for policy makers included in Chapter 4 of this report aim to support the development of a comprehensive roadmap for advancing digitalisation in agriculture and forestry, one of the key goals of the 4Growth project. Moving forward, it is crucial it to take concrete steps today to ensure digital tools are applied in ways that are both sustainable and equitable, leaving no one behind in the shift toward smarter, more efficient European farming and forestry sectors.

Figure 1: Summary of Future Requirements for Digital Solutions, Agriculture and Forestry Needs and Developments (Source: Future Impacts)

Cross-cutting Future Requirements for Digital Tools and Data Services
Robust data infrastructure, data quality
Standardisation, interoperability, seamless data integration of public and private data & systems
Reliable recording, tracing of inputs and logistics
Integrate diverse data, learn from use cases, deliver actionable insights
Trust in data sharing
Transparent quality standards, consumer understanding
Build trust, customer loyalty, interaction
Cybersecurity
Reduce reliance on multinational tech,
Avoid marginalization, level playing field

Key Future Needs for Agriculture & Forestry Where Digital Solutions Can Support	Developments Driving Change
Adapt practices, sustain yields, competitiveness	Environmental & Climate Pressures
Identify sustainable land-use opportunities	Policy & Regulatory Framework; Societal & Demographic Change; Environmental & Climate Pressures
Address emerging threats (extreme events, pests, diseases)	Environmental & Climate Pressures
Anticipate market developments (food, wood, agrochemicals)	Market Concentration & Power; Geopolitical & Economic Pressures
Climate-smart breeding, resilient plants/livestock	Environmental & Climate Pressures
Reliable machinery, predictive maintenance	Market Concentration & Power; Workforce Challenges & Skills
Enhance efficiency, reduce inputs, climate -smart practices	Geopolitical & Economic Pressures; Environmental & Climate Pressures
Digital farm administration, legal compliance, transparency	Policy & Regulatory Framework; Market Concentration & Power; Societal & Demographic Change
Quality assurance (infant nutrition, pharma, construction)	Policy & Regulatory Framework; Market Concentration & Power; Societal & Demographic Change
Accelerate innovation through data sharing	Environmental & Climate Pressures, Policy & Regulatory Framework; Market Concentration & Power; Societal & Demographic Change
Optimize resource use (water, fertilizer, pesticides)	Environmental & Climate Pressures, Policy & Regulatory Framework; Market Concentration & Power; Societal & Demographic Change
Support manual work, reduce pesticide use	Workforce Challenges & Skills, Infrastructure & Cybersecurity Challenges
Support/substitute labour (planting, pest control, harvesting)	Workforce Challenges & Skills, Infrastructure & Cybersecurity Challenges
Assist untrained workers, machinery maintenance	Workforce Challenges & Skills, Infrastructure & Cybersecurity Challenges
Direct sales, tailor output to consumer demands	Market Concentration & Power
New business models (community-based farming)	Societal & Demographic Change, Workforce Challenges & Skills, Market Concentration & Power
Collaboration (agriculture, forestry, energy, industry)	Policy & Regulatory Framework; Environmental & Climate Pressures

1. Introduction and Methodology

1.1 Starting Point and Objectives of the Report

The Horizon Europe programme funded 4Growth project[4] analyses the uptake of digital and data-driven solutions in agriculture and forestry in Europe, by documenting the current state and projecting the future evolution of the sector. The project's Foresight Module explores the changing framework conditions of agriculture and forestry and the digital transformation of these sectors by applying two core foresight methodologies via qualitative analysis: horizon scanning and scenario development. This report presents the outcome of the second horizon scanning cycle conducted between October 2024 and August 2025, as well as cross-cutting trend implications and key insights from the whole process of horizon scanning in the project.

The Foresight Module's Horizon Scanning integration in the 4Growth Project

The results of the foresight module feed into the Market Monitoring and Forecasting Tool (MMFT) by providing qualitative evidence to support the baseline assumptions (WP3). Results from the state of the are analysis of digital technologies (WP2) are taken up in the digital implications sections in chapter 3 and further developed. Findings from the 4Growth observatory (WP4) on the current perspective of agriculture and forestry stakeholders are compared with trends implications in chapter 3 and Annex 3. In addition, the MMFT baseline assumptions on technology penetration from 2025 to 2040 (WP3) enrich the qualitative results with a quantitative assessment of the level of market uptake of several technology categories. The findings from the Foresight Module's horizon scanning report are a building block to provide 4Growth policy recommendations (WP 4).

Horizon scanning is a foresight process of screening (scientific and other) literature, new articles and a variety of other sources to identify trends, i.e., developments of change. It is a structured bottom-up process, in this case looking at relevant developments documented in the last 5 years since 2020. The approach covers a "360-degree" perspective of social, technological, economic, environmental, and (geo-)political spheres, zooming in from more general and global topics to sector-specific topics[5].

Within the context of the 4Growth project, horizon scanning serves to identify current and future changes in the wider environment which are expected to impact on digitalisation in agriculture and forestry in Europe. The analysis is thus focussed on potential trends and their implications for agriculture and forestry in the EU, zooming into implications for the digitalisation transformation of the two sectors (i.e. applying an "outside-in" perspective). For

[4] This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101134855.

[5] For more details on the methodology, see the subsection 'Methodology'.

example, the reflection on implications covers aspects such as in how far the trends imply a growing need for specific digital solutions, or new opportunities, or what the potential hurdles could be for the uptake of digital solutions stemming from the trends.

Therefore, the **objective of the report** is to present an overview of trends - identified over the current period – that are relevant for the agriculture and forestry sectors, to feed into and support strategic reflections about their future developments and their effects on the sectors and digitalisation. Beyond this specific objective, the deliverable also aims at providing insights and inspiration to think about possible futures, which is covered in a section in each trend description indicating possible future developments paths. Each of the trends is also illustrated by three underlying signals, covering developments in different aspects of the trend, aiming to illustrate the breadth of the topic. Furthermore, the report aims to highlight the implications of the trend for the agriculture and forestry sectors and their digital transformation, which is explicitly covered in a respective concluding section of each trend description.

How to read this report: Readers can look at the overview of the trends and select only those that pique their interest, or they can read the whole report to get an overarching picture. Chapter 3 and chapter 4 highlight the cross-cutting implications of all trends identified as relevant for digitalisation in agriculture and forestry.

1.2 The Wider Context of Current Change

The world is in a polycrises mode: wars on multiple continents and in the direct neighbourhood, the aftermath of the COVID-19 pandemic, the long-term climate crises, geopolitical tensions with the raise of nationalism and protectionism, social inequality, and other major issues dominate the debate. It is becoming increasingly clear that societies and economies across the world need to actively become more resilient against these crises (Lawrence et al., 2024). The need to increase resilience also applies to the agriculture and forestry sectors (Pfenning-Butterworth et al., 2024; Think Tank EUROPA, 2023). Already today, multiple policy packages at the EU level address these sectors to help them advance in the transformation to sustainable business perspectives and climate neutrality, or to fight the loss of biodiversity.[6] Beyond that, specific policies address the digitalisation of these sectors[7]. Research shows that Europe and North America are on par global leaders in the current and planned application of digital tools in agriculture (Fiocco et al., 2023). However, given the challenging overall

[6] Such policies include the Vision for Agriculture and Food, the Farm to Fork Strategy as part of the European Green Deal, the reform of the Common Agricultural Policy, the Sustainable Food Systems Framework, the EU Forest Strategy for 2030, the Biodiversity Strategy, the Bioeconomy Strategy, or the Sustainable Finance Taxonomy (which guides investments towards sustainable projects, including into agri-food, forestry and bioeconomy) (von der Leyen, 2023).

[7] Examples include the Digital Europe Programme (which launches initiatives in the use of digital solutions to improve efficiency and sustainability, and pushes for smart farming and precision agriculture), the Forest Information System for Europe (aiming to enhance monitoring and management of forests) (EC, 2023a), the announced launch of the EU digital strategy on agriculture as part of the Vision of Agriculture and food (EC, 2025a), and the common European Data Space for Agriculture (Brunori et al., 2025). Furthermore, under the Digital Decade, the European strategy for data and its key pillars the Data Governance Act, the Data Act, and the Digital Markets Act, the AI Act provide a framework for digital data sharing services; it also aims at aligning digital platforms with EU values and principles to bring benefits to EU citizens and companies (EC, 2020a)

context, a continuous monitoring of change will be necessary to enable a more proactive stance, and to establish early awareness of existing change – as applied in this horizon scanning process.

1.3 Methodology

The core aim of the 4Growth Foresight Module (T3.2) is to highlight the impacts of fast-changing framework conditions in agriculture and forestry. The Foresight Module screens respective trends that can be expected to (probably or possibly) impact on the future of agriculture and forestry, as well as on the development of sector-specific digital technologies and their uptake in these sectors in Europe until 2040.

Generally, horizon scanning involves the systematic gathering of information and monitoring of trends to provide an early warning function on possible future changes; it is one of the most established methodologies applied in foresight, especially in the EU policy and research system (European Commission & Daheim, 2023; EC JRC, 2024a; UNDP, 2018; Cuhls, 2019; EEA & EIONET, 2023). Horizon scanning is crucial in foresight, as it provides the evidence for development trajectories (Dragt, 2023).

Within the context of horizon scanning, trends are defined as emerging patterns of change phenomena that have already led to or are likely to impact on other areas, i.e., on society, economy and politics (EFP, 2016). For the approach applied here, we understand trends as clearly observable phenomena of change, underpinned by evidence in the form of signals that point to the respective changes[8]. Signals represent observable aspects of the trends, ranging from early warning signs in niche areas to more mainstream developments. They indicate potential influences on digitalisation in agriculture and forestry, selected based on the expert judgement of the author team. Thus, the report covers already observable change (drawing from developments today and in the recent past, which can be expected to continue in the future). It does not cover potential future disruptive developments which do not stem from continuous past and present change. However, selected disruptions are in the focus of another element of the foresight module, i.e. in the scenarios developed within the scope of this project.

The methodology applied to identify and analyse trends thus draws from a literature review of a broad scope of publications, i.e., academic publications as well as grey literature, newspapers, websites, blogs, press releases, etc. To guide the search process, a “scanning grid” (i.e., a systematic structure for literature identification) was developed, providing a mapping of contextual areas that are expected to play a role for future digitalisation in European agriculture and forestry. This scanning grid is based on the STEEP systematics, a

8 Therefore, a trend can be ranging from a recent emerging phenomenon with a relatively high degree of uncertainty about its future significance up to a broader, more established trend which is far-reaching and observable across the EU or even globally (Sitra, 2019). As each trend is based on several signals (i.e., individual scanning hits based on one source) providing evidence of the development trajectory, signals indicate aspects of the observable change within the trend (Hendricks, 2021). Thus, signals can be sources in the form of newspaper articles, or studies covering a scientific analysis of a larger set of observable data. Therefore, signals can also cover recent developments or more long-standing changes. For more detail on terminology and different approaches in horizon scanning, and on e.g., related terms such as drivers of change, megatrends, weak signals etc, see especially Cuhls, 2019, EEA & EIONET 2023, Hines et al., 2019, Wilkinson, 2017.

widely used methodology in horizon scanning, which covers developments categorized by the areas of society, technology, economy, (the natural) environment, and politics (including policy) (Nhokovedzo, 2024; Bishop, 2009; Future Impacts & EMCDDA, 2022). To reflect the specific needs within this project, the STEEP categories were adapted to areas that are of relevance for digitalisation in agriculture and forestry in the EU (see Table 1))[9].

Table 1. 4Growth Horizon Scanning Grid (Source: Future Impacts)

Scanning Area (short title)	Detail on Issues of Interest within the Scope of the Scanning Area	Underlying STEEP category
Geopolitics	Geopolitical power and tensions, including international peace and conflicts that could influence global cooperation, as well as international trade of food, bioeconomy products, and technologies	Politics
Resource scarcity / Biodiversity crisis	Resource scarcity and biodiversity crisis, influencing the food-water-energy nexus, food security issues, role of the climate crises and impacts for agriculture and forestry	Environment
Technological advancements	Technology advancements in areas like digital technology, biotech, and food safety	Technology
Societal values	Global societal values and consumer preferences	Society
Regulatory framework	Regulatory frameworks in areas of climate, agriculture, bioeconomy policies, financing schemes for agriculture, forestry, and research and innovation, etc.	Politics
EU system	Development and functioning of the European Union and its systems	Politics
Agri-forest industry shifts	Industry shifts in agriculture, agrifood and forestry and related sectors as well as in digital industry, such as changes in business models, industrialisation, globalisation, and developments in the workforce of these sectors	Economy
Open scanning	Open scanning to identify relevant trends outside of the above-mentioned topics, aiming to allow for serendipity and for identifying blind spots which may result from the systematics of other scanning areas	(all categories)

As a result, the search grid allowed for a 360° view over the STEEP categories to identify blind spots as well as to zoom in from the wider general and global context to digital agriculture and forestry in Europe.

The horizon scanning process

[9] This adaptation was based on a literature review of existing foresight studies in the domain of digital farming, and precision farming (as comparable broad foresight studies in the domain of smart, digital forestry could not be identified so far). Two studies were particularly influential due to their fit with the 4Growth focus and due to their overarching European regional and policy focus: a study on transformative futures for farmers and rural communities (Barabanova & Krzystofowicz, 2023), as well as the scientific foresight study 'precision agriculture and the future of farming in Europe' (van Woensel et al., 2016).

The horizon scanning process consisted of six steps[10] during the first cycle, completed by September 2024, to prepare the draft report:

1. **Development of the scanning grid** (See above for more details)
2. **Identification and selection of studies and other sources to integrate:** Selection of sources and studies to integrate in the scanning; focused on recent sources published within the last 5 years (i.e., from 2019 onwards)[11].
3. **Review of sources:** Rigorous review and analysis of the sources to identify signals based on the scanning grid.
4. **Analysis of results:** Analysis of dominant themes and drafting of identified trends, including the clustering of related individual signals to reach a set of overarching trends.
5. **Collaborative trend identification:** Joint review of the proposed trends, realised in workshops with a team of researchers; categorising insights to the search grid and prioritisation of the long list according to a systematic set of criteria. The criteria applied are: coverage of the research topic, strategic relevance of the theme, potential strength of impact for agriculture/forestry and their digitalisation, new or surprising themes.
6. **Description of the identified trends:** Based on the resources identified and further detailed research, each trend was described in a systematic structure covering a summary and key words per trend. Additionally, past and future developments of the trend were brought together alongside recent signals within the scope of the trends, along with potential implications for the digitalisation of agriculture and forestry.

Using this approach from January to September 2024, ten trends were initially identified (as presented in this report in Annex 2), drawing from approximately 300 signals identified in the scanning (see Figure 2).

[10] While these steps build on each other and are generally realised consecutively, there is also an element of re-iterative refinement that was realized in the process of horizon scanning. For example, findings from a review of sources in one area of the scanning grid can provide insights into other relevant studies as well as inspiration for further research for more signals on a specific topic.
[11] Concerning the literature covered, the identification of studies and other sources (step 2) included a broad range of mainly European (and some global), foresight and trend reports with a general focus. Furthermore, the focussed scanning along the 4Growth Horizon Scanning grid dimensions provided a specific focus on publications on or related to European agriculture and forestry. Overall, approximately 200 sources were included in the scanning.

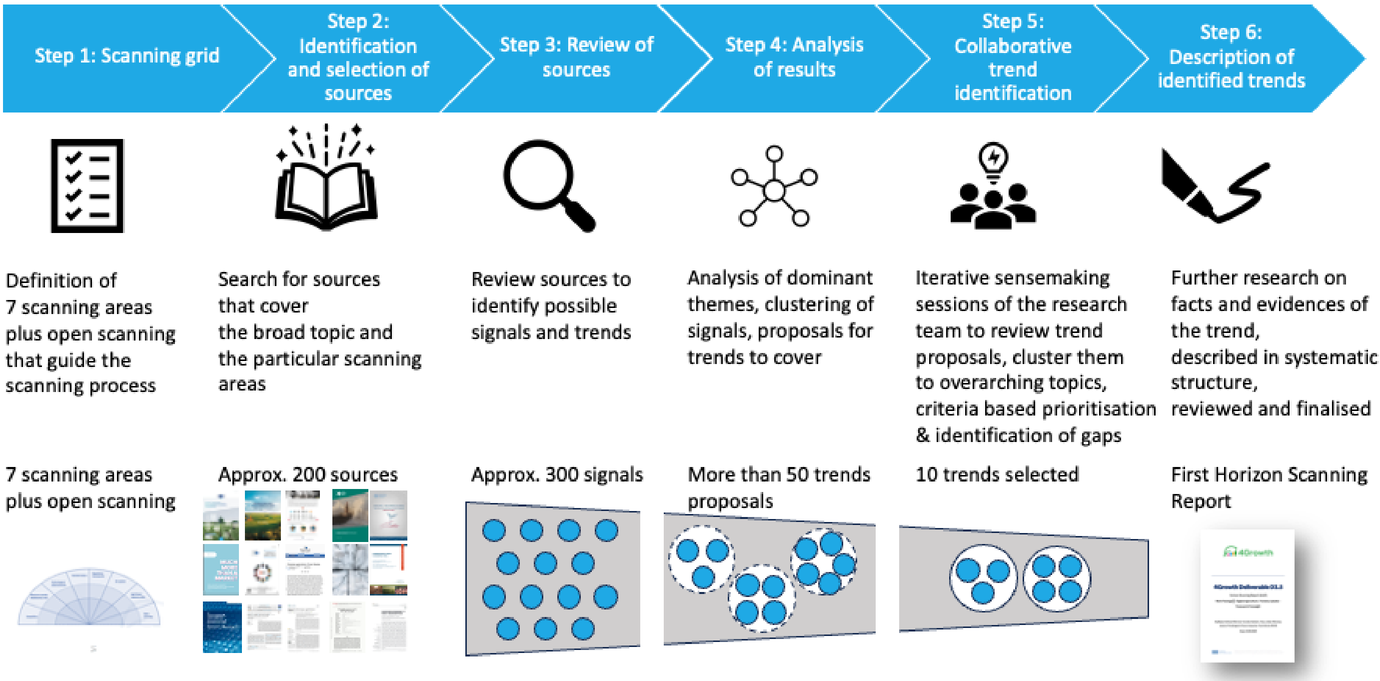

Figure 2. 4Growth Horizon Scanning process overview (in the first cycle January - September 2024) (Source: Future Impacts)

In the follow-up cycle (October 2024 to August 2025), this approach was slightly adapted to ensure potential gaps in the scanning so far are covered, so that the Final Horizon Scanning report captures the key trends shaping digitalisation in agriculture and forestry and aligns with the 4Growth Foresight Module's goals and overall project deliverables. The approach in this cycle consisted of the following steps:

7. **Blind Spot Check / Identifying gaps in the first set of trends**: In the first step, the research team reviewed the initial 10 trends, identifying possible gaps related to key drivers for the future of agriculture and forestry and digital solutions uptake. These gaps were refined through internal working meetings.
8. **Topics relevant for the framework scenarios**: Next, key factors shaping the draft Holistic Long-term Framework Scenarios were mapped against the trends, revealing additional topical gaps and sharpening the focus of the identified topics.
9. **Review and input from the 4Growth consortium**: In February 2025, draft topics identified so far were presented to the 4Growth consortium, with the research team providing feedback via a survey on missing or desired topics for inclusion.
10. **Clustering and definition of top trend themes and trend analysis**: Using this input, topics were reorganised into 10 main trend areas for further analyses, based on approximately 150 sources. In parallel, an open scanning continued to capture other relevant emerging topics.
11. **AI-based trend analysis of one topic:** To counteract the agriculture bias in a large part of the literature and sources and to experiment with new methodological approaches, VTT colleagues conducted an AI-driven advanced analysis on the

broader topic of "Digitalisation in forestry" using their technology platform[12], see section 2.10. This step builds on the approach used in a prior application of the tool for digital technology adoption in forestry, as part of 4Growth WP4, T4.2, reported in D4.8.

12. **Integration of insights from observatories and MMFT**: As a last step, insights from the WP 4 observatory surveys were incorporated, contrasting future digitalisation implications[13]. with current perceptions from key agriculture and forestry actors across Europe. In addition, insights from the latest MMFT baseline data on technology dissemination today and projections for 2040 were included, with these sources specifically enriching the order of magnitude of digitalisation uptake. Results are presented in the conclusions section.

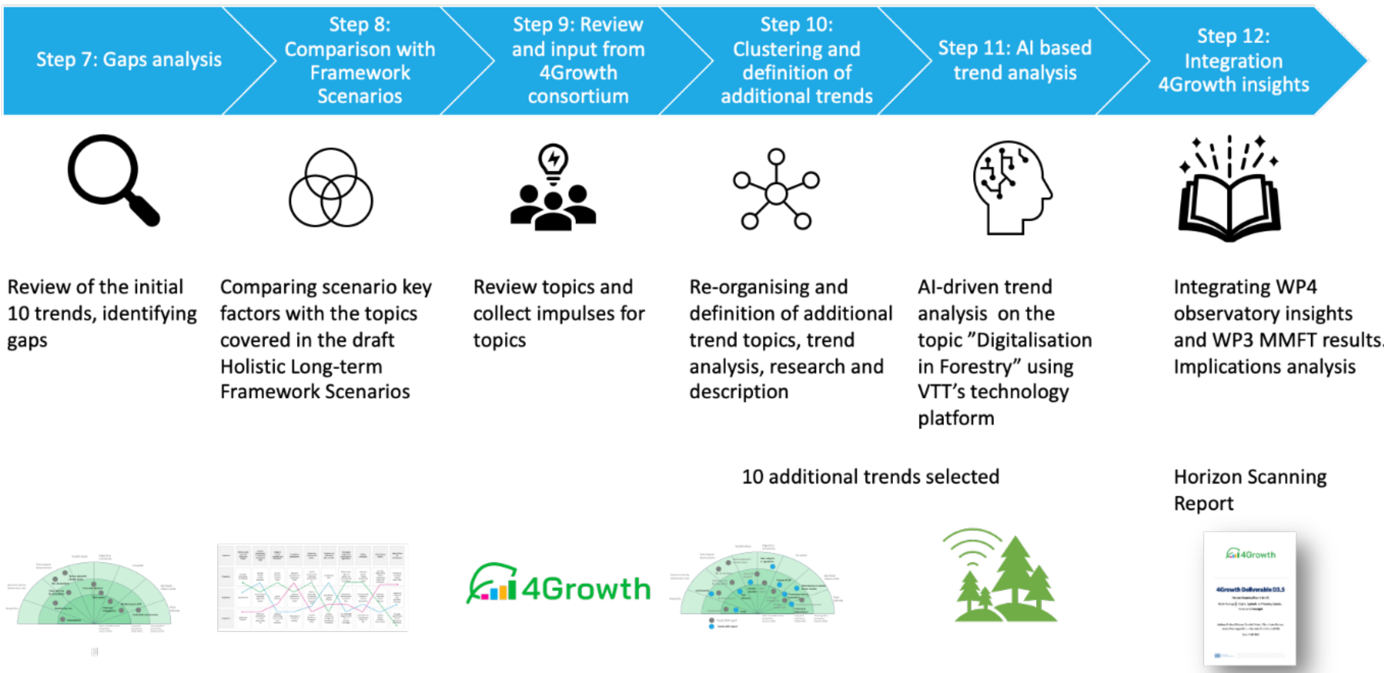

Figure 3. 4Growth Horizon Scanning process overview (second cycle October 2024 to August 2025) (Source: Future Impacts)

[12] As an input to Horizon Scanning in forestry, a review of over 1,000 documents exploring the intersection between forestry and digitalisation was conducted. Relevant articles were identified by examining resources from leading consultancies, institutions, and forestry-related organisations. The analysis was performed on VTT's internal technology platform using Large Language Models (LLMs) and Retrieval-Augmented Generation (RAG) methods. It provided insights into digital innovation, key actors and drivers, implementation challenges, sustainability impacts, policy support, regional trends, and future knowledge gaps.

[13] In the compilation of the trend report, mainly in the summary of trend implications and the summary of the 20 trends (Chapter 3, Annex 3 and Executive summary), the authors utilised generative AI models GPT-4/chatGPT from OpenAI and Le Chat from Mistral AI to assist the authors' own human-made analysis of parts of the report: they compared and summarised the implications for digital solutions in agriculture and forestry across the 20 trends. The authors' results were compared with AI-generated results to check for gaps and get inspiration for cluster titles. A similar approach was used to summarise the trend content in the developments presented in the executive summary. Furthermore, the Grammarly tools was used to improve the text. For the trend in section 2.10 "Digital Innovations and AI in Forestry", another AI-supported approach was used, see step 11.

Method explained: Selection of the Signals

The signals presented under each trend illustrate different dimensions of the trend and provide concrete evidence of observable ongoing developments. Selected through iterative reflection by the author team, they aim to highlight factors shaping digitalisation in agriculture and forestry, cover a broad trend spectrum, and offer fresh insights. These signals are not exhaustive but serve as illustrative deep dives, inviting the reader to consider additional signals and perspectives.

2. The 2025 Trends Update

The trend radar below maps the report's topics along the scanning grid. Although many trends impact multiple categories, each is assigned to a primary category for clarity, based on collaborative workshops. The radar also indicates when each trend is expected to become highly relevant for agriculture and forestry, from the centre (short-term) to the outer circles (beyond 2035). The time assessment for each trend, from short- to long-term, is based on literature analysis. However, individual signals may differ from the overall trend timeline—for example, within the Generative AI trend, agentic AI tools are expected later than other signals. The trend radar does not prioritize one trend over another, as the trends are highly interdependent. For instance, the climate crisis drives biodiversity loss, increases land scarcity, creates opportunities for climate-resilient technologies, influences legislation, and encourages new business models such as controlled environment farming.

Overall, the trends could be grouped under the following developments (as outlined in the executive summary):

- Geopolitical and Economic Pressures
- Policy and Regulatory Framework
- Environmental and Climate Pressures
- Market Concentration and Power
- Societal and Demographic Change
- Workforce Challenges and Skills
- Infrastructure and Cybersecurity Challenges

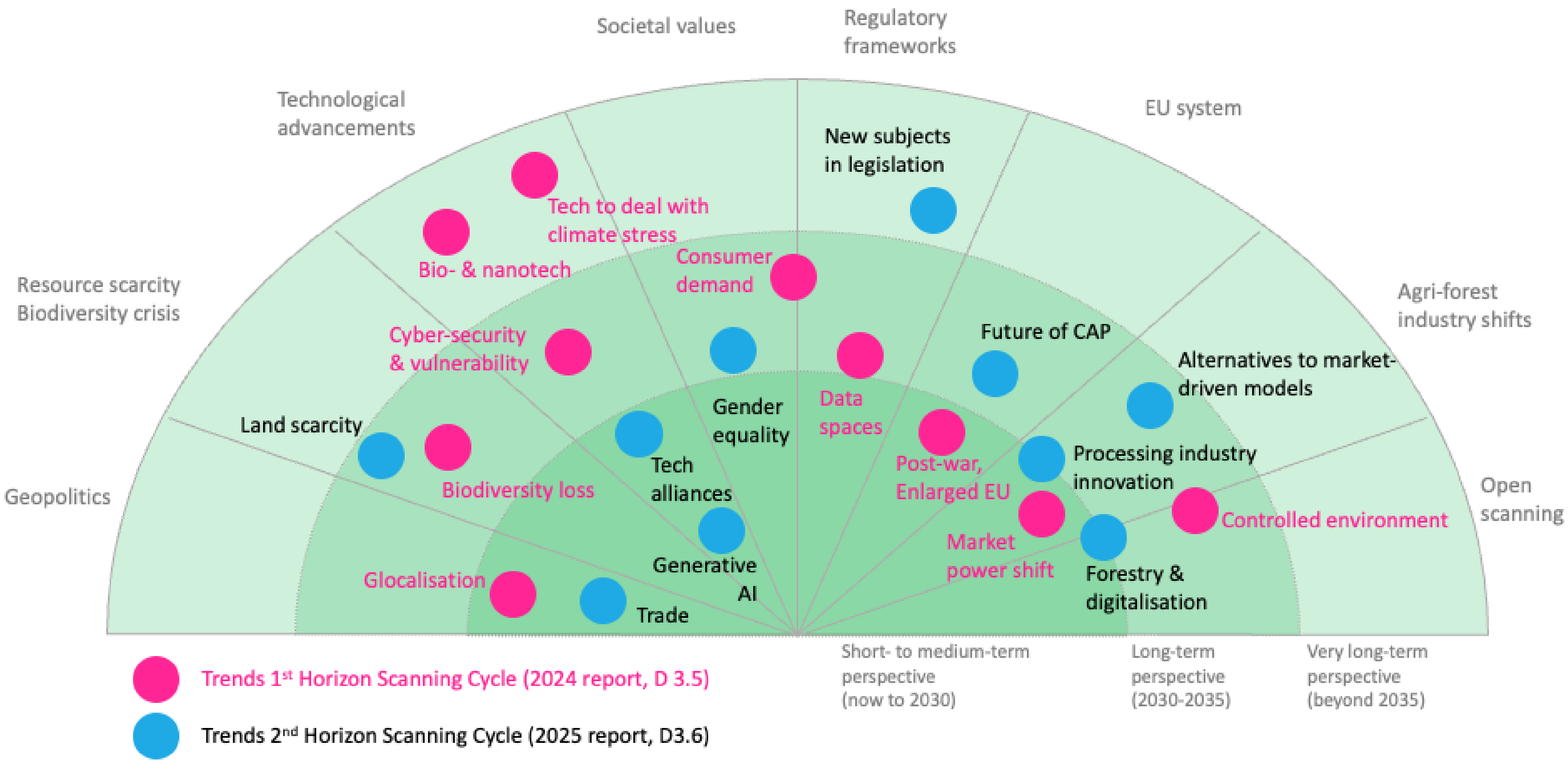

Figure 4. Trend Radar (Source: Future Impacts)

The table below lists all trends with both their shortened title—used for clarity reasons in charts and overviews—their full titles and the signals presented in the report.

Table 2 : Overview of Trends (with short and long titles) - (Source: Future Impacts)

Trend (short title)	Section	Trend (complete title)	Signals
Trends from the Second Horizon Scanning Cycle (2025 Report, D3.6)			
Land scarcity	2.1	Increasing Land Scarcity and Competition	Increasing Urban and Infrastructure Expansion Climate Impacts and Competing Land Demands Land Use for Renewable Energy and Carbon Capture
New subjects in legislation	2.2	Emerging Subjects in Legislation: Nature, Next Generations and Technologies	Integrating the Interests of Future Generations into Policymaking The Emergence of the Rights of Nature in Environmental Policy Evolving Regulatory Landscape of AI and Machines
Gender Equality	2.3	Gender Equality as Catalyst for Socially Sustainable Digital Agriculture and Forestry	Gender-Inclusive Agritech as a Business Opportunity Women Farmers Driving Diversified and Sustainable Agriculture Horizon Europe Projects Advancing Women-Led Innovation in Agriculture
Trade	2.4	Global Shifts in Primary Production and Trade Stability	The Changing Role of the EU in Global Food Trade Market Price Turbulences: Uncertainties Drive Speculation Trade Implications of Europe's shift to Agroecology
Alternatives to market driven models	2.5	Community-Supported Agriculture and Forestry as Resilient Alternatives	Evolving Models of Community-Based Forest Governance Unlocking the Digital Potential of Agri–Cooperatives Rise in Solidarity-Based Agriculture
Future of CAP	2.6	The Future of the EU's Common Agricultural Policy	Performance-Driven Financing in CAP CAP in an Enlarged European Union CAPs Role in Improving the Socioeconomic Viability of Rural Areas
Tech Alliances	2.7	Increasing Prominence of Tech-Agribusiness Alliances and Cross-Industry Innovation	Bayer and Microsoft Partner on Cloud-Based Agricultural Platform Syngenta Expands AI Capabilities via Cropwise Platform Military Drone Innovations Repurposed for Precision Farming
Processing industry innovation	2.8	Innovation in Food and Wood Processing Industries Drives Primary Production	AI and Automation in Food Processing Food Industry Driving Healthy and Personalised Nutrition Wood Processing Innovation and New Wood Products

Trend (short title)	Section	Trend (complete title)	Signals
Generative AI	2.9	Prospects for Generative Artificial Intelligence	A New Era of Decision Support Multi-modal Data Analysis Capabilities of Generative AI Agentic AI and Large Action Models: The Next Frontiers in Generative AI
Forestry & digitalisation	2.10	Digital Innovations and AI in Forestry (AI-supported trend analysis)	Remote Sensing and Mapping Technologies Data Analytics and Artificial Intelligence (AI) Digital Twins Specialized Software Platforms and Integrated Systems Automation and Robotics
Trends from the First Horizon Scanning Cycle (2024 Report, D3.5 – see updated version in Annex 2)			
Glocalisation	A2.1	Glocalisation – Pushed by Geopolitical Tensions	Export Limitations for Food Products: India's rice export ban Europe's Wood Import Independence – a Reaction to High Russian Export Tariffs in 2008 Fertilizer Dependency due to Russian War in Ukraine
Post-war enlarged EU	A2.2	Changed Perspectives for Agriculture and Forestry in a Post-war, Enlarged European Union that Includes Ukraine	Militarization and War Alter Biodiversity in Affected Areas Post-War Rebuilding of Ukraine's Agricultural and Forestry Sectors EU Enlargement to Redefine Common Agricultural Policy
Biodiversity loss	A2.3	Increasing Need to Tackle Biodiversity Loss	Spoonbill Population Threatened by Agricultural Activity Farmers Could Grow a Larger Variety of Crops on their Land, Supporting Biodiversity China's Ties to Foreign Agricultural Land are Affecting Biodiversity
Cybersecurity & vulnerability	A2.4	Cybersecurity Issues and Network Vulnerability Affect Digitalisation in Agriculture and Forestry	Espionage Enabling Equipment in Machines and Infrastructure Cyberattack on Food Processing Company Exemplifies the Vulnerability of Smart Farming Devices Connectivity Risks Due to Reliance on Single Networks and Providers
Bio- & nanotech	A2.5	Bio- and Nanotechnologies Can be a Lever for Next Generation Agriculture and Forestry	Bio- and Nano Tech for Cultivation of Climate Adaptive Plants and Animals Biosensor Technologies Enable Real-time Understanding of the State of the Local Environment Novel Nanomaterials Revolutionise Fertilizers with More Efficiency and Less Negative Side-effects

Trend (short title)	Section	Trend (complete title)	Signals
Tech to deal with climate stress	A2.6	Technology Solutions for Agriculture and Forestry to Deal with Climate Stress	Geoengineering: Agriculture and Forestry Contributes to e.g. Carbon Storage Microclimate Management: Using Nature-based Solutions to Adapt to the Climate Crisis Leaps in Low Energy Consuming Water Desalination Could Open New Opportunities for Agriculture and Land Use
Controlled environments	A2.7	Intensification of Biological Resource Production in Controlled Environments	Giant Vertical Farm Project GigaFarms in Construction in Dubai Advancements in Controlled Environment Production of Alternative Proteins European Commission Highlights the Role of Algae as Underexplored Bioeconomy Resource
Data spaces	A2.8	Next Level Decision Making Enabled by Digital Data Management and Spaces	On-Farm Data Spaces of Decision Making and Automation Corporate Companies Driving Agricultural Data Spaces Data Spaces for Policymaking and Reduction of Bureaucratic Burden
Consumer demand	A2.9	Rising Regulatory and Consumer Demand for Higher Food Quality, Safety, and Sustainability	Healthy, Organic, Home-cooked Food Trending on Social Media Rising Number of Food Supply Chain Management Start-ups Food Watch Demands EU-wide Mandatory Front-of-pack Nutrition Labelling “Nutri-Score”
Market power shifts	A2.10	Shift in Market Power in Agri-food and Forest Systems	Concentrated Agribusiness Sector Limiting Farm Supply Choices and Sale Options – Small Farms Decline Vertically Integrated Forest Companies are Lead Appliers and Developers of Digital Precision Solutions Increasing Influence of Food Companies and Fossil Fuel Energy Companies on Farms through Carbon Markets

2.1 Increasing Land Scarcity and Competition

Summary and Key Words[14]

Growing demand for land, driven by urbanisation, rising living standards, and infrastructure development, including renewables like solar and wind, is putting increasing pressure on arable land and forests. This is further exacerbated by the rising need for bioenergy and bio-based materials, creating competition between food production, forestry, and ecosystem services such as clean air and water. Furthermore, climate change impacts (e.g., desertification, erosion, wildfires) and related mitigation or adaptation measures (e.g., dams, flood polders) also reduce land availability. These challenges highlight the need to leverage digital solutions for the sustainable intensification of land use.

Key words: Land scarcity / Land grabbing / Erosion / Desertification / Urban sprawl / Soil degradation / Bioenergy / Solar PV / Wind power

Current and Future Developments of the Trend

Europe has highly intensive land use, with approximately 80% of its area dedicated to built environments, infrastructure, or agricultural/forestry activities. Between 2000 and 2018, built-up areas expanded by 6%, converting about 450 km² annually, mostly at the expense of agricultural land, pastures, and forests (EEA, 2021). Although the EU Agriculture Outlook (EC, 2024a) forecasts stable agricultural and forest land areas until 2035, over 60% of EU soils are degraded, reducing overall land quality (EC JRC, 2024b).

Climate change is worsening these pressures, with over 4% of EU land experiencing annual droughts between 2000 and 2022 (EC JRC, 2024b). At the same time, protected land in Europe grew from 24% to 26% between 2011 and 2021 (EC JRC, 2024b), supporting the Biodiversity Convention's target of 30% protected areas by 2030, including 10% strictly protected zones (Convention on Biological Diversity, 2022). These targets are being implemented through EU regulations such as the Nature Restoration Law (EU, 2024a).

Recent Signals within the Scope of the Trend

2.1.1 Increasing Urban and Infrastructure Expansion

Land consumption for buildings and infrastructure continues to rise. Between 2012 and 2018, approximately 3600 km² in EU28 were converted to urban use, mainly in suburban and peri-urban areas. Arable land accounted for 47% of this loss (approx. 1700 km²), and pastures for around 36% (1280 km²). Permanent crops and forests were less affected, 80 km² and 340 km² respectively, but both suffer indirect impacts, including biodiversity loss, reduced flood protection sue to soil sealing, weakened microclimate regulation, and reduced carbon sequestration (EC JRC, 2024b). This trend reflects a structural conflict between expanding spatial demands and the need to preserve land for agriculture and forestry.

[14] The summary parts are written without scientific references; respective citations are available in the Current and Future Developments of the Trend parts.

2.1.2 Climate Impacts and Competing Land Demands

Climate change is shifting climate zones northward and to higher elevations, reducing the availability of suitable arable land. Areas at high risk of desertification are expanding (ECA, 2018), and drought-related losses could increase fivefold under a 3°C warming scenario (EC JRC, 2020). Flooding, rainfall erosivity, and soil loss are intensifying (EC JRC, 2024b), while wildfires are expected to become more frequent. Already today, 26 billion tonnes of forest biomass are potentially vulnerable to windthrows (46%), fires (29%) and insect outbreaks (25%), with southern Europe particularly at risk (EC JRC 2020; 2024b). In parallel, climate mitigation measures, such as land used for flood protection or afforestation, also compete with agricultural land, further limiting arable land availability (Herold et al., 2024).

2.1.3 Land Use for Renewable Energy and Carbon Capture

Renewable energy expansion is often criticised for its land footprint. However, Weinand et al. (2025) highlight that recreational land use, such as golf courses, often consume more land than onshore wind or utility-scale solar PV. Meeting the REPowerEU targets will require a major scale expansion, tripling the annual reenable capacity additions by 2030. While some studies predict significant land demands (McKinsey, 2023), innovations like agrivoltaics offer potential synergies by combining energy production with agriculture. In contrast, biomass energy and BECCS (Bioenergy with Carbon Capture and Storage) are particularly land-intensive (Isermeyer, 2022; Chatham House, 2023). Identifying an optimal energy mix that balances land use for energy, food, forestry, and ecosystem protection is critical (Schlemminger et al. 2024).

Implications for Digitalisation of Agriculture and Forestry in Europe

Land scarcity demands efficient management to maximize productivity per hectare.

- This includes intensified, sustainable farming and forestry supported by farm management information systems (FMIS), variable rate technologies (VRT), remote monitoring, and precision input application.
- In forestry, remote sensing, AI, and decision support systems (DSS) enable climate-smart practices (Wang et al. 2025) that boost carbon stocks, wood quality and ecosystem resilience (IPCC, 2022).
- Nature-based solutions, use of by-products and residues, and combined land uses, such as agri-photovoltaics and forest pastures, offer further potential. Digital expert systems can help to find the approach that works in the given conditions and improves land efficiency.
- Digital tools also support pest and disease monitoring, fire risk management, and reducing supply chain losses. Moreover, AI accelerates the development of climate-resilient crops and livestock (Khan et al., 2022; Farooq et al., 2024).

2.2 Emerging Subjects in Legislation: Nature, Next Generations and Technologies

Summary and Key Words

As environmental degradation accelerates, environmental policy is becoming increasingly central, prompting a continual evolution of and more rapid changes in the regulatory landscape. The long-term impacts of policy decisions—particularly concerning climate change, biodiversity loss, and fiscal constraints—are strengthening the political imperative to account for the interests of future generations. Simultaneously, the growing influence of intelligent machines in decision-making is sparking early efforts to grant them specific rights. This marks a shift from viewing such entities as legal objects—owned, traded, and exploited—toward recognising them as legal subjects with autonomous interests.

Key words: Rights of nature / Rights of next generations / Rights of machines / Legal representation of groups without voice / Legal objects and subjects / Sustainability

Current and Future Developments of the Trend

The regulatory landscape is undergoing continuous transformation in response to urgent challenges such as the climate crises and digital transformation. While there is a growing synergy between the discourses on nature and the rights of future generations (Lawrence, 2022), the recognition of machine rights is emerging as a distinct and increasingly relevant area. Together, these three dimensions, nature, future generations, and intelligent machines, are shaping the trajectory of environmental and technological legislation and establishing specific requirements for digital solutions in agriculture and forestry.

The global propagation of environmental laws, initiated in the 1970s and accelerating markedly since the 1990s, has led most countries to adopt environmental frameworks, many of which are now enshrined in their constitutions (UNEP, 2019). Despite this progress, effective implementation and enforcement remain a critical challenge. A significant milestone occurred in 2008 when Ecuador became the first country to recognise nature as a legal subject, granting it rights previously reserved for legal persons. This paradigm shift has since inspired similar legal initiatives, particularly in Latin America. In Europe, as of February 2025, 67 legal proposals concerning the rights of nature are under development. However, their actual impact will hinge on whether they are translated into binding legislation (Haas et al., 2025).

References to future generations began appearing in national constitutions in the 1990s. Today, more than 80 constitutions include provisions aimed at their protection, typically addressing four key areas: the environment, natural resources, societal values, and public finance (Araújo & Koessler, 2021). While constitutional language alone does not guarantee *de jure* protection, it has opened legal avenues for challenging policies that endanger the interests of future generations, particularly in the context of climate change. The adoption of the UN 2030 Agenda for Sustainable Development in 2015, along with the Well-being of Future Generations (Wales) Act, has further operationalised this principle by establishing concrete goals and targets, thereby encouraging future-proofing and long-term accountability (Futurepolicy.org, 2021; UN DESA, 2024).

In contrast, the discourse on the rights of machines centres on regulating the societal impact of artificial intelligence and ensuring equitable access to technologies. In certain cases, machines have already been granted exceptional legal status - for example by being appointed to corporate management boards or even receiving citizenship (see e.g. BBC, 2014; Weller, 2017).

The future legal landscape will be shaped in part by the trickle-down effect of major European initiatives, such as the European Green Deal, the Green Industrial Deal and EU Digital Strategy, as their principles are embedded in national legislation and inspire regulatory innovations globally. However, future trajectories remain uncertain, as political dynamics continue to oscillate between increased regulatory intervention and tendencies toward market liberalisation.

Recent Signals within the Scope of the Trend

2.2.1 Integrating the Interests of Future Generations into Policymaking

As awareness grows around the long-term consequences of today’s policy decisions, particularly in relation to environmental degradation, biodiversity loss, and greenhouse gas emissions, there is increasing recognition of the need to consider future generations in responsible policymaking, despite their lack of direct representation. This principle has deep roots: the 1972 UN Stockholm Declaration emphasised the importance of environmental preservation for future generations, while the 1992 Rio Declaration called for meeting both present and future needs (Shelton, 2023). The 2015 Sustainable Development Goals expanded this vision to encompass peace and prosperity for both people and the planet. In 2015, Wales became the first European state to legally enshrine the well-being of future generations into policy, setting an example for others (Future Generations Commissioner for Wales, 2025). In 2023, legal scholars endorsed the recognition of the Human Rights of Future Generations (Rights of Future Generations, 2023). Building on this momentum, the UN Summit of the Future adopted the Declaration on Future Generations in 2024, formally integrating their interests into global decision-making processes (UNGA, 2024). Reflecting this shift, the European Commission appointed its first Commissioner for Intergenerational Fairness, who is currently preparing a dedicated strategy for 2025 (EC 2025b; EC JRC, 2025).

2.2.2 The Emergence of the Rights of Nature in Environmental Policy

Traditional environmental policy has typically adopted a human-centric approach, prioritising the protection of nature for human benefit. In contrast, the rights of nature paradigm recognises nature as a rights-holder with legal autonomy. This emerging perspective views humans as an interdependent part of the natural world and grants legal status to animals, plants, and ecosystems. Under this model, humans act as stewards who are prohibited from disrupting ecological systems (Max Planck Institute for Comparative and International Private Law, 2022). This shift was pioneered by Ecuador in 2008, incorporating nature's rights into its constitution (Max Planck Institute for Comparative and International Private Law, 2022). Inspired in part by Indigenous worldviews that emphasise harmonious coexistence with nature, countries such as Bolivia, Argentina, India, Panama, and New Zealand have since introduced similar measures. The Rights of Nature Law Library documents numerous global initiatives, including examples from Ireland and Spain (Center for Democratic and Environmental Rights, 2025). Support for the rights of nature is growing in Europe, where over 60 political initiatives are currently active across various policy cycles, and several countries are considering constitutional recognition (Haas et al., 2025). A significant milestone was the EU Environmental Crime Directive adopted in 2024, which criminalises serious environmental harm, including wildlife crimes, habitat deterioration, and pollution (EU, 2024b). This development marks a broader shift toward recognising nature's intrinsic value within legal systems.

2.2.3 Evolving Regulatory Landscape of AI and Machines

The growing intelligence and autonomy of machines are increasingly influencing decision-making processes. Over the past decade, AI systems have gained formal recognition, exemplified by a computer algorithm being appointed to a venture capital firm's board (BBC, 2014) and Saudi Arabia granting citizenship to a robot (Weller, 2017). These developments have sparked debates about rights, responsibilities, and taxation – such as proposals for a "robot tax" to address labour market imbalances. While circular economy initiatives support machine longevity through measures like the right to repair (EU, 2024c) and promote reuse and refurbishment (Bertelsmann Stiftung et al., 2025), these efforts primarily aim to reduce environmental harm, rather than confer rights to machines. Accordingly, current regulations centre less on machine rights and more on managing their societal impacts. Concerns over AI's risk to fundamental rights have prompted regulators responses. In 2024, the UN proposed a global governance framework to mitigate harms and promote equitable benefit sharing. The EU's AI Act, the world's first risk-based regulatory framework for AI, aims to ensure safety, uphold fundamental rights, and foster human-centric AI (EU, 2024d). This is part of a broader EU strategy to strengthen responsible AI adoption (EC, 2025c). Together, these developments illustrate a shifting regulatory landscape, where the focus remains on balancing the societal and ethical implications of increasingly intelligent machines.

Implications for Digitalisation of Agriculture and Forestry in Europe

The evolving regulatory focus on nature, future generations and machines may have important implications for digital agriculture and forestry:

- If machines / IT were granted rights and this applied also to digital tools and applications in agriculture and forestry, this would pose new challenges for providers and potentially users of these tools and services, i.e. it would bring with it new requirements for legal competencies and capacities in the sector.
- More far-reaching rights and regulation around protecting the interests of future generations can influence overall directions in how the EU agriculture and forestry develop, and what priorities in them are – e.g., with potentially increasing focus on nature and community services provided by agriculture and forestry. It could also bring about a stronger need for outreach and communication of economic actors in these sectors with communities and especially younger generations, in order to find solutions

in case of conflicting interests; digital tools applied in both sectors could also cater to these needs.

- Maintaining the good status of ecosystems and natural bodies requires robust monitoring of human activities. Digital tools, such as digital sensors, trackers, and remote sensing technologies, can provide reliable data to support due diligence and compliance with environmental regulations.
- Long-term effects should be considered proactively during agricultural and forestry planning. Digital solutions enable ex-ante assessments of impacts on biodiversity, soil health, and ecosystem services, including clean water, air quality, and carbon sequestration. Looking ahead, digital twins of ecosystems and agricultural/forestry activities will help to simulate planned activities over several seasons to understand long-term impacts on nature and future generations.
- Technology assessment of digital tools and machines will help identify unintended risks and possible side effects of their use, such as impacts on soil and water quality or biodiversity. Examples include digitally enabled tools like variable rate technologies that optimise the application of inputs, water, fertiliser, pesticides, seeds, according to site-specific needs, or drones for insect control. The results could be used to redesign and improve technological innovations to reduce risks and side effects.
- Machine maintenance to increase longevity and prevent damage is becoming more important: sensors measure the need for preventive maintenance, others identify objects in the field that can damage machines, and autonomous steering helps machines avoid danger spots. For example, drones already use multiple sensors, such as optical and acoustic, to measure distance and detect obstacles.
- The regulation of technology drives innovation in digital agriculture and forestry technologies, promoting their use in the transition to sustainable and regenerative agriculture. Harmonisation of regulation is a prerequisite for large-scale application and approval for use across different markets.

2.3 Gender Equality as Catalyst for Socially Sustainable Digital Agriculture and Forestry

Summary and Key Words

Gender equality in European agriculture and forestry is gradually improving, yet both sectors remain largely male-dominated. The digital transformation presents significant opportunities to empower women as innovators and entrepreneurs, promote financial inclusion, and support sustainable food systems, while also enhancing rural connectivity and resilience. Nevertheless, sociocultural constraints, unequal access to digital infrastructure, and gender biases within both the tech and the primary production industry as well as resource distribution continue to impede women's adoption of agritech. European policy frameworks are increasingly acknowledging gender equality as a cornerstone of digital transformation. A gender-inclusive agritech approach, tailored to women's needs, ensuring accessibility, offering

targeted training, and promoting women's participation in decision-making - will be key to unlocking the full potential of digitalisation and ensuring socially sustainable outcomes.

Key words: Gender equality / Gender-Inclusive Agritech / Women-led Innovation

Recent and Future Developments of the Trend

Women remain underrepresented in European agriculture and forestry. In 2020, 68.4% of all farm managers in the EU were men, while only 31.6% were women (Eurostat, 2024). Additionally, farmers under the age of 40 manage only 12% of European farms, with women representing just 3% of this younger group (Eurostat, 2020).[15] Notwithstanding, women´s participation, particularly in primary managing roles, is gradually increasing; for example, a significant share of new entrants into the agriculture are young women (Sutherland et al., 2015), though overall progress remains slow (Glazebrook et al., 2020; Roos et al., 2021). Beyond representation, the agriculture and forestry sectors continue to present systemic barriers to gender equality by perpetuating a male-dominated culture (ibid.).

The EU´s Common Agricultural Policy (CAP) for 2023-2027 emphasizes promoting gender equality and increasing women's participation in farming (EU CAP Network, 2024). The European Commission *Vision for Agriculture and Food* aims to attract more women into the agriculture and food economy and to establish a *Women in Farming Platform* (EC, 2025d). Recently, three EU-funded Horizon projects, *FLIARA*, *GRASS CEILING*, and *SWIFT*, have been launched to address gender disparities in agriculture and support women-led innovations in rural areas, focussing on research, training and policy development (EU DG AGRI, 2023).

In parallel with these policy developments, digitalisation is revolutionising the agricultural and forestry sectors. As automation reduces the need for physical labour and widens the range of professional roles, new opportunities may arise for women, especially those skilled in digital technologies (Tunberg, 2022). This digital shift presents a unique opportunity to empower women as innovators and entrepreneurs, improve financial inclusion, support sustainable food systems, and strengthen rural connectivity, thereby creating a more inclusive and resilient agricultural landscape. Women farmers are also increasingly associated with adaptive, diversified farming models that align with ecological and social innovation (Sutherland et al., 2023; Glazebrook et al., 2020). However, research shows that women often face sociocultural constraints, limited access to digital infrastructure, and restricted control over financial and productive resources, all of which hinder agritech adoption (Roos et al., 2021; WEF, 2024).

Globally, women have been largely overlooked as users of agritech, limiting not only their participation in agricultural innovation but also agritech's potential to boost productivity and equity within agricultural systems (WEF, 2024). To unlock the agritech's full potential, a gender-inclusive approach is essential, one that tailors technologies to women's specific needs, ensures accessibility and usability, offers training and support, and actively involves women in agricultural decision-making (WEF, 2024). As digitalisation advances, integrating this

[15] The data on gender of farm managers should be interpreted with caution. Given that 75% of European farms are family-run, the data typically records only one official manager, who is often male (Sutherland, 2023). This approach overlooks the contributions of women actively involved in farm management (ibid.).

approach into both policy and product development will be crucial for fostering socially sustainable outcomes in agriculture and forestry.

Recent signals within the scope of the issue

2.3.1 Gender-Inclusive Agritech as a Business Opportunity

An international shift is underway in how agritech is developed and marketed, growing recognition to gender inclusion both as an ethical priority and a strategic business opportunity. Studies indicate that, in low- and middle-income countries (LMICs), the feminisation of agriculture, driven by demographic and labour shifts, has expanded women's roles as producers and technology users (WEF, 2024). Rising smartphone ownership among women is also reducing barriers to digital access and accelerating agritech uptake (ibid.). Gender is increasingly integrated into Environmental, Social, and Governance (ESG) frameworks, now widely embraced by global asset managers (ibid.). Evidence suggests that women in LMICs demonstrate strong repayment behaviours, making them reliable financial partners (ibid.). Additionally, many companies find that engaging with women builds trust, eases market entry, and strengthens brand presence in rural communities (ibid.). Together, these factors position gender-inclusive agritech as a compelling business opportunity for the future.

2.3.2 Women Farmers Driving Diversified and Sustainable Agriculture

Research increasingly shows that women farmers are more likely to adopt diversified, sustainable, and community-oriented agricultural practices (EU CAP Network 2024; Glazebrook et al., 2020; Sutherland et al., 2015; Sutherland, 2023). These include organic farming, agroecological approaches, direct-to-consumer sales, community-supported agriculture, agri-tourism, and multifunctional land use (Glazebrook et al., 2020). Such approaches often serve both economic and social purposes - strengthening rural resilience, promoting food system sustainability and building stronger ties between producers and communities (Sutherland et al., 2015; Sutherland, 2023). Women-led farms tend to prioritise environmental stewardship, animal welfare, and health-conscious food production. Many women enter farming as entrepreneurs or career changes, rather than inheritors of family farms, brining diverse professional backgrounds and a greater willingness to experiment. This often translates into adaptive business models focussed on niche markets, sustainable value chains, and innovation beyond production efficiency (Unay-Gailhard & Bojnec, 2021). Their openness to innovation extends to agritech: several firms now see women as early adopters, helping to drive the uptake and visibility of tech-enabled sustainable practices (WEF, 2024).

2.3.3 Horizon Europe Projects Advancing Women-Led Innovation in Agriculture

The Horizon Europe projects FLIARA, GRASS CEILING, and SWIFT are tackling gender inequality in agriculture by supporting women-led innovations through research, training, and policy development (EU DG AGRI, 2023). While digital transformation is not their primary focus, innovation is broadly defined to include ecological, social, and digital dimensions. For instance, SWIFT promotes resilient, inclusive, and sustainable rural development through both digital and ecological transitions (EU CAP Network, 2024). Similarly, FLIARA is building a

Community of Practice to enable networking, training, and knowledge sharing among stakeholders, including access to smart solutions and digital tools that support women entrepreneurs (FLIARA, 2025). GRASS CEILING focuses on developing smart-agri skills for women and integrating digital tools into sustainable farming practices (GRASS CEILING, 2025).

Implications for Digitalisation of Agriculture and Forestry in Europe

In the mid- to long-term, advancing gender equality is not only a social imperative but also a strategic enabler of inclusive digital transformation in agriculture and forestry. The following implications highlight the gendered dimensions of digitalisation in these sectors:

- Gender equality calls for inclusive agritech design: it can broaden its innovation potential and improve adoption rates. Technologies tailored to a wider range of users, including women and other underrepresented groups, can foster more sustainable and socially responsive agricultural practices to meet their demands. Examples are digital solutions in niche markets such as agroecology, direct-to-consumer sales, and multifunctional land use.
- Gender-responsive data systems will become increasingly important for evidence-based policymaking. As digital agriculture grows, the availability of gender-disaggregated data will be vital for tracking participation, shaping inclusive funding programmes, and evaluating the broader social impacts of the digital transformation.
- Digital innovation ecosystems are likely to shift towards more participatory and decentralised models. Women-led farms and grassroots initiatives tend to emphasise cooperation, sustainability, and adaptability; values that align with emerging trends in digital knowledge sharing, peer networks, and open-source agritech platforms.
- Tech providers that engage diverse user groups may gain competitive advantages. Firms that co-create solutions with women farmers and rural entrepreneurs can tap into underserved markets, benefit from higher rates of innovation adoption, and enhance the social relevance and market fit of their products.

However, the digital transition may reinforce existing inequalities without targeted interventions. Unequal access to digital infrastructure, training, and financial resources risks marginalising smallholders and women-led farms unless policy frameworks and private sector actors proactively ensure equitable uptake.

2.4 Global Shifts in Primary Production and Trade Stability

Summary and Key Words

Food and wood markets are globally interdependent, with the EU serving as both importer and exporter in each. Disruptions, whether from actual supply issues or artificial factors such as tariffs and speculation, create significant challenges for international trading. While the global food market is projected to grow, prospects for wood products are also strong, particularly as wood replaces more energy-intensive materials. The EU remains reliant on resource inputs, notably agrochemicals such as fertilisers. In the context of geopolitical tensions and food security concerns, what would a sustainability transition in European agriculture mean? Adopting agroecological practices could improve self-sufficiency across Europe, even if yields decline under certain conditions.

Keywords: Global trade / Imports and exports / Foreign markets / Self-sufficiency / Resource dependency

Current and Future Developments of the Trend

Food and wood markets have become more globalised over recent decades. Since 2000, global food trade has doubled in volume and increased fivefold in value (FAO, 2024). Between 2000 and 2023, Europe's agriculture imports and exports (excluding EU27 intra-trade) more than tripled (WTO, 2025). To reduce import dependence, the Common Agricultural Policy (CAP) was introduced in 1962 to ensure food supplies and support farmer incomes (OECD, 2023). Following single market liberalisation in 1993, intra-EU trade expanded markedly (Budzyńska & Durakiewicz, 2024).

The EU's wood sector is export-oriented, with 35% of sawn wood production shipped to Asian Countries, primarily China, Japan, Saudi Arabia and South Korea, in 2021 (Eggers et al., 2024). Over half of EU pulp production is exported to China (Eggers et al., 2024). However, the EU faces supply gaps, especially in round softwood imports (Eggers et al., 2024). Political efforts to boost self-sufficiency are expected to encourage regionalised supply chains and greater domestic wood sourcing. In this context, the New European Bauhaus initiative promotes using wood in construction as a sustainable alternative to energy-intensive materials.

The global food market is projected to grow until 2050 due to population growth and changing diets. In contrast, EU agricultural production growth is slowing, with potential declines animal production (EC, 2024b). Increased global competition means slower export growth through 2035. The EU will remain a net exporter, expanding exports of some crops while potentially reducing oilseed imports (EC, 2024b). The EU-MERCOSUR agreement will open markets for agriculture and forestry producers while protecting sensitive products (EC, 2024c). A major potential shift could come if Ukraine joins the EU, significantly boosting the bloc’s agricultural production capacity.

Recent Signals within the Scope of the Trend

2.4.1 The Changing Role of the EU in Global Food Trade

The EU is a major global producer of agricultural commodities and maintains a positive agricultural trade balance in monetary terms (Loi et al., 2024). Since the 1990s, global food trade patterns have shifted as traditional and emerging suppliers like the USA, Brazil, Argentina, Malaysia, Indonesia, and Ukraine have entered the market, driven by the Green Revolution and market liberalisation. While the EU is a net importer of calories for vegetable proteins and feedstuff, losing market share in volume, it remains a leading exporter of high-value agro-products, such as spirits, wine, cheese, and cigarettes, that do not directly impact food availability or security (Schiavo et al., 2021). Overall, EU’s import dependency is under 10%, but for certain products, a high concentration on the top 4 suppliers and regional concentration of imports are evident: especially animal products and cereals, imports are highly concentrated among the top four suppliers and specific regions. These imports include critical raw materials and fertilisers (e.g., soya beans and soya bean meal for poultry and pig feed, phosphates and potash for fertilisers), where the top two suppliers control 50 to 85% of the market (Loi et al., 2024). Consequently, livestock farming and conventional agriculture, which rely heavily on fertiliser inputs, are most vulnerable to trade disruptions.

2.4.2 Market Price Turbulences: Uncertainties Drive Speculation

In April 2025, US President Trump announced new tariffs of at least 10% for imported goods affecting agricultural producers globally (Ali, 2025). As agriculture is intensively integrated into global value chains, it is highly sensitive to trade policies and retaliatory tariffs. Estimations show that the new tariffs could lead to a contraction of global agrifood trade by 3.4 to 4.7% (Glauber et al., 2025). In addition, financial investors in agricultural commodities increasingly influence market prices and accelerate volatility. Speculation can exploit market uncertainties to profit, by influencing food trading (Marson & Saccone, 2025; Manogna & Kulkarny, 2024; Foodwatch, 2023). Despite financial regulations in the US and EU, commodity futures price volatility has increased since 2021. The growing share of speculators increases the risk that price formation is driven by financial strategies rather than market fundamentals (Kornher et al., 2022). According to Food Watch (2023), 80% of wheat purchases at the peak of the food crisis 2022, after Russia invaded Ukraine, can be interpreted as speculative - made by investment funds and banks. Producers, particularly smallholders suffer, as they depend on sales and input prices: They cannot react to price fluctuations due to growing cycles and infrastructure costs. The Russian war's surge in energy prices disrupted fertiliser markets and reduced fertiliser use, potentially contributing to crop reduction and food crises (Jia et al., 2024).

2.4.3 Trade Implications of Europe’s shift to Agroecology

Industrialised farming relies on resource-intensive methods that deliver high yields but depend on globally integrated supply chains, particularly for agrochemicals and feed. This raises the question: would a transition to more environmentally farming and forestry practices create a food supply gap and affect global food trade? Agroecological practices involve phasing out pesticides and synthetic fertilisers, incorporating legumes into crop rotations, using natural grasslands, and enhancing biodiversity through features such as hedges, trees, and ponds. While these methods typically reduce yield expectations, they offer opportunities to replace imported vegetable proteins- especially through increased legume use and the elimination of bioeneregy crops. A study by French research institutes IDDR and INRAE suggest that, by replacing energy- and resource-intensive inputs and promoting more plant-based diets, Europe could achieve agricultural self-sufficiency by 2050 (Schiavo et al., 2021; INRAE, 2020). However, this transition depends on reduced consumption of animal products and ultra-processed foods, in favour of a healthier dietary patterns. The European Green Deal and the Farm to Fork strategy support these sustainability goals (Loi et al., 2024). To effectively reach political goals, a closer alignment between agricultural, trade, and environmental policies is essential to avoid outsourcing environmental harm via imports produced under lower standards (OECD, 2023; Matthews, 2022). Consumer behaviour in Europe is gradually shifting, with leading food retailers beginning to promote plant-rich diets (Madre Brava, 2024; GFI Europe, 2023).

Implications for Digitalisation of Agriculture and Forestry in Europe

The digital sector itself is vulnerable to trade dependencies, posing risks to the supply of hardware (e.g., computers, electronics and optical products) as well as software, cloud services and AI solutions (Loi et al. 2024, Bria et al., 2025). In agriculture and forestry, many digital tools are embedded in heavy machinery, making these sectors particularly exposed to import dependencies for critical raw materials such as copper and iron ore, which are essential for producing equipment and integrated digital systems (Loi et al., 2024).

At the same time, digitalisation presents opportunities to strengthen the EU's internal resilience by reducing reliance on external suppliers and supporting growth and competitiveness of European agriculture and forestry:

- Agriculture and forestry have a long tradition of machinery sharing through "machinery rings" which facilitate equipment lending, repair, and mutual support (Bredehöft & Zimmermann, 2022). Digital platforms can enhance this model by enabling shared use of advanced, high-cost machinery, reducing downtimes and avoiding redundant investments.
- Digital sales platforms empower producers by reducing reliance on volatile markets and intermediaries. They enable direct-to-consumer models, including innovative approaches like solidarity agriculture, where consumers and producers share organisation, financing and yield risks.
- Precision farming technologies improve input efficiency, reducing the need for energy-intensive fertilisers, pesticides, and herbicides. Some robots, for instance, target weeds or pests directly, replacing specific chemical applications.
- Digital tools support a shift from agrochemical inputs to nature-based solutions such as mulching or planting soil-enriching intercrops. Multi-purpose precision devices and digital advisory services can guide adoption of these practices.
- AI-based tools aid in forecasting and risk assessment, helping farmers make informed decisions by stimulating market trends and environmental risks.

2.5 Community-Supported Agriculture and Forestry as Resilient Alternatives

Summary and Key Words

While embedded in largely neoliberal economic systems, certain niches within European agriculture and forestry are adopting alternative models of trade, ownership, and resource governance. Often grounded in historical traditions, these community-supported practices show strong potential for long-term resilience. They emphasise accessibility, solidarity, mutual trust, interpersonal connection, and small-scale, commons-based approaches, echoing aspects of the modern sharing economy. Increasingly, digital tools are being used to enhance coordination and may help scale and adapt these models for broader impact.

Key words: Cooperatives / Commons / Solidarity Economy / Post-Capitalism

Current and Future Developments of the Trend

Under dominant market-liberal paradigms, European agriculture and forestry are shaped by profit-driven logics and competitive pressures. Farmers, traders, and consumers are embedded in volatile global value chains governed by short-term incentives and speculative markets.

However, across Europe, a range of alternative economic models are (re)emerging that challenge the commodification of land, food, and forest resources. Rooted in community-based approaches, these models emphasise collective ownership, shared resource use, and participatory governance, functioning as democratic counter-models to mainstream capitalism. They tend to prioritise environmental sustainability and equitable access, particularly for marginalised and precarious groups, while reconnecting urban and rural communities (agrathaer GmbH & Leibniz Centre for Agricultural Landscape Research, 2017). Many of these initiatives are inspired by anti-capitalist imaginaries that view the commons as a transformative mode of social organisation (Vaccaro et al. 2023), and are often driven by a distinct demographic: young, urban, educated, and socially engaged actors (URGENCI 2016). In 2015, around 2,800 community-supported agriculture initiatives operated across 22 EU countries, feeding an estimated half million people, a number that has likely grown (URGENCI, 2016). Similarly, commons-based systems for the managing land, water, and forests, often rooted in customary rights and local governance, represent another key strand of these alternative models (Lawrence et al., 2020).

Looking ahead, digital technologies hold strong potential to support and scale these systems. They can enhance coordination, facilitate decentralised decision-making, improve real-time resource tracking, and foster inclusive participation across dispersed communities. When integrated within cooperative or commons-based frameworks, digital infrastructures may also reduce reliance on corporate agritech platforms and strengthen the long-term resilience of local socio-ecological systems.

Recent signals within the scope of the issue

2.5.1 Evolving Models of Community-Based Forest Governance

Across Europe, community-managed forests reflect a long-standing governance tradition (Lawrence et al., 2020). While rooted in historical systems of collective ownership and use rights, these models have evolved in response to modern legal frameworks and governance innovations (Lawrence et al., 2020). Today, they include a wide variety of locally adapted arrangements that empower communities, especially in rural and remote areas, to govern and benefit from forest resources (Lawrence et al., 2020). A defining feature of these systems is their focus not on profit distribution but on shared access and management of forests for subsistence and livelihoods. This includes sustainable harvesting of firewood, mushrooms, and grazing rights, often based on customary entitlements and local knowledge (Lawrence et al., 2020). For instance, in the Transylvanian Forest Commons in Romania, communities collectively manage forest lands primarily for firewood collection and grazing, while also engaging in commercial leases (Vasile, 2019). In parts of Scandinavia, „Everyman´s Rights“ allow all individuals to collect wild mushrooms and berries (La Mela, 2014). Looking ahead, digital technologies could enhance these governance models, through tools for online decision-making, digital mapping of resource use, and platforms supporting transparent financial management and community engagement.

2.5.2 Unlocking the Digital Potential of Agri–Cooperatives

Agricultural cooperatives, member-owned organisations that facilitate collective access to resources, services, and markets, represent long-standing alternatives to conventional agri-business models in Europe. However, they have lagged behind agritech firms in adopting digital technologies (Ghalandarzadeh et al., 2025; Santos et al., 2024). Several structural factors contribute to this gap, including limited connectivity in rural areas where most cooperatives are concentrated, and disparities in digital capacity linked to cooperative size and national economic context. Larger cooperatives in wealthier countries tend to perform better in implementing digital tools (Jorge-Vázquez et al., 2021). Despite these challenges, there is broad consensus that digital transformation holds significant promise for cooperatives. Benefits include enhanced interactivity, multidirectional knowledge exchange, improved market access, and increased organisational efficiency (Ghalandarzadeh et al., 2025). In a sector increasingly dominated by corporate agritech platforms, cooperatives offer a counter-model grounded in data sovereignty, democratic participation, and mutual support.

2.5.3 Rise in Solidarity-Based Agriculture

First developed in Japan in the 1960s, solidarity-based agriculture has evolved into a globally adopted niche model aimed at ensuring affordable access to fresh, healthy food while supporting ecological farming practices (agrathaer GmbH & Leibniz Centre for Agricultural Landscape Research, 2017). The solidarity model is a niche segment focussed on smallholder farmers engaged in speciality crops, like horticulture, fruits, and vegetables, along with livestock farming for meat and dairy, and, to a lesser extent, small-scale forestry or tree nurseries. Members contribute to overall production costs, often on a sliding scale based on individual means, instead of buying individual products, and receive regular shares of the harvest through decentralised urban hubs or farm pick-ups. In Germany, the model is expanding rapidly, with nearly 500 solidarity farms currently in operation and around 100 more in development (Netzwerk Solidarische Landwirtschaft e.V., 2025). One example is the Gemüse Syndikat in Berlin, which offers fair wages for farm workers, avoid synthetic fertilisers and pesticides, and fosters community engagement through “participation days” where consumers help on-site (Gemüse Syndikat, 2025). Beyond affordability and ecological benefits, solidarity-based agriculture also revitalises connections between urban consumers and rural producers, ties that have been eroded by industrialised and globalised food systems (agrathaer GmbH & Leibniz Centre for Agricultural Landscape Research, 2017).

Implications for Digitalisation of Agriculture and Forestry in Europe

The (re)emergence of community-based agriculture and forestry as alternatives to dominant capitalist, market-driven models carry important implications for the digital transformation of these sectors.

- The intensive interaction of partners in co-operatives and between producers and consumers in commons- and cooperative-based models can benefit from targeted digital support through sharing, sales and coordination platforms. It could be a means for scaling up. To provide this kind of functionalities, platforms need to manage safe direct exchange between market actors, incorporate control, finance and safety functions which usually intermediaries provide, like retailers.
- Cooperatives of primary producers like “Maschinenring” provide access to machines through shared investment and infrastructure, pooling resources, technical know-how: they provide shared access to advanced and specialised technologies particularly for small farms and forest operators. Digital solutions as part of shared machines must contain closed data systems for different users. In this way can cooperatives facilitate digital transformation among smallholders who would otherwise remain excluded from innovation pathways.
- Cooperatives and community supported organisations often follow a mutual support ethos. Data systems require an easy to handle and fully traceable system of which data is shared for collaborative learning, cooperative decision-making and real-time coordination.
- To protect data sovereignty within community-based digital infrastructures, robust legal and regulatory frameworks are needed. Cooperative solution provides can ensure collective ownership and control over data, countering the extractive tendencies of dominant agritech providers.
- Given the ecological focus and inclusive ethos of specific cooperatives, especially in serving marginalised communities, digital ecosystems need targeted group specific business models to suit the specific structural and financial as well as support mechanisms for introducing the technology in the cooperative (Jorge-Vázquez et al., 2021).

2.6 The Future of the EU’s Common Agricultural Policy

Summary and Key Words

The Common Agricultural Policy (CAP) is the European Union's primary framework for supporting agriculture, rural development, and environmental sustainability across member states. Established in 1962, it is structured around two pillars: direct payments and market measures (Pillar I), and rural development programs (Pillar II). The CAP aims to ensure fair income for farmers and the forestry sector, encourage environmentally sustainable practices, and strengthen the socio-economic fabric of rural areas. Many small- and medium sized farmers depend on the CAP for income and access to essential resources, helping them stay competitive and maintain food production in the face of larger market players.

Key words: Green Deal / Agroecology / Biodiversity strategy / Regenerative agriculture / Social conditionality / Rural economies / Direct payments / Policy reform

Current and Future Developments of the Trend

The future of the CAP is not just about agriculture and forestry, but about how land, food, ecosystems, and rural societies interact with broad EU priorities like the European Green Deal (EC, 2019), strategic autonomy (EC, 2021a), and digital transformation (EC, 2020a). The latest CAP reform, adopted in 2021 for the period 2023–2027, aims to make the CAP more flexible for Member States, distribute funds more fairly, and contribute to the EU's environmental and climate objectives (EU, 2021; EC, 2021b). Additionally, 25% of direct payments are reserved for "eco-schemes"—voluntary practices that contribute to climate and environmental goals (ibid.). However, discussions on the future of CAP are already underway, with indications of major reforms that could reshape European agriculture in the coming decades, guided by the core principles of strategic autonomy and resilience EP, 2024; Guyomard et al., 2024; European Commission, 2020b).

Recent Signals within the Scope of the Trend

2.6.1 Performance-Driven Financing in CAP

Performance-driven financing marks a major shift in the CAP, linking payments to measurable outcomes rather than land area or historical entitlements. Under the 2023–2027 framework, payments are increasingly tied to eco-schemes and performance indicators, promoting greener practices and improved resource management (EC, 2021b). Under this model, funds are allocated based on the achievement of predefined objectives—such as biodiversity gains or emissions reductions—rather than mere compliance with administrative rules. Farmers using intensive practices that degrade soil, pollute water, or increase emissions risk losing a portion of their direct payments. This results-based approach encourages innovation and adaptive management, especially through digital tools for collecting, monitoring and analysing indicators. However, challenges remain, particularly the lack of robust data for some environmental metrics and the need for interoperable systems that e.g., integrate satellite and farm-level data (ECA, 2021). While the post-2027 CAP is currently under discussion, it's performance-orientated focus on specific objectives and indicators is expected to continue.

2.6.2 CAP in an Enlarged European Union

Without major reform, EU enlargement will likely place considerable financial and structural strain on the CAP (Cornago, 2025). Integrating large agricultural economies like Ukraine would demand either a significant budget increase or a major reallocation of existing funds (Darvas & Mejino-Lopez, 2024; Lindner et al., 2023). Under existing rules, EU enlargement to include all current candidate countries is estimated according to the think tank Centre for European Reform (Cornago, 2025) to raise the CAP budget by 22–25%, with Ukraine as the primary beneficiary due to the size of its agricultural sector. To remain effective in an enlarged EU, the CAP may need to continue shifting toward targeted, performance-based financing that rewards sustainable production practices over land size alone. This includes tightening eligibility, strengthening links to environmental outcomes, and expanding co-financing mechanisms (Cornago, 2025). Enlargement may also accelerate efforts to limit direct payments and redirect funding toward rural development, agri-environmental schemes, and climate resilience (Euractiv, 2023a; Euractiv, 2023b).

2.6.3 CAPs Role in Improving the Socioeconomic Viability of Rural Areas

The CAP plays a key role in strengthening the socioeconomic viability of rural areas by funding both agricultural and non-agricultural development. Between 2014 and 2022, CAP rural programs invested about €8.6 billion (9% of total European agricultural fund for rural development spending) in rural-development measure like public infrastructure, renewable energy, digital hubs, and community centres (EC, 2024d; PAC Network, 2024). With digitalisation a key pillar of the rural vision for a “stronger, connected, resilient, and prosperous rural areas by 2040” (EU, n.d.), investments have targeted broadband expansion, digital hubs, and smart farming to reduce the urban-rural digital divide (EC, 2023b). However, significant gaps in high-speed internet access and digital skills persist, limiting transformation in agriculture, forestry and rural economies (EC, 2021c). Independent reviews credit CAP’s role in diversifying rural economies and combating depopulation but urge stronger links with social and environmental policies (EESC, 2021). Long-term rural prosperity depends on combining CAP funds with coordinated investments in education, transport, digital infrastructure, and social inclusion.

Implications for Digitalisation of Agriculture and Forestry in Europe

- Digitalisation it is becoming the backbone of CAP, fundamentally shaping how policy is delivered, monitored, and its impact measured across agriculture and forestry in Europe.
- The CAP incentivises the adoption of precision technologies, such as variable rate application tools and GPS-guided machinery, through eco-schemes and rural development funds, encouraging farmers and forest managers to transition towards data-driven practices (EU, 2021).
- Several EU Member States are already embedding agricultural technology and digital-governance tools into their CAP Strategic Plans to improve efficiency, transparency, and real-time monitoring capacities. Examples of these digital tools include digital farm logs, e-extension services, open agri-data platforms, and systems for remote monitoring and sensing, which help streamline administrative processes and improve sustainability tracking (EC, 2025d).
- To effectively implement these digital components, public administrations require robust digital infrastructure and strong analytical capacity to develop CAP Strategic Plans and manage fund disbursement.
- A major challenge remains bridging the gap between top-down innovation and bottom-up adoption; CAP must support the practical uptake of digital tools by farmers and forest owners, not just promote high-level technological investments.

- Early and inclusive investment in secure, interoperable digital ecosystems is essential to ensure that European agriculture and forestry sectors can meet their climate goals and strengthen food security through digital innovation.
- However, rural areas still face significant connectivity challenges: only 60% of EU rural households have access to high-speed internet, compared to an EU average of 86%, highlighting a digital divide that could undermine CAP's digital ambitions (ECn, 2021c).
- Addressing rural connectivity gaps may require collaboration with emerging technologies such satellite internet, including through initiatives like the EU's IRIS project, which can help extend digital services to remote agricultural and forested regions.

2.7 Increasing Prominence of Tech-Agribusiness Alliances and Cross-Industry Innovation

Summary and Key Words

Digital agriculture and forestry markets are undergoing rapid transformation, driven by the expanding influence of major digital technology companies and multinational agribusinesses. At the same time, new solution providers are repurposing technologies originally developed for other sectors for use in agriculture and forestry. This surge is fuelled by substantial profit potential and increasing demand from farmers for integrated, technology-driven solutions. While this convergence of industries offers promising gains in productivity, resource efficiency, and environmental sustainability, it also raises critical concerns. These include the risk of increased market concentration, heightened dependency for producers, and unequal access to technologies among stakeholders. Addressing these challenges will be key to ensuring that the digital transformation of agriculture and forestry remains inclusive and beneficial for all.

Key words: Tech Giants / Market Concentration / Integrated Solutions / Platform Economy, Digital Ecosystems / Cross-industry innovation / Dual-use technologies

Current and Future Developments of the Trend

Successful implementation of connectivity in agriculture could contribute EUR230 billion to global GDP by 2030, with approximately EUR46 billion in Europe alone (McKinsey, 2020). Tech giants such as Microsoft, Apple, Amazon, Google, and Alibaba are increasingly leveraging their expertise in data analytics, artificial intelligence, cloud computing, and the Internet of Things (IoT) to strengthen their foothold in the agri-food and forestry sectors (Grain, 2021). These companies provide core digital infrastructure and services, focusing on data monetisation, platform subscriptions, and the creation of expansive digital ecosystems. In parallel, multinational agribusinesses, spanning machinery, chemicals, seeds, and biotechnology, are expanding their digital portfolios. Major players such as Syngenta/ChemChina, Bayer/Monsanto, BASF, Corteva, FMC, John Deere, and CLAAS are acquiring and partnering with agritech firms to offer fully integrated, data-driven crop management solutions. These solutions aim to deliver precision recommendations and optimize input use, while also establishing more direct sales channels to farms (Grain, 2021).

The interplay between tech corporations providing digital backbones and agribusinesses capitalising on their established market presence is likely to entrench digital platforms as the dominant organizational model in agriculture and forestry (Sauvagerd et al., 2024). This convergence deepens the integration between input suppliers and those controlling data flow, access to food, and connections to consumers (Grain, 2021). While these developments promise notable advancements in productivity, resource efficiency, and environmental performance, they also risk reinforcing monopolistic structures. Key concerns include data ownership, equitable technology access, and the marginalisation of small farms- potentially exacerbating the digital divide (Sauvagerd et al., 2024). At the same time, new and unexpected partnerships may emerge between tech companies and agribusinesses, alongside the development of innovative, cross-industry products (Amplify, 2025).

Recent Signals within the Scope of the Trend

2.7.1 Bayer and Microsoft Partner on Cloud-Based Agricultural Platform

Climate FieldView, Bayer's flagship digital agriculture platform, integrates data from sensors, satellites, and farm equipment to provide AI-driven visualisations and recommendations on seeding, fertiliser application, and crop protection. Its core strength lies in data integration from various sources such as weather, soil quality, and crop health, into a unified platform (Huang, 2025). While the platform supports data-informed decision-making for farmers, its embedded product suggestions have sparked concerns about potential bias favouring Bayer's proprietary seeds and chemicals (Amplify, 2025). According to Costenaro (2025), Bayer's digital offering is a key asset that is not profitable on its own but serves as a strategic enabler for its core business of selling seeds and crop protection produces. Originally developed by The Climate Corporation, acquired by Monsanto in 2013 prior to its merger with Bayer, FieldView has been operational since 2015 and now covers over 90 million hectares in more than 20 countries (Bayer, 2023). In November 2021, Bayer formed a strategic partnership with Microsoft to migrate FieldView's core functionalities to Microsoft Azure Data Manager for Agriculture. This collaboration aims to improve data interoperability and accelerate innovation by leveraging a scalable, cloud-based platform for agricultural data (Future Farming, 2021). This case exemplifies how digital agriculture is increasingly shaped by the symbiotic relationships between agribusiness giants and global cloud service providers.

2.7.2 Syngenta Expands AI Capabilities via Cropwise Platform

Syngenta's Cropwise platform integrates satellite imagery, weather data, and field-specific inputs to provide farmers with actionable insights for crop and input management. Spanning over 40 million hectares, it includes region-specific tools such as Land.db (US), Strider (Brazil), Modern Agricultural Platform (China), and Cropio (Eastern Europe) (Grain, 2021). In 2024, Syngenta launched GHX 2.0, enhancing Cropwise with AI driven seed recommendations, predictive models, and precision agriculture tools (Business Wire 2024). Future upgrades will add computer vision for pest and disease detection and sustainability analytics to help reduce environmental impact (Business Wire 2024). By aggregating data across its global platforms, Syngenta's continuously refines its AI capabilities, consolidating knowledge within a platform model shaped by the commercial interests of a few dominant agritech firms.

2.7.3 Military Drone Innovations Repurposed for Precision Farming

Drone technologies originally developed for military use are increasingly being adapted for precision agriculture. The war in Ukraine has accelerated the development of low-cost, resilient drone systems, many of which are now repurposed for farming, already a major civilian application (Farmonaut, 2025). These advanced drones offer features such as high autonomy, AI-powered data analysis, swarm scalability, and reliable performance in challenging conditions like low visibility or smoke (Farmonaut, 2025). While cross-sector innovation enhances digital agriculture, it also exposes regulatory gaps. The rapid civilian adoption of dual-use drone technologies often outpaces regulation, raising concerns around privacy and governance (EPRS, 2025).

Implications for Digitalisation of Agriculture and Forestry in Europe

- The growing influence of tech giants and multinational agri-corporations in digital agriculture and forestry carries significant implications for Europe, particularly in market structure, access, Digital agri- and forest-tech solutions promise optimised resource use, reduced environmental impact, and increased yields in agriculture and forestry through tailored, data-driven decision support. To increase the quality of the support, two pillars are important: Advanced analytic capacities based on leveraging AI, IoT, and big data analytics; and widespread adoption of digital solutions. Agrochemicals and machinery providers have already long-established access to farmers and forest operators to roll out digital solutions, digital giants and tech startups provide the digital knowledge.
- Regulatory frameworks around data ownership, privacy, and competition will become increasingly critical. The risks of market concentration and data monopolies reduce trust of independent farmers and forestry operators to get solid neutral advice and keep control of their own production data and business secrets.
- Dependence on a limited number of global tech and agribusiness providers poses strategic vulnerabilities. The concentration of essential digital infrastructure, often hosted on non-European servers, raises concerns about food security, data sovereignty, and geopolitical risks, underscoring the need for European digital autonomy in agriculture and forestry.
- Long-term sectoral resilience depends on balancing innovation benefits with reduced dependency on dominant platforms. Encouraging open standards, interoperability, and support for smaller-scale tech providers can foster a more diverse digital ecosystem that strengthens European agriculture and forestry's adaptability and inclusiveness.
- Cross-industry innovation accelerates the influx of dual-use technologies in agriculture and forestry, necessitating robust governance to ensure ethical deployment, privacy protection, and clear civilian oversight.

2.8 Innovation in Food and Wood Processing Industries Drives Primary Production

Summary and Key Words

The food and wood processing industries are increasingly shaping agriculture and forestry by setting standards and influencing production practices. As key buyers and gatekeepers, they respond to evolving consumer demands—such as health concerns in food and sustainability in wood products—and enforce corresponding requirements upstream. At the same time, technological advances are enabling innovations like wood-plastic composites and personalized nutrition. These trends are expanding market opportunities and reshaping how agrifood and wood materials are produced, tracked, and valued.

Key words: Food industry / Wood processing industry / Personalised nutrition / Wood products

Current and Future Developments of the Trend

The global food market was valued at EUR 8 trillion in 2024 and continues to grow with a rising population and shifting nutrition habits (Oyedijo & Akenroye, 2024). In Europe, approximately 1% of food and drink companies are large enterprises, yet they generate more than half of the sector's turnover. The remaining 99% are SMEs, predominantly micro-enterprises (Van der Velde et al., 2023; Lloyds, 2022). These few large companies wield significant market power, enabling them to set quality standards, production methods, traceability requirements, and pricing across entire food value chains, right down to the farm level.

The food industry operates within a broader ecosystem that includes agricultural, nutritional, and healthcare systems (Venkataraman et al., 2019). Its supply chain is complex, involving numerous actors who transform raw materials into final products (Garnett et al., 2020; Oyedijo & Akenroye, 2024). Regulations around food safety, quality, and plant and animal health (such as the EU Food Safety Policy; EC, 2025e), are increasingly stringent. These regulatory and consumer-driven requirements cascade upstream, influencing supplier practices and production systems.

The wood industry shows similar dynamics. Global demand for wood is rising, and although the sector is less concentrated than food, a small number of multinational firms dominate sawmilling and pulp and paper production (CEPI, 2024). Technological progress and growing demand are driving the development of new wood-based materials and chemicals. Resulting value chains incorporate the use of forestry by-products and wood-processing waste, opening new business opportunities beyond traditional wood products such as panels, sawn wood, paper, and cardboard. Emerging products include e.g. bio-based chemicals and textile fibres (Eggers et al., 2024).

Both sectors increasingly shape primary production. As processing industries advance, they require raw materials tailored to evolving technical and regulatory standards. This drives agriculture and forestry toward data-intensive, digitally integrated, and quality-focused systems, positioning downstream innovation as a key force in transforming upstream practices.

Recent Signals within the Scope of the Trend

2.8.1 AI and Automation in Food Processing

The food processing industry is undergoing a profound digital transformation to streamline operations, enhance product quality, and reduce waste (Jagtap et al., 2024). Digital solutions are enhancing multiple stages of the food value chain (Venkataraman et al., 2019; Innova Market Insights, 2024). For instance, AI-driven ingredient informatics is being used to design food products and develop flavours (Sawano, 2024). Manufacturing Execution Systems (MES) automate production processes, while predictive maintenance reduces machine downtime (Möller, 2025). Advanced sensor-based inspection enables real-time monitoring to ensure compliance with safety and quality standards. Digitalisation also improves visibility, traceability, and adaptability, key to mitigating disruptions and strengthening food security (Jagtap et al., 2025). Furthermore, shared digital ecosystems allow food processors to transfer quality screening and supply chain management tasks to upstream producers. One example is Stocky AI, a start-up that uses AI to connect agrifood suppliers and buyers, supporting inventory and order management, pricing strategies, and waste reduction (Ewing-Chow, 2025).

2.8.2 Food Industry Driving Healthy and Personalised Nutrition

Over the past two decades, consumer interest in healthy eating and digestive well-being has risen significantly, alongside sustainability, convenience and personalised nutrition – reflecting rapidly evolving consumer preferences (Mellentin, 2024; Eastlake, 2025; Pellegrini, 2024). Aging populations, the rise of non-communicable diseases, and human enhancement in sports are expected to be major market drivers (GMI 2025). Major food companies are increasingly active in this high-end segment, which blurs the line between nutrition and pharmaceuticals. While it offers strong revenue potential, it also presents challenges (Ess Team, 2025; Rashidinejad, 2024). Emerging products include functional foods with targeted health benefits (Sloan, 2020), probiotic items enriched with omega-3 fatty acids and other supplements, and personalised nutrition tailored to individual needs (Food 4 Future, 2024). Future personalised nutrition may draw on genomics, health records, nutritional status, and wearable sensors (Herrero et al., 2021). Two primary approaches are evolving: customised foods manufactured to individual specifications, and modular product systems that consumers combine themselves (Buxel, 2024). Despite technical and commercial challenges, the sector is attracting investment from the biomedical field, as well as established food and pharmaceutical companies and startups (FSA, 2023). This shift is creating demand for crops with specific health-promoting traits, such as enhanced nutrient content or gut health benefits. Additionally, clean production, free from agrochemicals and harmful residues, is increasingly vital for both consumer trust and brand reputation (Sustainability Directory, 2025).

2.8.3 Wood Processing Innovation and New Wood Products

Innovations in wood processing are enhancing efficiency, sustainability, and product diversity. In terms of efficiency, Industry 4.0 technologies, such as advanced scanning systems and automated material handling, are optimizing logging, log sorting, and CNC-controlled sawing and cutting, maximizing high-value output (General Kinematics, 2024). The pulp and paper industry is also advancing by exploring alternative fibre sources and adopting low-energy drying and processing methods that improve both efficiency and product quality. Reuse of wood waste is gaining momentum, with new high-value applications such as using sawdust and wood shavings in water remediation or as fillers in high-performance composites like cement (Mallakpour et al., 2021). Meanwhile, innovative biobased materials are outperforming traditional wood products. Engineered composites like Cross-Laminated Timber (CLT) offer enhanced strength and stability, serving as sustainable alternatives to concrete and steel in construction. Lignin-based carbon fibres, lightweight yet strong, are emerging in sectors such as textiles, packaging, biochemicals, and biofuels (Doriane, 2023).

Implications for Digitalisation of Agriculture and Forestry in Europe

Although food and wood processing manufacturers slightly lag behind other industries in digital adoption (Hanacek, 2025), innovations in downstream processing are increasingly shaping primary production practices:

- Digital tools help food manufacturers meet regulatory requirements more efficiently by streamlining reporting, enabling evidence-based risk management, and reducing administrative burdens (Hanacek, 2025).
- Digital platforms enable closer integration of farmers into supply chains, allowing them to sell directly to retailers and processors via online marketplaces.
- The demand for precision-cut wood and digitally optimised CNC sawing influences tree selection, requiring digital forest monitoring and data on individual tree characteristics for harvest planning.
- New wood-based products like Cross-Laminated Timber (CLT) can utilize a wider range of species and wood waste, reducing the need for highly specific digital forestry tools (Eggers et al., 2024).
- Meeting demands for traceability, origin, pollutant levels, and nutritional content requires comprehensive monitoring. Digital sensors, data systems, and decision-support tools track pesticide use, feed practices, and nutrient levels throughout the crop cycle.
- Breeding programmes may increasingly rely on digital tools to improve wood quality, growth rates, and disease resistance, paralleling efforts in crop breeding for nutritional traits.
- AI-driven decision-making, combined with sensors and machine control, support optimal harvesting aligned with processing requirements.
- Digital tools to measure and account for carbon storage across the life cycle of wood-based products, as well as in the agrifood cycle, help to specify the climate impacts of food and wood consumption.

- Processing industries can mandate the use of specific digital platforms, tools and data standards by suppliers, especially in premium segments requiring full traceability and product transparency.

2.9 Prospects for Generative Artificial Intelligence

Summary and Key Words

Generative Artificial Intelligence (Generative AI) has garnered significant public attention and is being rapidly adopted in a wide array of application fields. The fundamental component of generative AI is its ability to produce new content, including text, images, videos, sounds, and codes, based on deep learning models and extensive data training. Recent advancements in generative AI integrate various AI tools and competencies, enabling the learning of data structures in novel domains such as molecular biology, natural imagery, and other data types. Agriculture and forestry can benefit from advanced data analysis, such as image-based pattern recognition. Generative AI tools also enable intuitive interaction with machines and software, elevating decision support for farming and forestry strategies through enhanced reflection and discussion.

Key words: Generative AI / Agentic AI / Decision support systems / Data analysis / Cross-sector innovation

Current and Future Developments of the Trend

Generative AI represents a subset of AI tools designed to create new data in the form of unstructured output, such as text, images, videos, sounds, and code. This capability is based on pattern recognition inspired by pre-existing data on which these tools are trained. The outputs generated by AI are often nearly, and sometimes fully, indistinguishable from real data (Vujović, 2024; Bradley et al., 2024). The global interest in generative AI surged in 2022 following the release of ChatGPT by OpenAI. Since then, numerous services and tools have been launched by various digital technology providers, finding applications in fields such as marketing, entertainment, software development, education, and personal productivity (Bradley et al., 2024). Market expectations for non-sector specific Generative AI from 2022 to 2032 predict an annual growth rate of 25% (Sai et al., 2025).

Generative AI is evolving rapidly, with new applications continuously emerging across tasks and sectors, including in agriculture and forestry, particularly through its integration into digital enhanced Agriculture 4.0 (Sai et al., 2025). These advancements also extend into new data types, such as molecular and genetic data, building on improvements in pre-existing AI and machine learning tools. Consequently, the boundaries between generative AI and other AI tools are fluid, making exact differentiation challenging. Sai et al. (2025) identify potential farming applications of generative AI in areas such as farm layout design, crop growth simulation, crop breeding, precision irrigation and nutrition management, and enhanced Agriculture 4.0 applications, farmer education and training, and personalised advisory services. McKinsey projects that the global growth potential of analytical AI and generative AI will increase from USD 85 billion in 2022 to as much as USD 4.6 trillion by 2040, with an annual growth rate ranging from 17% to 25% (Bradley et al., 2024).

Recent Signals within the Scope of the Trend

2.9.1 A New Era of Decision Support

Decision cycles are rapidly shortening as generative AI can make proposals within seconds. AI-enabled rapid experimentation and learning can be utilised to stress-test alternative options (FTSG, 2025). According to Javid et al. (2023), AI has already been extensively applied to decision-making in farming. The potential applications for agriculture are broad, providing opportunities to advance precision farming, crop improvement, pest and disease management, and supply chain management (Pallottino et al., 2025). For instance, virtual agronomy advisors can mine datasets on weather, soil conditions, pest and disease pressure, and provide evidence-informed decision support (Nuscheler et al., 2024). In research, generative AI, combined with other AI tools, can scan large datasets of patents and scientific research to generate initial hypotheses. Additionally, analysing vast genomic data can be used to propose sequences for crop innovations (Nuscheler et al., 2024). In marketing and sales, AI can micro-segment the customer base, monitor real-time demand, and act as a sales co-pilot (Nuscheler et al., 2024).

2.9.2 Multi-modal Data Analysis Capabilities of Generative AI

Rapid advances in visual interpretation are highly relevant for various monitoring activities, ranging from remote sensing to image-based ground sensors, such as those used to estimate plant health. The ability to analyse combined text, audio, and image inputs from diverse sources enables the resolution of complex problems. Advancements in healthcare use cases, which connect medical imagery with patient records for enhanced diagnostics (FTSG, 2025), could offer cross-industry innovation potential for agriculture and forestry. For example, these advancements could be applied to assess the growth status or health of plants and livestock. Today, citizen science initiatives, such as wild bee monitoring or bird counting projects, already utilise simple photos combined with conventional GPS tracking as the basis for large-scale biodiversity monitoring. These initiatives exemplify collaborative learning between humans and AI, where AI-driven image recognition serves as a dialogic partner in real-time interaction (Sharma et al., 2024).

2.9.3 Agentic AI and Large Action Models: The Next Frontiers in Generative AI

Agentic AI represents the next level in technological development, characterised by autonomous decision-making, goal-setting, and adaptive problem-solving capabilities. These systems can take decisions and act, interact with their environment, and refine their strategies over time, with limited supervision. This is marking a significant advancement in AI technology (FTSG, 2025, Hosseini & Seilani, 2025). Large action models extend the capabilities further, being able to execute tasks autonomously (FTSG, 2025). For instance, in agriculture, this could mean identifying a weed through photo image sensor analytics and tasking a robotic device, such as a gripper arm, to remove the weed. This level of automation and interaction within digital environments signifies a leap towards more dynamic and context-aware AI systems.

Implications for Digitalisation of Agriculture and Forestry in Europe

- The increasing investor interest in AI and generative AI solutions has significant repercussions for fundraising in traditional technology sectors. As investment capital flows into the AI domain, there is a potential decline in investor interest in non-digital technologies or non-AI-supported digital technologies in agriculture and forestry (FTSG, 2025).
- According to a McKinsey (2023b) study, the added value of generative AI to industry revenue in agriculture is estimated to be between 0.6% and 1.0%, which is the lowest among all sectors. For comparison, the high-tech sector, which performs the best, sees an added value of 4.8% to 9.3% of total industry revenue.
- Agentic AI will have be able to collaborate with humans and other agents, planning actions through linear workflow models. Initially, it can simplify and automate back-office tasks, such as accounting, purchasing, sales, and human resource management, benefiting from advancements in other sectors (Sukharevsky et al., 2025). Later, it may support agriculture and forestry-specific tasks, including crop selection and precision farming activities. It can synthesize data and provide reporting and documentation for public authorities and supply chain partners, as well as make decision proposals based on market developments (Nuscheler et al., 2024). The strength of Agentic models lies in their ability to handle less likely situations and adapt in real-time (Yee et al., 2024).
- Natural language processing is making technology interfaces more user-friendly. Machines and digital devices can be managed through simple real-time conversations, as machines generate outputs in easily understandable language and conversation formats (FTSG, 2025). This advancement allows complex machines and processes to be operated more easily by non-experts and non-specialists. It simplifies interaction with complex machines and data, making expert systems more accessible to non-IT specialists, smallholders and semi-skilled workers. Additionally, generative AI has the potential to change the nature of work by augmenting the capabilities of individual workers. For example, it can indicate whether a plant is a weed or a crop, or provide advice on maintaining machinery, thereby automating some of their individual activities such as milking, planting, weeding, and harvesting (Chui et al., 2023).
- The nearly indistinguishable output from generative AI compared to human-generated data, such as text, pictures, and sounds, opens new avenues for cyber risks (Abbas & Taeihagh, 2024; BSI, 2025). Imagine a speculative event, where generative AI produces deepfakes that lead to false decisions by farmers or cause autonomous machines to act destructively, the implications could be severe.

2.10 Digital Innovations and AI in Forestry

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This section is an excerpt of the in-depth sectoral trend report on digitalisation in forestry (see Annex 1[16]). Its structure follows the report's five technology categories. The report and analysis were carried out by our partners at VTT, Arash Hajikhani, Sari Vainikainen, Sajad Ashouri, using the VTT technology platform and AI-supported retrieval-augmented generation (RAG) techniques, based on a comprehensive review of over 1000 documents.

Summary and Key Words

The forestry sector, traditionally reliant on extensive manual labour and conventional methodologies, is undergoing a profound transformation driven by the integration of digital innovations and advanced technological trends. This shift is not merely incremental but represents a fundamental re-imagining of forest management, from inventory and planning to harvesting, logistics, and environmental monitoring. A diverse array of technologies, including artificial intelligence (AI), drones, satellite remote sensing, geographic information systems (GIS), digital twins, and specialized software platforms, are converging to create a more precise, efficient, and sustainable approach to forestry.

Key words: Forestry / Remote sensing and mapping / Data analytics / Digital twins / Software platforms / Automation and robotics

Current and Future Developments of the Trend

The forestry sector is amid a profound and necessary transformation. Driven by the urgent imperatives of climate change, biodiversity loss, and the global demand for sustainable resources, digital technologies are no longer merely supplementary tools but fundamental enablers of a more precise, efficient, and environmentally responsible forest management paradigm. From the intricate mapping capabilities of LiDAR and satellite imagery to the predictive power of AI in identifying pest outbreaks and optimising harvests, and the transparent mechanisms of blockchain in carbon markets, digitalisation is reshaping every facet of how we interact with and manage our forests.

Recent Signals within the Scope of the Trend

2.10.1 Remote Sensing and Mapping Technologies

One of the most impactful categories of digital innovation in forestry revolves around Remote Sensing and Mapping Technologies. These technologies enable the collection of vast amounts of data on forest landscapes without requiring extensive physical presence on the ground, thereby enhancing efficiency and reducing operational costs (Murray et al., 2020). Light Detection and Ranging (LiDAR), for instance, is a laser-based surveying technology that

[16] The full version of the trend report provides additional insights on the actor landscape, adaptation and implementation challenges, environmental impacts and sustainability contributions, public funding, policy and institutional support, geographic trends and regional case studies, as well as critical knowledge gaps and future outlook.

creates highly detailed three-dimensional maps of forests, capturing information about topography, vegetation height, and even individual tree structures (Choudhry & O'Kelly, 2018; RPS Group, 2025). This granular data is invaluable for optimising road construction, planning harvest operations, and assessing standing timber inventory (Choudhry & O'Kelly, 2018; FORSight Resources, LLC, 2005). Companies like RPS Group leverage advanced LiDAR systems, such as the Riegl VQ-1560 II-S, to achieve up to 60 points per square meter, minimising shadowing in dense forest canopies and visualising trees in unprecedented detail for hydrological studies and habitat identification (RPS Group, 2025). Similarly, satellite imagery, both optical and radar-based, provides high-frequency, global coverage, enabling real-time monitoring of deforestation, forest degradation, and even the prediction of agricultural impacts (Hardcastle & Felenbok, 2020; Planet Labs PBC, 2025). Planet Labs PBC, for example, offers high-frequency satellite imagery that identifies endangered forests and predicts agricultural impacts, supporting compliance with regulations like the European Union Deforestation Regulation (EUDR) (Planet Labs PBC, 2025). Drones (Unmanned Aerial Vehicles or UAVs) complement satellite data by providing high-resolution, localised imagery for tasks such as collecting forest inventory data, detecting pest and disease outbreaks, and offering early warnings of forest fires (Choudhry & O'Kelly, 2018; Sveaskog, 2024). Some startups are even utilising drones for reforestation, selecting ideal planting sites and firing germinated seedlings into the soil, which can reduce reforestation costs by 80% while increasing survival rates (Murray et al., 2020). The integration of these diverse remote sensing data sources into Geographic Information Systems (GIS) forms the backbone of modern forest management, allowing for sophisticated spatial analysis, mapping, and decision-making (American Forest Management, 2025; FORSight Resources, LLC, 2025). GIS is used to manage and update cartographic bases of forest assets, integrate within management systems, and facilitate the transfer of digital map material, ensuring that information about cultural remains or sensitive areas is considered during forestry operations (Valor Florestal, 2018; Larsson-Stern, 2016).

2.10.2 Data Analytics and Artificial Intelligence (AI)

Data Analytics and Artificial Intelligence (AI) represent another transformative trend, moving beyond mere data collection to intelligent interpretation and predictive capabilities. AI and machine learning (ML) algorithms are increasingly applied to large datasets derived from remote sensing, ground sensors, and operational records to automate analysis, detect anomalies, and provide predictive insights (Capgemini, 2021; Choudhry & O'Kelly, 2018). For instance, AI-powered systems are being developed to support operators in forest management decisions, using sensor technology from autonomous vehicles to measure, position, and classify trees in real-time with centimetre-level accuracy (Sveaskog, 2023). Nordic Forestry Automation (NFA) has developed such an AI system that automates data collection and reporting for forest owners, increasing transparency and enabling alternative management methods that promote biodiversity and carbon storage (Sveaskog, 2023). In Sweden, Sogeti Sweden, in collaboration with Sveaskog, developed a Geo Satellite Intelligence solution that uses AI and satellite images to visualise the progression of spruce bark beetle infestations, enabling quick management of affected trees and mitigating ecosystem damage (Capgemini, 2025). Beyond pest control, AI is also being explored for optimising timber cutting and sorting ('aptering' in Swedish) to increase timber value and transport efficiency, moving from manual, experience-based processes to data-driven, AI-supported decision-making (Sveaskog, 2022). Furthermore, AI-driven insights are enhancing environmental monitoring, with platforms like Climate TRACE using AI, satellite image processing, and machine learning to monitor greenhouse gas emissions globally, even pinpointing specific industrial sources (Hardcastle & Felenbok, 2020). The integration of AI and data analytics extends to urban forestry, where systems are used to rapidly and accurately count trees, measure their characteristics, and pinpoint illegal felling activity (Accenture, 2018). Davey Resource Group, in partnership with greehill, is pioneering Smart Tree Inventory Solutions using vehicle-mounted LiDAR and machine learning to create 4D digital twins of urban trees, providing high-precision, objective data for urban forest management (The Davey Tree Expert Company, 2025).

2.10.3 Digital Twins

The concept of Digital Twins is gaining traction in forestry, offering virtual replicas of physical forests or operational processes. Stora Enso, a major European renewable materials company, aims to develop a digital twin of an entire forest to track and protect biodiversity, providing decision support for forestry practitioners (Deloitte Insights, 2023). These digital twins can model different biodiversity scenarios based on various external conditions and management interventions, offering a powerful tool for proactive environmental stewardship (Elofsson et al., 2023). Beyond entire forests, digital twins are also being applied to individual trees in urban settings. Greehill, in partnership with Davey Resource Group, uses LiDAR and 360-degree high-resolution photography to create 3D digital twins of urban trees, enabling automated analysis of tree health, maintenance needs, and ecosystem benefits (The Davey Tree Expert Company, 2023). This level of detail allows for more thoughtful planning of tree maintenance and planting projects, enhancing urban sustainability and resilience (The Davey Tree Expert Company, 2023).

2.10.4 Specialized Software Platforms and Integrated Systems

Specialised Software Platforms and Integrated Systems are crucial for operationalising these digital innovations across the forestry value chain. Enterprise Resource Planning (ERP) systems, adapted from industrial production, are integrating various company areas to streamline information flow and support data-driven decision-making in forest management (Valor Florestal, 2018; Hyöky et al., 2023). Platforms like Skogstorget in Sweden offer forest owners a digital hub for managing their forest holdings, ordering services, and tracking progress in real-time (Mellanskog, 2024). This platform, along with a digital advisor (MAI) powered by AI, provides continuous updates on forest growth and enables digital ordering of services like young forest clearing (Mellanskog, 2025). Other specialised software includes harvest scheduling tools, such as Remsoft Spatial Planning System and Woodstock models, which optimise timber allocation and integrate non-timber resources like wildlife habitat and wetlands into planning (FORSight Resources, LLC, 2025). Carbon accounting tools and platforms, like those from NCX, are enabling landowners to participate in forest carbon markets by providing transparent, science-driven methodologies for quantifying carbon sequestration and facilitating the sale of carbon credits (NCX, n.d.; NCX, 2022). These platforms often leverage cloud-based data storage and management, ensuring secure data handling and accessibility (Accenture, 2025). Enterprise Resource Planning (ERP) systems are being actively transformed within the forestry industry, with Finnish expertise playing a notable role. EY Finland, for instance, has explored how the forestry industry can transform its ERP systems to streamline operations and enhance data flow, indicating a focus on integrated digital solutions for complex industrial processes (Hyöky et al., 2023). This transformation extends to robust ESG (Environmental, Social, and Governance) reporting, where technology is fast-tracking the journey to more comprehensive and transparent sustainability disclosures, a critical aspect for Finnish companies operating in a highly regulated European market (Hyöky & Virranta, 2023). These developments underscore a strategic commitment to leveraging digital tools for both operational efficiency and advanced sustainability performance.

2.10.5 Automation and Robotics

Finally, Automation and Robotics are increasingly being deployed to enhance efficiency and safety in forestry operations. While fully autonomous forestry machines are still emerging, AI-based driver assistance systems are supporting operators in real-time decision-making during thinning operations (Sveaskog, 2023). Robotic Process Automation (RPA) is being used to reduce repetitive administrative tasks, freeing up human capital for higher-value activities (Deloitte Insights, 2023). In the broader landscaping sector, electric and autonomous lawn mowers are being adopted for sustainability and cost savings, with companies like Electric Sheep deploying AI-powered autonomous mowers (Bromfield et al., 2024). Although not yet widespread in traditional forestry, these trends indicate a future where automated systems will play a more significant role in physically demanding or repetitive tasks, further enhancing productivity and safety. The convergence of these digital innovations is fundamentally reshaping the forestry sector, enabling more informed decision-making, optimising resource utilization, and fostering a more sustainable and resilient approach to forest management.

Implications for Digitalisation of Forestry in Europe

Digital innovations are actively contributing to critical environmental goals in forestry.

- They enable more accurate measurement, reporting, and verification of greenhouse gas emissions and carbon sequestration, providing the necessary data for effective climate change mitigation strategies (Resource Management Service, LLC, 2024; NCX, n.d.).
- By facilitating early detection of infestations and wildfires, supporting targeted conservation efforts, and enabling the creation of digital twins for comprehensive ecosystem monitoring, these technologies are bolstering biodiversity conservation and enhancing overall ecosystem health (Deloitte Insights, 2023; Capgemini, 2025).
- Furthermore, digital tools are instrumental in promoting sustainable soil and water management through precision forestry techniques, reduced impact logging, and smart irrigation systems (Choudhry & O'Kelly, 2018; American Forest Management, 2025).
- The emergence of nature-based solutions, often underpinned by digital platforms, signifies a growing recognition of the economic value of ecological services, fostering

new avenues for sustainable finance and investment (Kurth et al., 2025; Roland Berger GmbH, 2023).

However, the path forward is not without its complexities. The successful integration of digitalisation hinges on overcoming significant adaptation and implementation challenges.

- These include the persistent issues of data quality, standardization, and interoperability across diverse systems and stakeholders (Hardcastle et al., 2022; PwC, 2025).
- Infrastructural limitations, particularly in remote forest areas, continue to pose barriers to real-time data flow and technology deployment (Choudhry & O'Kelly, 2018).
- A critical human dimension involves addressing skills gaps and workforce adaptation, ensuring that forestry professionals are equipped with the necessary digital competencies and that automation is embraced as an opportunity rather than a threat (Murray et al., 2020; Habgood & Lys, 2024).
- Moreover, the fragmented ownership structures of forests globally, coupled with evolving and sometimes inconsistent regulatory frameworks, demand concerted efforts to foster collaboration and create supportive policy environments (Choudhry & O'Kelly, 2018; Prepscius et al., 2025).

Looking ahead, the future of forestry is undeniably digital. What digitalisation enables is a shift from reactive management to proactive, data-driven stewardship, allowing for more informed decisions that balance economic productivity with ecological integrity. It offers unprecedented transparency across supply chains, empowering consumers and regulators to demand sustainably sourced products. It unlocks new financial mechanisms that incentivise conservation and carbon sequestration, transforming forests into active participants in the global climate economy.

3. Response of Digitalisation for Agriculture and Forestry to Challenges: Cross-cutting Trend Implications

How do emerging trends and developments shape future requirements for digital solutions in agriculture and forestry? By “future requirements”, we mean the criteria that digital tools and data services must meet to address the evolving conditions faced by agricultural and forestry operators. In this way, trends directly drive the necessary capabilities of future digital solutions. This chapter draws on the full range of insights from the 4Growth Horizon Scanning and trend research conducted in 2024 and 2025 (see Chapter 2 and Annex 2). It summarises the overarching implications of the analysed trends, highlighting key insights how digitalisation of agriculture and forestry is responding to challenges through to 2040. Beyond the Horizon Scanning results, we also integrate findings from the ongoing observatories’ surveys (as reported in Chlouveraki & Kasimati, 2025b / D4.13 report) and the second iteration of the Market Monitoring and Forecasting Tool (MMFT) market modelling (Flytkjaer et al., 2025 / D3.2 report). For the MMFT data, we refer to the results of the market penetration of technologies[17] in the EU27. Foresight insights are contrasted with the current assessment and future expectations of European farmers and forestry operators from the 4Growth Observatories. The outlook is further supported by market size estimates from the 4Growth MMFT, balancing qualitative insights with quantitative market data. As the 4Growth project is ongoing, both observatory insights and MMFT data are presented here as intermediary results.

Our analysis is organised by the functionalities of digital solutions — that is, the specific benefits or value they provide to farmers and forestry operators in the agriculture and forestry ecosystem. The digital functionalities draw on the taxonomy developed by Muench et al. (2022) and is further specified for digitalisation in agriculture and forestry[18] using insights from the 4Growth State of the Art analysis of digital technologies in agriculture and forestry (Chlouveraki & Kasimati, 2025a). Annex 3 presents a structured overview table of this analysis.

[17] Market penetration is defined as the proportion of the market that has been realised, i.e. how much of the addressable market is covered by the installed base. The installed base is the quantity of the technology actively in use during a specific year (Flytkjaer et al., 2025). Disclaimer: In the absence of secondary data, the MMFT relies on assumptions that require ongoing validation.
18 However, in practice, digital tools are often multifunctional or build on one another. For example, decision-support systems may rely on monitoring data and simulation tools, and in turn provide inputs to precision farming devices. Because of this overlap, the boundaries between functional categories are fluid, and not all 4Growth technology categories map neatly onto every function.

Monitoring

- Rising competition, geopolitical tensions, and climate- and demand-related pressure on productive land (linked to trends[19] such as *Glocalisation, Trade, Tech to deal with climate stress, Land scarcities, Controlled environments*) are **driving forestry operators to improve efficiency.** They face increasing pressure to **enhance competitiveness, strengthen food security, and reduce resource dependencies**. Monitoring agricultural and forestry production conditions[20] is a basis for decision support systems and certain precision farming technologies.
- Climate change, along with shifting climate zones (as reflected in trends such as *Land scarcity, Biodiversity loss, Controlled environment, Forestry and digitalisation*) is increasingly affecting the **spread of pests and diseases, as well as the frequency and intensity of extreme weather events like droughts and wildfires**. Environmental monitoring for these risks can support the development of early warning systems to help manage agricultural and forestry production threats more effectively.
- Climate action, environmental and biodiversity policies (reflected in trends such as *Future of CAP, Biodiversity loss, Consumer demand, Market power shifts, Forestry and digitalisation*) increasingly require performance-based measurement of applied practices. This opens new **income opportunities for agriculture and forestry, including carbon farming, environmentally friendly practices, and habitat restoration**. Monitoring plays a key role in verifying and tracing these beneficial actions. It can also support or even replace formal reporting requirements, helping to reduce bureaucratic hurdles.

Findings from the 4Growth observatories highlight that monitoring technologies are currently essential, particularly for forest monitoring and climate risk assessment. In addition, CAP policies require robust monitoring and performance tracking, while forest strategies increasingly call for remote sensing and forest mapping (Chlouveraki & Kasimati, 2025b). The MMFT reports a current market penetration of recording and mapping technologies at 3%, projecting this to reach 13% by 2040. However, specific segments, such as remote sensing hardware (like drones, handheld devices, sensors) and ground sensing software (programmes that process and analyse satellite or aerial imagery for plant growth, infrastructure mapping, and geological analysis) are both projected to reach 35% market penetration by 2040 (Flytkjaer et al., 2025).

What are the future key requirements? Effective monitoring will require robust data infrastructure and expert analysis, integrating diverse sources such as public and private satellites, drones, and local field data in reliable and intelligent ways. Trust is essential: farmers and forestry operators must retain full control over shared data to preserve their independence. Providers of proprietary data should also receive tangible benefits, such as reduced administrative reporting, when authorities or supply chain partners use monitoring data to assess production performance or meet compliance obligations.

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[19] Trend names mentioned in italics are short titles, Table 3 gives an overview of short and long titles.
[20] combined with automated image processing and interpretation

Simulation and prediction

- Raising geopolitical tensions, trade disruptions, and the growing dominance of oligopolistic market players (as reflected in trends such as *Glocalisation, Trade, Market power shift, Tech alliances, Generative AI, Post-war enlarged EU, Forestry and digitalisation*) underscore the **increasing impact of market volatility**. Predictive capabilities are increasingly important to foresee developments in food and wood product markets, as well as in input markets for agrochemicals, seeds and feed. Building preparedness and developing de-risking strategies is becoming increasingly important for resilience.
- Growing climate stress, such as droughts, storms, shifting climate zones, alongside declining soil quality and the spread of new pests and diseases, is driving the need for **adaptations to practices** (see the trends *Land scarcity, Tech to deal with climate stress, Legal subjects, Forestry and digitalisation, Controlled environment, Data spaces*). Digital twins, virtual representations of entire farms and forests created using remote sensing, ground sensors and operational records, provide predictive insights into current growth cycles and can generate learnings for adaptation needs.
- Climate stress, resource scarcity and geopolitical tensions are **intensifying the need for innovation** (see trends *Bio-nano tech, Land scarcity, Glocalisation, Trade*, etc.). Increased investment in research and development is essential to identify and develop climate-resilient breeds of livestock, crops and plants: design next-generation veterinary drugs, fertilisers, and pesticides to overcome resistance and minimise side effects; and identify domestic alternatives for protein and carbohydrate sources to reduce import dependency.
- Increasing pressure on farm and forestry competitiveness, coupled with greater weather volatility (see trends Market power shifts, Tech alliances, Alternatives to market driven models, Data spaces, Land scarcity, Biodiversity loss, Forestry and digitalisation etc.), is reducing the availability of redundant machinery. **Business continuity is critical, especially for specialised equipment** used in time sensitive activities like planting and harvesting. However, the growing complexity of electronic components and their use in harsh environmental conditions make digital-enabled machines more prone to failure. As a result, predictive maintenance is becoming essential to minimise downtime and ensure operational reliability.

The 4Growth observatories report widespread use of predictive analytics tools, such as yield prediction, disease detection, forest growth modelling, and supply chain optimisation, as some of the most common digital solutions in agriculture and forestry. Crop modelling, combined with precision agriculture tools, is increasingly used to optimise fertilizer and pesticide management. Tools to better align production with market demand significantly enhance innovation capacities, like the development of new tools and services, and smart specialisation strategies (Chlouveraki & Kasimati, 2025b). While the MMFT does not cover these specific functions, respective technology markets are captured under digital solutions that translate data into actionable insights for decision-making (such as Farm Management Information

Systems (FMIS) and Decision Support Systems (DSS) and in the “Monitoring / Mapping Technologies” markets (Flytkjaer et al., 2025)[21].

What are the future key requirements? Effective simulation and prediction tools must integrate diverse data sources, address gaps, and learn from historical or similar cases, while delivering locally tailored insights. Digital models should handle the complexity and variability of natural systems without excessive computational demands. Outputs must provide clear, actionable guidance to farmers, forestry operators, researchers, and policymakers, supporting risk anticipation, early warning systems, and strategies such as climate-smart practices and climate-adaptive crops and livestock.

Decision support for the management of agricultural and forestry systems

- Growing competition, raising geopolitical tensions causing supply risks and market volatilities, increasing power of supply chain partners, stricter regulatory demands, and changing perceptions of work in farming and forestry (reflected in trends such as *Glocalisation, Trade, Market power shift, Tech alliances, Tech to deal with climate stress, Post-war enlarged EU, Forestry and digitalisation, Alternatives to market driven models, Processing industry innovation, Consumer demands, Gender equality*) are driving the need to **reduce fertilizer, pesticides, and irrigation use while improving yields.** Hence, cultivation practices must be adapted and optimized through climate smart approaches, with farmers and forestry operators requiring tailored decision support and guidance.
- Rising regulatory demands, supply chain transparency requirements, and quality standards (highlighted by trends such as *Future of CAP, New subjects in legislation, Processing industry innovation, Market power shifts, Consumer demands*) drive the need for digital solutions that **automate documentation, reporting** and supply chain tracking to ensure **quality management and accountability**.

The observatory findings confirm these needs: farmers and forestry operators recognise the value of data-driven decision support tools and are increasingly adopting them to improve yield and quality. These tools can support enhanced crop planning, enable timely interventions, and optimise harvest scheduling. In addition, cloud and blockchain technologies are used for data traceability, transparency and secure exchange in agricultural value chains, as well as AI-driven analytics for supply chain optimisation (Chlouveraki & Kasimati, 2025b). The MMFT indicates that decision support systems in forestry are more widespread in 2025 compared to Farm Management Information systems with 10% penetration rate in forestry and 2% in farms. The outlook to 2040 indicates a further widening of the gap with 65% market penetration in forestry compared to 10% in farms (Flytkjaer et al., 2025).

What are the future key requirements? Integrating decision support tools smoothly into administrative reporting systems for both public authorities and supply chain partners is becoming increasingly crucial to alleviate administrative burdens. Digital tools should be

[21] According to the 4Growth State of the Art analysis that guided the MMFT structure (D2.3; Chlouveraki & Kasimati, 2025a), predictive analytics tools are part of Farm Management and Information Systems as well as in Recording / Mapping Technologies.

crafted to simplify administrative reporting for public authorities and supply chain partners. This can be accomplished by ensuring that authorities and partners possess the necessary capabilities to process and validate this data effortlessly. Harmonization and standardization are essential for achieving interoperability between various systems and organizations. European Agricultural Data Spaces serve as a platform to host data from different domains and stakeholders in the agriculture and forestry sectors, facilitating secure data sharing. Robust European data regulations foster trust in data spaces by mandating regular forward-looking evaluations to tackle emerging challenges, risks, and opportunities.

Automation and robotics (including precision farming)

- The same mix of trends[22] motivating the use of decision support systems to reduce cost, lower inputs and raise yields (as above) also increasingly fuels the adoption of automation and robotics. Precision farming devices, in particular, enable accurate input application, helping to **cut costs, reduce import dependence, and minimise environmental impacts.**
- In addition, workforce shortages and skills gaps (as highlighted in the trends *Post-war enlarged EU, Market power shifts, Alternatives to market driven models*) call for wider spread application of (semi-)automated machines equipped with sensors and actuators that **support workers or even substitute labour-intensive tasks** like planting, pest control, growth monitoring, and harvesting.

The 4Growth observatories confirm that these trend implications are already evident today: Precision agriculture tools are among the most commonly and actively used, delivering cost reductions, resource optimisation, higher yields, and labour efficiencies. Automation and robotics are especially common in dairy and horticulture to support labour savings (Chlouveraki & Kasimati, 2025b). The observatories also highlight concerns over proprietary data from sensors that limit data sharing, an issue covered in the trends *Market power shifts* and *Tech alliances*.

According to the MMFT baseline results, the market penetration of Variable Rate Technologies (VRT) is expected to grow form 2% in 2025 to 6% in 2040. Guidance and Controlled Traffic Farming currently have a 10% adoption rate, projected to rise to 56% by 2040. Robotics and Smart Machines are used in 3% of agricultural operations in 2025, with expected growth to 25% by 2040. In specific areas, automation adoption is significantly higher, for example, milking robots may reach 90% market penetration, planting robots 50%, and harvesting robots 42% by 2040 (Flytkjaer et al., 2025).

What are future key requirements? While precision farming and forestry can reduce reliance on resource-intensive imports, digital devices and data centres still depend on critical raw materials and energy. This reliance on a few global tech companies poses strategic and cybersecurity risks. To address these challenges, automation and robotics should support resource-efficient, innovative, and nature-based practices, aiding ecosystem restoration and

[22] growing competition, raising geopolitical tensions causing supply risks and market volatilities, growing power of supply chain partners, raising regulatory demands as well as a shifting self-conception of the work in farming and forestry

the preservation of fertile soils and biodiversity. Strengthening European digital providers and enabling stakeholders to access tools and data equitably is essential, alongside continually enhancing defences against cyberattacks, espionage, misinformation, and market manipulation.

Communication and market integration

- Increasing competition, evolving consumer demands, shifting self-perceptions among agriculture and forestry actors, and growing expectations from supply chain partners such as processors and retailers are driving the need for new business models. These developments, as reflected in *Market power shifts, Glocalisation, Trade, consumer demand, Gender equality, Alternatives to market driven models, Processing industry innovation,* are encouraging primary producers to **bypass intermediaries by engaging directly with consumers and partners by digital sales platforms.** In addition, digital communication platforms are enabling community-based farming initiatives and supporting alternative business ventures such as farm holidays and on-site product processing and sales.
- Climate policies and emerging **carbon markets** (as mentioned in the trends *Future of CAP, Tech to deal with climate stress, Market power shift*) offer new revenue opportunities for agriculture and forestry through the provision of **carbon sequestration services** to clients such as energy providers and emission-intensive industries.

Observatory findings support these trend implications: respondents view digital technologies as catalysts for innovation, enabling new service models, research collaborations, and agritech entrepreneurship. (Chlouveraki & Kasimati, 2025b)[23].

What are future key requirements? It is crucial to prevent the marginalisation of less-digitised smallholders and agroecological models. This can be achieved by expanding digital tools for diverse tasks, designing multipurpose solutions, and developing business models for low-budget clients. Transparent, reliable communication of quality standards, supported by fraud-proof channels and validation tools, is essential to meet consumer demand for health and supply chain transparency. With increasing consumer individualisation, understanding micro-segments and providing customised offers and personalised communication will be increasingly important.

Overarching perspective

- Geopolitical tensions (as described in the trends *Glocalisation, Cybersecurity & vulnerability*) are shifting public investment priorities towards security, often at the expense of closing **infrastructure gaps in peripheral rural areas**. Furthermore, the rise of hybrid warfare **increases cybersecurity threats**, leaving digital agriculture and forestry solutions particularly exposed and vulnerable.

[23] There is no specific 4Growth technology category related to communication and market integration, they are covered by FMIS and DSS, covered under the topic “Decision support for the management of agricultural and forestry systems”.

- Dominate players, especially those forming proprietary technology platforms (see trend *Tech alliance, Generative AI*), are creating **challenges for interoperability** of data and devices.
- Many of these actors are established giants in the agrochemical and agritech sectors. Their growing influence, alongside intensifying competition in agriculture and forestry (see trends *Future of CAP, Post-war enlarged EU*), is fostering **mistrust and limiting data sharing**. However, in response to these pressures, there is a revival of cooperative organisational models in agriculture and forestry, built upon trust and collective data governance (as reflected in the trend *Alternative models to market-driven models*).

In this context, the observatories highlight the need for strong incentives to promote widespread data sharing, which is essential for enabling benefits such as regulatory compliance (see topic *monitoring a*bove), supply chain optimisation (see topic *decision support for the management of agricultural and forestry systems* above) and accelerated innovation (see topic *simulation and prediction* above). However, barriers such as technical integration issues and a lack of trust limit widespread data exchange. Observatories suggest the promotion of open innovation ecosystems and clear data sharing norms (Chlouveraki & Kasimati, 2025b).

4. Conclusions for Policymakers and Future Outlook

Chapter 4 draws on the full range of insights from the 4Growth Horizon Scanning and trend research conducted in 2024 and 2025 to provide learnings for policymakers as well as an outlook.

4.1 Learnings and Conclusions for Policymakers

EU policies and strategies strongly shape agriculture, forestry, and digitalisation across Europe. The 4Growth trend analysis provides forward-looking evidence for adapting the EU's agricultural, forestry, and digital policies to facilitate the digital transformation of these sectors. In the following list, we provide overarching impulses for long-term digital, agriculture and forestry policies at the European and national levels, involving public authorities, digital services providers, researchers, farmers, forestry operators, associations and other intermediaries. These are not concrete recommendations; specific proposals will be developed in cooperation with the 4Growth consortium, drawing on the full spectrum of 4Growth research findings.

- **Make digitalisation a means to reduce administrative burdens**: The proposed EU enlargement, including major agricultural players like Ukraine, and the push for sustainable agriculture and forestry requests shifting from area-based to **performance-based subsidies**. To **reduce administrative burdens and simplify legislation, environmental and field monitoring data** can provide evidence to assess agricultural and forestry performance. Therefore, the **Common Agricultural Policy (CAP) should enable seamless data integration** for public monitoring, accountability, and funding disbursement. **Process automation in public administration,** such as AI-driven data integration, accuracy verification, and validity checks, can support this transition.
- **Establish guardrails to ensure digitalisation becomes a key enabler of resilience in agriculture and forestry** by supporting climate action, supply chain stability, reducing one-sided dependencies, and enhancing cyber risk preparedness. These measures should also facilitate effective risk mitigation and adaptation measures and strategies:
- Utilize digitalisation to improve competitiveness, climate adaptation and risk preparedness: To boost the competitiveness of agriculture and forestry by 2040, as per the European Commission's Vision for Agriculture and Food, policies shall address challenges like climate stress, new pests and diseases, and wildfires. This calls for increased digitalisation and research innovation focused on climate-adaptive plants and livestock, climate-smart practices, and digital early warning systems to anticipate risks and prepare solutions and strategies.
- **Support open strategic autonomy through digitalisation**: One-sided dependencies risk threatening Europe's food and wood supply security, making its **resource base vulnerable to external influences.** The Vision for Agriculture and Food stresses the need to mitigate these risks and create a **fair global level playing field** for global cooperation and a competitive agri-food sector. To approach open strategic autonomy, focus shall be placed on key inputs like phosphate and potash, poultry and pig feed, and certain cereals.
- **Ensure digitalisation does not generate unmanageable risks**: Digital agriculture and forestry face **risks from dependence on few multinational providers** of services, software, and hardware. Geopolitical tensions or competition could lead to service withdrawing, biased market intelligence, or illegal activities such as espionage or market manipulation. **Cybersecurity threats** from hackers and cyber warfare add to these risks. A competitive digital agriculture and forestry sector, requests strong **European digital providers and a diverse range of agricultural and forestry actors**—from smallholders to large companies—that can **engage on a level playing field**, as outlined in the European Digital Markets Act. Capacities for fighting cyberattacks, espionage, disinformation and market manipulation are needed.
- **Finally, safeguard that digitalisation is based on smooth trustworthy data sharing:** Promoting **data sharing** requires harmonised data formats, standardized interfaces, and technical integration—supported by political commitment to **universal standards**. Building **trust and ensuring fair access to proprietary data** are equally vital. To boost user confidence, digital policies like the Data Governance Act, Data Act, Digital Services Act, and AI Act—which govern **data access in European Agricultural Data Spaces**— requires regular forward-looking evaluation to enable timely updates that reflect technological advances (e.g., agentic AI) and address new risks in AI, data sharing, and cybersecurity.

4.2 Future Outlook

The trends laid out in this report highlight the **need to further advance digitalisation in agriculture and forestry to address a range of evolving challenges**, including intensifying global competition, supply chain vulnerabilities, market and power concentration across value chains, increasing regulatory requirements, mounting climate and environmental pressures, and significant societal and demographic shifts.

Alongside technological progress, **digital tools and data-driven solutions in agriculture and forestry can provide solutions** for more efficient and climate smart practices, automate tasks to address workforce shortages and skills gaps, support new business models, and reduce administrative burdens and complexity in supply chain management. Nevertheless, **integration still faces several significant challenges** such as adapting to increasingly extreme outdoor conditions, deploying applications in remote areas with limited digital connectivity and power, and managing the complexity of natural systems like plant and livestock growth. **Data flows in these sectors are equally complex**, originating from diverse sources such as satellites and field sensors, and involving a wide range of public and private stakeholders.

Beyond technological challenges, successful digital solutions must clearly demonstrate added value to evolving farm and forestry businesses. The sectors are currently in a state of transition: smallholders increasingly require integrated business models to remain viable, while large-scale operators must adapt their industrial-sized operations to climate impacts, rising input costs, and changing regulatory. The diversity of agriculture and forestry businesses, spanning various crops, livestock, processing stages, business models, etc., demands specialised digital solutions, and success is not guaranteed across all applications.

To maximise the value of digitalisation, technologies, their practical application, and the surrounding regulatory and economic frameworks must evolve in a strategic and coordinated manner. However, the future is uncertain and new challenges and disruptions will appear, both expected and unexpected ones. To be prepared, stakeholders, from agriculture and forestry businesses and technology providers to investors and policy makers, must remain vigilant, constantly monitoring emerging signals and shifting trends to adapt their digitalisation strategies.

This report concludes the 4Growth Foresight Module's Horizon Scanning process. Its findings will update and enrich the draft Holistic Long-term Framework Scenarios from D3.7 (Spring 2025), with the final version due in September 2026. Together, the Horizon Scanning report and Framework Scenarios will be used to derive further policy implications for digitalising agriculture and forestry in Europe within the overall 4Growth proposals.

Annex 1: Forestry and Digitalisation: A Deep Synthesis Report

Introduction

The global landscape is undergoing profound transformations driven by twin imperatives: addressing the escalating climate crisis and safeguarding the planet's intricate ecosystems. Central to these efforts is the forestry sector, a domain historically rooted in traditional practices but now poised at the precipice of a digital revolution. Forests are not merely sources of timber; they are critical carbon sinks, bastions of biodiversity, regulators of hydrological cycles, and vital components of rural economies. As such, the sustainable management of these invaluable natural assets is paramount for climate mitigation, ecological stability, and policy efficacy. Digitalisation, encompassing a broad spectrum of advanced technologies, offers unprecedented opportunities to enhance the efficiency, transparency, and sustainability of forestry operations, transforming how forests are monitored, managed, and utilized. This report delves into a comprehensive synthesis of findings from over a thousand documents, exploring the multifaceted interplay between forestry and digitalisation, and articulating its implications for environmental stewardship, economic viability, and societal well-being.

The urgency of this intersection stems from the dual pressures of increasing demand for forest products and the escalating threats posed by climate change, deforestation, and biodiversity loss. Traditional forestry practices, while foundational, often struggle to keep pace with the scale and complexity of these modern challenges. Manual inventory methods, for instance, can be subjective and infrequent, leading to suboptimal decision-making and missed opportunities for proactive management (Behounek, 2018; The Davey Tree Expert Company, 2025). Similarly, the vastness and remoteness of many forest landscapes make comprehensive monitoring and rapid response to disturbances, such as pest outbreaks or wildfires, exceedingly difficult without technological assistance (Choudhry & O'Kelly, 2018). Moreover, the global push towards a low-carbon economy and nature-positive outcomes places new demands on the forestry sector to quantify its environmental contributions, ensure supply chain transparency, and adapt to evolving regulatory landscapes (Hardcastle et al., 2022; Prepscius et al., 2025).

Digitalisation emerges as a powerful enabler in navigating these complexities. Technologies such as artificial intelligence (AI), drones, satellite remote sensing, geographic information systems (GIS), and advanced data analytics are no longer futuristic concepts but are actively being integrated into various facets of forestry. These tools promise to provide real-time, high-resolution data, automate labour-intensive tasks, enhance decision-making, and foster greater transparency across the forest value chain (Choudhry & O'Kelly, 2018; Capgemini, 2021). For instance, AI-powered systems are being developed to monitor forest health, detect pest infestations, and even optimize timber harvesting, leading to more sustainable and profitable outcomes (Sveaskog, 2023; Capgemini, 2025). Digital platforms are facilitating carbon accounting, connecting landowners to emerging carbon markets, and enabling more robust measurement, reporting, and verification (MRV) of climate benefits (Hardcastle et al., 2022;

NCX, n.d.). Beyond operational efficiencies, digitalisation is also fostering new business models, such as nature-based solutions and sustainable finance, which leverage technology to create economic value from ecological services (Kurth et al., 2025; Roland Berger GmbH, 2023).

However, the path to a fully digitized and sustainable forestry sector is not without its challenges. Issues such as data quality, interoperability between disparate systems, the need for specialized skills, and the inherent complexity of forest ecosystems pose significant barriers to widespread adoption (Deloitte, World Economic Forum, & NTT Data, 2024; Brennan et al., 2025). Furthermore, the fragmented ownership structures of forests globally, coupled with conservative management approaches by public and small private owners, can hinder the rapid uptake of new technologies (Choudhry & O'Kelly, 2018). This report aims to provide a granular analysis of these innovations, their drivers, the challenges they face, and their profound implications for environmental sustainability across diverse geographic contexts. By synthesizing a vast dataset, this study offers a comprehensive overview of the current state and future trajectory of digitalisation in forestry, providing insights for policymakers, industry stakeholders, and researchers committed to a more resilient and sustainable planet.

Methodological Overview

This report is structured based on an extensive review of over 1,000 documents that explore the intersection between forestry and digitalisation. Each document within the dataset underwent meticulous extraction and categorization into predefined metadata fields, enabling systematic synthesis and comparative analysis.

The methodology for synthesizing insights from this comprehensive dataset involved a multi-layered analytical process designed to provide deep, integrated understanding rather than mere summarization. Initially, relevant articles were identified by examining resources from leading consultancies, institutions, and forestry-related organizations. Keywords such as "forestry" and "digital forestry" were used for targeted searches, and the top 50 retrieved links formed the foundation of the initial dataset. Subsequently, each document underwent structured analysis through iterative reading and re-reading, with retrieval augmented generation (RAG) techniques employed to enhance the quality and accuracy of information extraction. Prompt engineering was carefully applied to optimize the RAG model's responses.

Thematic integration was essential for structuring the final report, with categories emerging organically from the dataset content, thereby supporting an inductive approach to understanding digital trends in forestry. A significant component of this synthesis was cross-referencing entries to identify connections, contrasts, and reinforcing evidence across the dataset. For instance, under the theme "Adaptation Challenges," recurring issues such as "data quality" and "skills gaps" were consistently noted across various geographic regions and technology applications, facilitating a robust discussion of common barriers. Similarly, the analysis of the "Environmental Challenges and Solutions" metadata field specifically pinpointed digital innovations addressing environmental objectives like carbon sequestration, biodiversity protection, and soil health improvements. The "evidence" sub-field within each entry was meticulously scrutinized to ensure empirical relevance and support for each claim.

The synthesis aimed to represent broad thematic coverage and rich comparative detail by strategically selecting the most illustrative and impactful examples for discussion. Entries featuring detailed case studies, quantifiable outcomes, or concrete implementations were prioritized. For example, in discussing drone applications, a detailed case study indicating that drones reduced reforestation costs by 80% while improving survival rates was prioritized over general mentions of drone technology (Murray et al., 2020).

When multiple documents provided similar insights, the most relevant, recent, or generalizable sources were chosen to avoid excessive citations, thereby enhancing readability without sacrificing the strength of substantiation. The iterative nature of this analytical process allowed for ongoing refinement of arguments and integration of emerging insights, resulting in a cohesive and comprehensive synthesis. Consequently, this report represents not merely a summary of individual documents but a deeply integrated analysis that reveals overarching trends and critical nuances shaping the evolving relationship between forestry and digitalisation.

Digital Innovations and Technological Trends in Forestry

The forestry sector, traditionally reliant on extensive manual labour and conventional methodologies, is undergoing a profound transformation driven by the integration of digital innovations and advanced technological trends. This shift is not merely incremental but represents a fundamental re-imagining of forest management, from inventory and planning to harvesting, logistics, and environmental monitoring. A diverse array of technologies, including artificial intelligence (AI), drones, satellite remote sensing, geographic information systems (GIS), digital twins, and specialized software platforms, are converging to create a more precise, efficient, and sustainable approach to forestry. These innovations can be broadly grouped into thematic categories, each with distinct applications, significant impacts, and illustrative examples drawn from the comprehensive dataset.

One of the most impactful categories of digital innovation in forestry revolves around **Remote Sensing and Mapping Technologies**. These technologies enable the collection of vast amounts of data about forest landscapes without requiring extensive physical presence on the ground, thereby enhancing efficiency and reducing operational costs (Murray et al., 2020). Light Detection and Ranging (LiDAR), for instance, is a laser-based surveying technology that creates highly detailed three-dimensional maps of forests, capturing information about topography, vegetation height, and even individual tree structures (Choudhry & O'Kelly, 2018; RPS Group, 2025). This granular data is invaluable for optimizing road construction, planning harvest operations, and assessing standing timber inventory (Choudhry & O'Kelly, 2018; FORSight Resources, LLC, 2005). Companies like RPS Group leverage advanced LiDAR systems, such as the Riegl VQ-1560 II-S, to achieve up to 60 points per square meter, minimizing shadowing in dense forest canopies and visualizing trees in unprecedented detail for hydrological studies and habitat identification (RPS Group, 2025). Similarly, satellite imagery, both optical and radar-based, provides high-frequency, global coverage, enabling real-time monitoring of deforestation, forest degradation, and even the prediction of agricultural impacts (Hardcastle & Felenbok, 2020; Planet Labs PBC, 2025). Planet Labs PBC, for example, offers high-frequency satellite imagery that identifies endangered forests and predicts agricultural impacts, supporting compliance with regulations like the European Union

Deforestation Regulation (EUDR) (Planet Labs PBC, 2025). Drones (Unmanned Aerial Vehicles or UAVs) complement satellite data by providing high-resolution, localized imagery for tasks such as collecting forest inventory data, detecting pest and disease outbreaks, and offering early warnings of forest fires (Choudhry & O'Kelly, 2018; Sveaskog, 2024). Some startups are even utilizing drones for reforestation, selecting ideal planting sites and firing germinated seedlings into the soil, which can reduce reforestation costs by 80% while increasing survival rates (Murray et al., 2020). The integration of these diverse remote sensing data sources into Geographic Information Systems (GIS) forms the backbone of modern forest management, allowing for sophisticated spatial analysis, mapping, and decision-making (American Forest Management, 2025; FORSight Resources, LLC, 2025). GIS is used to manage and update cartographic bases of forest assets, integrate with management systems, and facilitate the transfer of digital map material, ensuring that information about cultural remains or sensitive areas is considered during forestry operations (Valor Florestal, 2018; Larsson-Stern, 2016).

Data Analytics and Artificial Intelligence (AI) represent another transformative trend, moving beyond mere data collection to intelligent interpretation and predictive capabilities. AI and machine learning (ML) algorithms are increasingly applied to large datasets derived from remote sensing, ground sensors, and operational records to automate analysis, detect anomalies, and provide predictive insights (Capgemini, 2021; Choudhry & O'Kelly, 2018). For instance, AI-powered systems are being developed to support operators in forest management decisions, using sensor technology from autonomous vehicles to measure, position, and classify trees in real-time with centimetre-level accuracy (Sveaskog, 2023). Nordic Forestry Automation (NFA) has developed such an AI system that automates data collection and reporting for forest owners, increasing transparency and enabling alternative management methods that promote biodiversity and carbon storage (Sveaskog, 2023). In Sweden, Sogeti Sweden, in collaboration with Sveaskog, developed a Geo Satellite Intelligence solution that uses AI and satellite images to visualize the progression of spruce bark beetle infestations, enabling quick management of affected trees and mitigating ecosystem damage (Capgemini, 2025). Beyond pest control, AI is also being explored for optimizing timber cutting and sorting (aptering) to increase timber value and transport efficiency, moving from manual, experience-based processes to data-driven, AI-supported decision-making (Sveaskog, 2022). Furthermore, AI-driven insights are enhancing environmental monitoring, with platforms like Climate TRACE using AI, satellite image processing, and machine learning to monitor greenhouse gas emissions globally, even pinpointing specific industrial sources (Hardcastle & Felenbok, 2020). The integration of AI and data analytics extends to urban forestry, where systems are used to rapidly and accurately count trees, measure their characteristics, and pinpoint illegal felling activity (Accenture, 2018). Davey Resource Group, in partnership with greehill, is pioneering Smart Tree Inventory Solutions using vehicle-mounted LiDAR and machine learning to create 4D digital twins of urban trees, providing high-precision, objective data for urban forest management (The Davey Tree Expert Company, 2025).

The concept of **Digital Twins** is gaining traction in forestry, offering virtual replicas of physical forests or operational processes. Stora Enso, a major European renewable materials company, aims to develop a digital twin of an entire forest to track and protect biodiversity, providing decision support for forestry practitioners (Deloitte Insights, 2023). These digital twins can model different biodiversity scenarios based on various external conditions and management interventions, offering a powerful tool for proactive environmental stewardship (Elofsson et al., 2023). Beyond entire forests, digital twins are also being applied to individual trees in urban settings. Greehill, in partnership with Davey Resource Group, uses LiDAR and 360-degree high-resolution photography to create 3D digital twins of urban trees, enabling automated analysis of tree health, maintenance needs, and ecosystem benefits (The Davey Tree Expert Company, 2023). This level of detail allows for more thoughtful planning of tree maintenance and planting projects, enhancing urban sustainability and resilience (The Davey Tree Expert Company, 2023).

Specialized Software Platforms and Integrated Systems are crucial for operationalizing these digital innovations across the forestry value chain. Enterprise Resource Planning (ERP) systems, adapted from industrial production, are integrating various company areas to streamline information flow and support data-driven decision-making in forest management (Valor Florestal, 2018; Hyöky et al., 2023). Platforms like Skogstorget in Sweden offer forest owners a digital hub for managing their forest holdings, ordering services, and tracking progress in real-time (Mellanskog, 2024). This platform, along with a digital advisor (MAI) powered by AI, provides continuous updates on forest growth and enables digital ordering of services like young forest clearing (Mellanskog, 2025). Other specialized software includes harvest scheduling tools, such as Remsoft Spatial Planning System and Woodstock models, which optimize timber allocation and integrate non-timber resources like wildlife habitat and wetlands into planning (FORSight Resources, LLC, 2025). Carbon accounting tools and platforms, like those from NCX, are enabling landowners to participate in forest carbon markets by providing transparent, science-driven methodologies for quantifying carbon sequestration and facilitating the sale of carbon credits (NCX, n.d.; NCX, 2022). These platforms often leverage cloud-based data storage and management, ensuring secure data handling and accessibility (Accenture, 2025). Enterprise Resource Planning (ERP) systems are being actively transformed within the forestry industry, with Finnish expertise playing a notable role. EY Finland, for instance, has explored how the forestry industry can transform its ERP systems to streamline operations and enhance data flow, indicating a focus on integrated digital solutions for complex industrial processes (Hyöky et al., 2023). This transformation extends to robust ESG (Environmental, Social, and Governance) reporting, where technology is fast-tracking the journey to more comprehensive and transparent sustainability disclosures, a critical aspect for Finnish companies operating in a highly regulated European market (Hyöky & Virranta, 2023). These developments underscore a strategic commitment to leveraging digital tools for both operational efficiency and advanced sustainability performance.

Finally, **Automation and Robotics** are increasingly being deployed to enhance efficiency and safety in forestry operations. While fully autonomous forestry machines are still emerging, AI-based driver assistance systems are supporting operators in real-time decision-making during thinning operations (Sveaskog, 2023). Robotic Process Automation (RPA) is being used to reduce repetitive administrative tasks, freeing up human capital for higher-value activities (Deloitte Insights, 2023). In the broader landscaping sector, electric and autonomous lawn mowers are being adopted for sustainability and cost savings, with companies like Electric

Sheep deploying AI-powered autonomous mowers (Bromfield et al., 2024). Although not yet widespread in traditional forestry, these trends indicate a future where automated systems will play a more significant role in physically demanding or repetitive tasks, further enhancing productivity and safety. The convergence of these digital innovations is fundamentally reshaping the forestry sector, enabling more informed decision-making, optimizing resource utilization, and fostering a more sustainable and resilient approach to forest management.

Sectoral Landscape: Actors and Drivers

The digital transformation of the forestry sector is not a monolithic phenomenon but a dynamic interplay of diverse actors and powerful drivers across various interconnected sectors. While traditional forestry supply chain actors remain central, the landscape is increasingly shaped by the growing influence of digital technology companies, public research institutions, and innovative startups. These entities, along with the broader environmental monitoring, agriculture, and financial sectors, are collectively driving the adoption and evolution of digital innovations in forestry.

Forestry Supply Chain Actors form the historical and foundational core of the sector, encompassing everything from timberland owners and forest managers to pulp and paper industries, sawmills, and manufacturers of wood products. Companies like Sveaskog in Sweden, Weyerhaeuser in North America, and Samling Group in Malaysia are prime examples of large-scale forestry supply chain actors that are not only adopting but also actively developing and implementing digital innovations (Sveaskog, 2023; Weyerhaeuser Company, n.d.; Syarikat Samling Timber Sdn Bhd, 2024). Sveaskog, as Sweden's largest forest owner, has been instrumental in developing digital tools for joint planning with the reindeer industry, integrating high-quality digital maps into forest management plans, and investing in AI companies like Nordic Forestry Automation (Sveaskog AB, 2023; Sveaskog, 2023). Similarly, Weyerhaeuser, a major private timberland owner in the U.S., provides its own suite of software tools like ForteWEB™ and Javelin® for wood product design and engineering, demonstrating an integrated approach to digital adoption within the supply chain (Weyerhaeuser Company, n.d.). Samling Group in Malaysia utilizes GIS and GPS for spatial information, ERP systems for financial control, and implements reduced impact logging (RIL) systems, showcasing the integration of digital tools into operational practices (Samling Reforestation (Bintulu) Sdn Bhd, 2023). These companies are driven by the need to optimize operations, enhance efficiency, ensure sustainable resource management, and meet evolving market demands for traceable and certified timber products (American Forest Management, 2024; Samling Timber Malaysia, 2024).

Digital Companies (Software and Hardware Providers) are emerging as increasingly influential players, providing the foundational technologies and specialized solutions that power the digital transformation in forestry. Firms like Capgemini, Accenture, Deloitte, and PwC, primarily known for their consulting and IT services, are actively developing and deploying AI platforms, data analytics tools, and geospatial solutions tailored for environmental and forestry applications. Capgemini, for instance, developed a data-driven app for tracking urban forest growth and biodiversity in collaboration with a non-profit, and its subsidiary Sogeti Sweden leveraged AI and satellite images to detect spruce bark beetle infestations (Capgemini, 2025; Capgemini, 2025). Accenture, in partnership with Planet Labs PBC, utilizes high-frequency satellite imagery for deforestation analysis and biodiversity monitoring, and has developed the Squiirrel mobile app to connect seed collectors and growers, accelerating global reforestation efforts (Planet Labs PBC, 2025; Accenture, 2025). Deloitte's AI Institute has explored AI applications in various public services, including urban forestry, for tasks like illegal felling detection (Accenture, 2018). PwC offers a suite of digital solutions for sustainability reporting, supply chain due diligence, and environmental data management, including tools for geolocation and automated data verification (PwC, 2024; Prepscius et al., 2025). These digital companies are driven by the expansive market opportunity to apply their technological expertise to the complex challenges of natural resource management, offering solutions that enhance transparency, efficiency, and compliance. In addition to these, consulting and technology firms with a strong presence in specific regions are driving digital adoption. For example, EY Finland is a significant actor in this landscape, actively contributing to the digital transformation of the forestry industry by advising on ERP system modernization and the integration of technology for robust ESG reporting (Hyöky et al., 2023; Hyöky & Virranta, 2023). Their work highlights the increasing role of professional services in guiding traditional industries through complex digital transitions, emphasizing data-driven insights and compliance with evolving sustainability standards. This demonstrates how specialized consulting expertise, often rooted in regional industrial strengths, acts as a key driver for digital innovation.

Public Research Institutions play a critical role as innovators, knowledge producers, and facilitators of technology transfer. Universities, government agencies, and research institutes often develop foundational methodologies, conduct long-term monitoring, and provide open-source data that underpins many digital forestry applications. The USDA Forest Service, for example, is a primary funder and developer of the i-Tree® software suite, which quantifies the ecological and economic value of ecosystem services provided by trees (The Davey Tree Expert Company, 2025). Similarly, the US Forest Service developed a robust stochastic wildfire simulation used in wildfire hazard scores, demonstrating the public sector's contribution to risk assessment tools (Willis Limited / Willis Re Inc., 2018). In Sweden, research institutes like Skogforsk collaborate with forestry organizations to develop digital tools for forest management, such as the AI-based quote model for young forest clearing (Mellanskog, 2024). The European Space Agency (ESA) and NASA are instrumental in providing Earth observation satellite data and developing collaborative platforms like the Multi-Mission Algorithm and Analysis Platform (MAAP) that facilitate access to forest biomass data for the scientific community (Capgemini, 2020). Public research institutions are driven by mandates for scientific advancement, public good, and informing policy, often leading to the development of open-source tools and methodologies.

Start-ups and Venture-Backed Firms are agile innovators that are rapidly developing and commercializing niche digital solutions for forestry. Companies like NCX (Natural Capital Exchange) are creating forest carbon marketplaces that leverage high-resolution forest mapping, probabilistic modelling, and remote sensing to enable landowners to participate in carbon markets (NCX, n.d.; NCX, 2022). NCX's Harvest Deferral Credit (HDC) bidding process and its focus on a "ton-year accounting approach" exemplify how startups are innovating in the financial mechanisms of nature-based solutions (NCX, n.d.). AirForestry in Sweden is pioneering drone-based thinning technology that operates without ground contact, addressing soil damage risks (Sveaskog, 2024). Nordic Forestry Automation, a startup founded by researchers, is developing AI-based driver assistance systems for forestry machines, attracting investment from major forestry companies (Sveaskog, 2023). These startups are often characterized by their rapid prototyping, specialized expertise, and ability to attract venture capital, filling innovation gaps and bringing disruptive technologies to market. Their drivers include identifying unmet needs in the market, leveraging cutting-edge technologies, and scaling solutions for environmental and economic impact.

Beyond these core actors, several other sectors contribute significantly to the digital forestry landscape. The **Environmental Monitoring** sector, broadly defined, underpins many of the digital innovations, as tools like GIS, remote sensing, and data analytics are fundamentally designed to track and assess environmental conditions (e.g., deforestation, biodiversity, water quality, carbon stocks). The **Agriculture** sector often serves as a source of inspiration and adapted technologies, with practices like precision agriculture, advanced genetics in seedlings, and soil sensors finding direct applications in forestry (Choudhry & O'Kelly, 2018; RMS, 2025). The **Financial Services** sector is increasingly involved through the development of carbon markets, green bonds, and nature-based investment funds, which leverage digital platforms for trading, valuation, and risk assessment (Capolaghi, 2023; Mercer LLC, 2024). The **Forestry Machinery Companies** are integrating digital control systems, onboard computers, and telematics into their equipment, enabling precision forestry and automated operations (Sveaskog, 2019; Choudhry & O'Kelly, 2018). Finally, the **Public Sector and Government Agencies** play a crucial role not only as users and funders but also as regulators, setting standards (e.g., EUDR, TCFD, SBTi) that drive the adoption of digital traceability, reporting, and sustainable practices across the value chain (Prepscius et2025; Godshall & Weick, 2023). The synergistic collaboration among these diverse actors, driven by both commercial imperatives and environmental goals, is propelling the digital transformation of forestry into a new era of precision, efficiency, and sustainability.

Adaptation and Implementation Challenges

Despite the transformative potential of digitalisation in forestry, its widespread adaptation and successful implementation are frequently hampered by a complex array of challenges. These barriers span technological, infrastructural, human, and governance dimensions, often exacerbated by the unique characteristics of forest ecosystems and the diverse ownership structures within the sector. Addressing these challenges is paramount for realizing the full benefits of digital technologies in achieving sustainable forest management and climate resilience.

One significant challenge lies in **Data Quality and Integration**. Many existing datasets in forestry are fragmented, inconsistent, or lack the resolution required for advanced digital applications (Hardcastle & Felenbok, 2020; FORSight Resources, LLC, n.d.). For instance, traditional forest inventories can be subjective and infrequent, leading to outdated or missing critical management data (Behounek, 2018). While technologies like LiDAR and satellite imagery offer high-resolution data, their integration with legacy systems and the sheer volume of data generated can be overwhelming (Martorelli & Pelino, 2018; Jones et al., 2023). Companies often struggle to distil complex data sets into a single source of truth that provides actionable insights (Agrawal et al., 2020). The process of standardizing data, ensuring its accuracy, and integrating it across multiple IT systems remains a significant hurdle (PwC, 2025; IBM, 2020). This is particularly evident in sustainability reporting, where data quality, automation gaps, and technology misalignment are common, with many organizations still relying on spreadsheets (PwC, 2025).

Infrastructural Limitations and Connectivity Gaps pose a substantial barrier, especially in the remote and rugged terrains where many large-scale commercial forests are located (Choudhry & O'Kelly, 2018). Reliable internet and mobile network coverage are prerequisites for real-time data transfer, cloud-based applications, and remote monitoring tools. While some mobile apps offer offline support, the overall effectiveness of digital solutions is constrained by the availability of robust digital infrastructure (Mellanskog, 2023). Even in urban environments, the "right digital infrastructure" is necessary to advance AI applications (Accenture, 2018). Furthermore, the high upfront investment required for advanced digital technologies, such as vehicle-mounted LiDAR or AI-powered autonomous systems, can be prohibitive, particularly for smaller landowners or fragmented operations (Bromfield et al., 2024).

Skills Gaps and Workforce Adaptation represent a critical human-centric challenge. The adoption of digital technologies demands a workforce that is AI-fluent, digitally skilled, and comfortable with data-driven decision-making (Deloitte AI Institute, 2021; IBM, n.d.). However, the forestry sector, like many traditional industries, faces challenges in attracting younger workers to roles that may involve shift work, rote tasks, or remote locations (Murray et al., 2020). Existing employees often require significant upskilling and reskilling to adapt to new digital tools and automated processes. Employee hesitation towards automation is also a factor, as seen in Stora Enso's experience with Robotic Process Automation (Deloitte Insights, 2023). The need for close collaboration with operators to build truly useful systems in the forest further underscores the importance of human adaptation and training (Sveaskog, 2023).

Governance, Regulatory Complexity, and Fragmentation create a challenging environment for digital innovation. The absence of common measurement standards for complex environmental issues like biodiversity, unlike the more established metrics for greenhouse gas emissions, complicates the development and adoption of digital tools (Ebihara et al., 2023). Evolving and often inconsistent regulatory frameworks, particularly in areas like deforestation-free supply chains (EUDR), demand continuous adaptation and can impose significant administrative burdens on companies (Prepscius et al., 2025; Brennan et al., 2025). The fragmented ownership of forests globally, with a high proportion of publicly owned or small private forests, means that a lack of scale and expertise among many owners can hinder the adoption of advanced technologies (Choudhry & O'Kelly, 2018). Public owners, often balancing diverse commercial, social, and environmental objectives, tend to be more conservative in their management styles, further slowing digital uptake (Choudhry & O'Kelly, 2018). Moreover, the lack of consensus on how to measure and price co-benefits in carbon markets, coupled with political and regulatory risks in largely unregulated markets, adds to the uncertainty for project developers (Hardcastle et al., 2022).

Regional Specificity and Contextual Adaptation present unique hurdles. Forestry practices and environmental conditions vary significantly across different countries and regions, requiring digital solutions to be highly adaptable and context specific. For example, the challenges of operating in remote areas with high rainfall and steep terrain, as faced by

Samling in Malaysia, necessitate specialized harvesting systems and careful planning that digital tools must accommodate (Samling Reforestation (Bintulu) Sdn Bhd, 2023). Similarly, planting trees in urban environments requires overcoming limitations posed by compacted soils, underground infrastructure, and space constraints, demanding tailored digital mock-ups and environmental analyses (Arcadis, 2025). The need for site-specific prescriptions for interventions like fertilization and drainage, often based on data from soil sensors, further emphasizes the importance of localized adaptation (Choudhry & O'Kelly, 2018).

In conclusion, while digital technologies offer immense promise for the forestry sector, their successful implementation hinges on overcoming significant hurdles related to data quality and integration, infrastructural limitations, skills gaps, regulatory complexities, and the need for context-specific adaptation. Addressing these challenges requires concerted efforts from technology providers, industry stakeholders, policymakers, and researchers to foster collaboration, invest in capacity building, and develop flexible, interoperable solutions that can truly revolutionize forest management.

Environmental Impacts and Sustainability Contributions

Digital technologies are profoundly reshaping the forestry sector's capacity to address critical environmental challenges and contribute to global sustainability goals. By enabling more precise monitoring, efficient resource management, and transparent reporting, these innovations offer powerful solutions for climate change mitigation, biodiversity conservation, soil health, and water quality.

Climate Change Mitigation and Carbon Sequestration

Digitalisation plays a pivotal role in enhancing the forestry sector's contribution to climate change mitigation, primarily through improved carbon accounting, enhanced sequestration, and reduced emissions from operations. Advanced methodologies for **GHG Inventory and Carbon Accounting** are leveraging digital tools to measure and report scope 1, 2, and 3 greenhouse gas emissions from forestry operations, as well as land and product-based carbon removals (Resource Management Service, LLC, 2024). Companies like Resource Management Service (RMS) are developing sophisticated approaches to track carbon stock in managed forests, including above and belowground biomass, using proprietary growth and yield models and forest inventory data (Resource Management Service, LLC, 2024). This granular data allows for more accurate baseline assessments and monitoring, which is crucial for the credibility of carbon offset markets (Hardcastle et al., 2022).

Forest Carbon Projects and Carbon Credit Platforms are a direct outcome of this digital evolution. Platforms like the Natural Capital Exchange (NCX) utilize high-resolution forest mapping, probabilistic modelling, and remote sensing to enable landowners to participate in carbon markets by deferring timber harvests (NCX, n.d.; NCX, 2022). This "ton-year accounting approach" incentivizes mass landowner participation by rewarding verified carbon storage over specific time periods, driving real, immediate, and scalable climate impact (NCX, n.d.). BCG is actively helping the American Forest Foundation scale up a nature-based carbon credit program with a target of delivering 1 billion tons of climate impact by 2050 (Boston Consulting Group, 2025). These programs not only sequester carbon but also generate economic value, making climate action financially viable for landowners (Kurth et al., 2025).

Digital tools also support the certification and trading of these credits, ensuring transparency and credibility in a nascent market (Hardcastle et al., 2022).

Beyond sequestration, digitalisation contributes to **Emissions Reduction in Forestry Operations and Supply Chains**. The electrification of forestry road transport, as seen in Sweden's TREE project involving Sveaskog and Scania, aims to significantly reduce CO2 emissions by introducing electric trucks for timber transport (Sveaskog, 2023). This project, co-funded by the Swedish government innovation agency Vinnova, estimates a reduction of approximately 260,000 tons of CO2 per year if 50% of forestry truck transport is electrified (Sveaskog, 2023). Digital tools for supply chain optimization, such as route optimization and fleet management systems, are helping the shipping industry reduce greenhouse gas emissions, with potential for a 10% reduction from mass adoption (Adkins & Potey, 2020). Within mills, innovations like continuous drying kilns use 50% less energy, and non-heated wastewater evaporation units use 20% less energy, directly reducing the carbon footprint of wood product manufacturing (Weyerhaeuser Company, n.d.). The transition to 100% renewable electricity in offices and the adoption of electric vehicle fleets by companies like ZS also contribute to reducing Scope 1, 2, and 3 emissions (Agarwal et al., 2022; Peters, 2024).

Biodiversity Conservation and Ecosystem Health

Digital innovations are providing unprecedented capabilities for monitoring, assessing, and actively managing biodiversity and ecosystem health within and around forest landscapes. **Advanced Monitoring Technologies** such as drones with computer vision are used to count trees, monitor flora and fauna, and detect infestations like bark beetles before they spread, thereby protecting forest ecosystems (Deloitte Insights, 2023). In Sweden, AI and satellite imagery are leveraged to visualize the progression of spruce bark beetle outbreaks, enabling rapid intervention and mitigating large-scale forest destruction (Capgemini, 2025). Beyond pests, AI-powered platforms utilizing hyperspectral drone imagery can detect invasive species based on unique spectral signatures, enabling precise differentiation from native vegetation and targeted removal by automated robots, as demonstrated in India to restore natural habitats and reduce fire risks (Capgemini India, 2024).

The development of **Digital Twins of Forests** offers a holistic approach to biodiversity protection. Stora Enso's ambition to create a digital twin of an entire forest is explicitly linked to tracking and protecting biodiversity, providing decision support for sustainable forest management (Deloitte Insights, 2023). These digital replicas can model different biodiversity scenarios, allowing for proactive planning and adaptive management (Elofsson et al., 2023). In urban settings, 3D digital twins of trees, created using LiDAR and high-resolution photography, enable automated analysis of tree health, canopy size, and overall urban forest vitality, supporting efforts to enhance urban biodiversity and resilience (The Davey Tree Expert Company, 2023).

Nature-based Solutions (NbS), often enabled by digital tools, are gaining prominence for their co-benefits to biodiversity and climate resilience. Reforestation programs, such as Oliver Wyman's GROWTrees initiative, involve planting trees in selected projects globally to protect wildlife, support indigenous communities, and improve climate resilience (Oliver Wyman, 2022). The Miyawaki method, a dense, fast-growing forest creation technique, is being implemented in urban areas with data-driven apps to track and prove its efficiency in encouraging up to 100 times more biodiversity than standard planting (Capgemini, 2025). Sustainable forestry practices, including setting aside critical habitats, adapting harvesting methods, and reconnecting fragmented forests, are explicitly described as improving biodiversity and creating more stable and resilient ecosystems (Elofsson et al., 2023). For example, Suzano's initiative to connect fragmented forests in Brazil aims to reconnect 1,850 fragmented land parcels, allowing plant and animal species to extend their habitat and increase genetic variability (Elofsson et al., 2023). Certification schemes like FSC and PEFC, supported by digital traceability systems, ensure that timber comes from sustainably managed forests that protect biodiversity and ecosystem integrity (Precious Woods, n.d.; American Forest Management, 2024).

Soil Health and Water Quality

Digitalisation and sustainable practices are crucial for safeguarding soil health and water quality, which are fundamental to forest ecosystems. **Precision Forestry** techniques, enabled by digital tools, allow for site-specific management, including targeted fertilization and drainage based on data from soil sensors (Choudhry & O'Kelly, 2018). Research in South Africa demonstrates that such targeted soil preparation can significantly improve forest yield, while minimizing environmental impact (Choudhry & O'Kelly, 2018). Reduced impact logging (RIL) methods, often guided by digital planning tools, are applied to minimize soil erosion and compaction, maintaining infiltration rates and protecting soil carbon pools (Marsden & Parose, 2021; Syarikat Samling Timber Sdn Bhd, 2024).

For water quality, **Best Management Practices (BMPs)** are implemented, often supported by digital mapping and monitoring systems. These practices include maintaining riparian management zones (RMZs) or buffer strips along waterways, restricting tree cutting in sensitive areas, and minimizing soil disturbance to protect water quality and aquatic habitats (American Forest Management, 2025). Regular water quality monitoring, conducted by external consultants and supported by laboratory analysis, is a standard practice in certified forest management units (Samling Plywood (Lawas) Sdn Bhd, 2023). Digital mapping systems are also used to register wetlands, which is a prerequisite for restoration activities aimed at strengthening forest ecosystems and binding carbon into the ground (Sveaskog AB, 2023).

In urban contexts, **Stormwater Management** is a key environmental contribution of digitally managed urban forests. Urban tree canopy assessments, using high-resolution GIS data, help communities manage stormwater and water resource initiatives (The Davey Tree Expert Company, 2025). Green infrastructure solutions like permeable pavements and green roofs are adopted in urban areas to mitigate stormwater runoff and improve energy efficiency, often planned and monitored with digital tools (Bromfield et al., 2024). The integration of treated wastewater systems into afforestation projects and the deployment of rainwater harvesting systems are examples of how digital planning and monitoring can optimize water use in water-scarce regions (FTI Consulting, 2025).

In summary, digital innovations provide a powerful toolkit for addressing a wide range of environmental challenges in forestry. From precise carbon accounting and real-time biodiversity monitoring to optimized soil and water management, these technologies enable a more proactive, data-driven, and ultimately more sustainable approach to managing the world's forests.

Public Funding, Policy, and Institutional Support

The role of public funding, policy frameworks, and institutional support is critical in shaping the trajectory of digital innovation in forestry. Governments, public research institutions, and international agencies act as catalysts, enablers, and regulators, influencing the development, adoption, and scaling of digital technologies for sustainable forest management. However, gaps in support mechanisms and inconsistencies in global approaches can either accelerate or hinder progress.

Public Funding as a Catalyst for Innovation: While the development of many digital forestry technologies is increasingly driven by private investment and market forces, public funding remains crucial, particularly for early-stage research, pilot projects, and initiatives with broader public good benefits. The Swedish government innovation agency, Vinnova, for instance, co-funded the TREE project, which focuses on the electrification of forestry road transport, demonstrating public support for high-impact, sustainable innovations (Sveaskog, 2023). Similarly, the EU's Green Deal program provides financial support for collaborative projects like TREEADS, which integrates various digital technologies for wildfire prevention, detection, and restoration across European countries (Capgemini Sweden, 2025). In the U.S., the USDA Forest Service is a primary funder of the i-Tree® software suite, a public-private partnership that quantifies the ecological and economic value of urban trees, highlighting the role of public agencies in developing widely accessible tools (The Davey Tree Expert Company, 2025). The Inflation Reduction Act in the U.S. has also funnelled significant public funding into urban and community forestry programs, enabling cities to implement smart tree inventories and other digital management efforts (The Davey Tree Expert Company, 2023). These examples underscore that public funding often de-risks nascent technologies, bridges funding gaps where private capital may be risk-averse, and supports initiatives that yield societal benefits beyond immediate commercial returns (Brennan et al., 2025; Ibounig et al., 2023). Furthermore, strategic national initiatives often provide a framework for public support. Finland's 'Moonshots for Green Growth' program, for instance, exemplifies a concerted effort to maximize the nation's growth and 'handprint' in the green transition, with digital innovation implicitly underpinning many of its objectives (Ibounig et al., 2023). This public-private collaboration aims to drive sustainable economic development through technological advancements, including those relevant to the forestry sector. Such initiatives indicate a proactive policy stance to foster an environment conducive to green technologies and digital solutions, often involving significant public funding and institutional backing to de-risk investments and accelerate adoption across key industries.

Policy and Regulatory Frameworks as Drivers: Government policies and regulatory frameworks are powerful drivers for the adoption of digital technologies in forestry, often by mandating transparency, sustainability, or traceability. The European Union Deforestation Regulation (EUDR) is a prime example, requiring companies to map and report every part of their supply chain to ensure products do not originate from recently deforested land or contribute to forest degradation (Prepscius et al., 2025; FTI Consulting, 2024). This regulation necessitates the implementation of digital traceability systems, geolocation data collection, and robust data management solutions for compliance (Capgemini Invent, 2025; EY Global, 2024). Similarly, the Taskforce on Climate-related Financial Disclosures (TCFD) and the emerging Taskforce on Nature-related Financial Disclosures (TNFD) frameworks, often supported by government funding, are pushing companies to integrate climate and nature-related risks into their financial disclosures, which in turn drives the adoption of advanced analytics and reporting platforms (Godshall & Weick, 2023; Mercer LLC, 2024). National policies, such as France's Article 29 or Germany's Supply Chain Act, also impose specific disclosure requirements that necessitate digital data management and reporting (Godshall & Weick, 2023). These regulatory pressures compel companies to invest in digital solutions to ensure compliance, manage risks, and maintain market access.

Institutional Support and Collaboration: Public research institutions, government agencies, and international organizations provide crucial institutional support through research, data provision, standard-setting, and collaborative initiatives. Organizations like the Japan International Cooperation Agency (JICA) and Boston Consulting Group (BCG) are collaborating to conceptualize "Forest Stack," a unified Digital Public Infrastructure (DPI) for forest management aimed at enhancing conservation and unlocking economic opportunities like carbon credits (Bijapurkar et al., 2024). The USDA Forest Service manages the Forest Inventory and Analysis (FIA) program, providing nationally standardized forest data and online databases that are fundamental resources for policy, management, and scientific investigations (FORSight Resources, LLC, 2009). International bodies like the European Space Agency (ESA) and NASA make vast amounts of satellite data freely available, spurring commercial and public sector innovation in Earth observation and environmental monitoring (Jones et al., 2023). Furthermore, collaborations between public institutions and private entities, such as the partnership between The Nature Conservancy and Willis Towers Watson to develop wildfire resilience insurance, demonstrate how shared goals can drive innovative solutions (The Nature Conservancy & Willis Towers Watson, 2021). These institutional frameworks foster an environment conducive to digital innovation by providing foundational data, setting common standards, and promoting multi-stakeholder collaboration.

Gaps and Contrasts in Support Mechanisms: Despite these advancements, significant gaps and regional disparities exist in public funding and policy support for digital forestry. Many reports highlight a general "lack of explicit public funding" for digital forestry technologies, suggesting that private sector investment often leads the way, sometimes without direct government grants (e.g., Bain & Company, 2024; Hardcastle et al., 2022). While Europe is often cited as a leader in setting science-based targets and implementing comprehensive sustainability regulations like the EUDR (Bailey et al., 2022; Godshall & Weick, 2023), other regions may lag in developing supportive policy environments or providing sufficient public funding. The complexity and length of permitting processes in some regions can also hinder the deployment of green technologies, even with public funding mechanisms in place (Brennan et al., 2025). Moreover, the effectiveness of public support can be undermined by a lack of integrated environmental action, where companies may set targets but struggle with comprehensive implementation across all impact areas (Bailey et al., 2022). The need for specialized expertise and education pathways to support emerging green technologies also points to a gap in human capital development that public institutions could further address (Ibounig et al., 2023). Globally, the challenge remains to scale public funding and policy frameworks to match the urgency and magnitude of the environmental challenges facing forests, ensuring that digital innovations are not only developed but also widely adopted and effectively implemented across diverse contexts.

Geographic Trends and Regional Case Studies

The adoption and impact of digitalisation in forestry exhibit distinct geographic trends, shaped by regional policy contexts, economic drivers, and specific environmental challenges. While certain technologies and approaches are globally applicable, their implementation often reflects local priorities and collaborative ecosystems. Examining key regions provides a granular understanding of these dynamics.

Europe: A Hub for Integrated Digital and Sustainable Forestry

Europe, particularly the Nordic countries, stands out as a leader in integrating digital technologies with sustainable forestry practices, often driven by strong environmental policies and a mature forest industry. Sweden, for instance, showcases a comprehensive approach to digital forestry. Sveaskog, the largest forest owner in Sweden, has been at the forefront of adopting and developing digital tools. This includes the implementation of AI-based driver assistance systems for forestry machines, enabling more cost-effective implementation of forest management methods that promote biodiversity and carbon storage (Sveaskog, 2023). Sveaskog also utilizes digital maps and stand descriptions for forest management planning, with continuously updated data integration to ensure accuracy (Sveaskog AB, 2023). The country's commitment to digital transformation extends to logistics, with Sveaskog and Tieto rolling out digital delivery notifications for timber, enabling automated timber measurement and integrated digital workflows (Sveaskog, 2019). The Mistra Digital Forest program, funded by the public research foundation Mistra, further highlights Sweden's emphasis on a digitized forestry (Sveaskog, 2019).

Beyond Sweden, European initiatives demonstrate a strong focus on environmental monitoring and compliance through digital means. The European Union's Green Deal program supports collaborative projects like TREEADS, which integrates virtual reality for firefighter training, aerial drones with LiDAR and EO/IR cameras for real-time monitoring, and seed capsules with restoration gel for ecological recovery after wildfires across 14 European countries and Taiwan (Capgemini Sweden, 2025; Capgemini, 2025). This showcases a proactive, technologically advanced approach to a critical environmental challenge. European companies are also leading in setting science-based targets for emissions reduction and disclosing "financed emissions," driven by frameworks like TCFD and TNFD, which necessitate robust digital reporting and analytics platforms (Bailey et al., 2022; Mercer LLC, 2024). The EU Deforestation Regulation (EUDR) is a significant policy driver, compelling companies importing to or trading within the EU to implement digital supply chain mapping and traceability systems to ensure deforestation-free products (Prepscius et al., 2025; FTI Consulting, 2024). This regulatory environment fosters a demand for digital solutions that can provide geolocation data, automate verification, and standardize data exchange across complex supply chains (Capgemini Invent, 2025).

Urban forestry in Europe also demonstrates digital innovation, as seen in Capgemini's collaboration with Omstilling NU in Denmark to develop a data-driven app for tracking urban forest growth and biodiversity using the Miyawaki method. This initiative aims to increase biodiversity and carbon capture in urban environments through standardized data collection (Capgemini, 2025). The Netherlands, with projects like the hydrogen-powered residential neighbourhood in Hoogeveen and the Afsluit Dike project incorporating a fish migration river, exemplifies integrated urban and environmental planning leveraging advanced technologies (Arcadis, 2021). The strong emphasis on sustainability, coupled with a robust technological infrastructure and supportive policy environment, positions Europe as a key region for the advancement of digital forestry.

North America: Innovation in Forest Management and Carbon Markets

North America, particularly the United States, is a significant hub for digital innovation in forestry, driven by both private industry and public research institutions, with a notable focus on forest carbon markets and wildfire management. Consulting forestry firms like Mason, Bruce & Girard (MB&G) have a long history of pioneering digital applications, from the first known use of aerial photos for timber mapping in the U.S. in 1940 to the development of growth modelling and inventory management software in the 1980s (Lord, 2021). Today, MB&G offers comprehensive geospatial services, remote sensing (including LiDAR), and custom data management for forest inventory and carbon analysis (Mason, Bruce & Girard, Inc., n.d.). Similarly, American Forest Management (AFM) utilizes GIS and remote sensing, biometric tools, and resource planning analytics across millions of acres of U.S. forestland (American Forest Management, 2025).

The development of **Forest Carbon Markets** is a major digital trend in the U.S. Companies like NCX (Natural Capital Exchange) are creating digital marketplaces that connect landowners to carbon markets, using high-resolution forest mapping and probabilistic modelling to quantify carbon sequestration (NCX, n.d.). NCX's "ton-year accounting approach" and its annual updates of harvest baselines using data science are examples of how digital platforms are enabling scalable and transparent carbon crediting (NCX, n.d.). The Family Forest Carbon Program, supported by AFM, provides private landowners with access to the voluntary carbon market without costly inventories, leveraging platforms like Finite Carbon's CORE carbon platform (American Forest Management, 2025). Public funding, such as the Inflation Reduction Act, is also channelling resources into urban and community forestry programs, supporting the adoption of smart tree inventories and related digital tools (The Davey Tree Expert Company, 2023).

Wildfire Management is another critical area of digital innovation in North America. The U.S. Forest Service has developed sophisticated stochastic wildfire simulations that are integrated into tools like the Willis Re Wildfire Hazard Score for risk assessment and insurance applications (Willis Limited / Willis Re Inc., 2018). These models incorporate hourly weather data, elevation, slope, and vegetation to predict fire behaviour. The Nature Conservancy and Willis Towers Watson have even launched a first-of-its-kind wildfire resilience insurance policy that accounts for ecological forest practices like thinning and prescribed burns, demonstrating the integration of nature-based solutions with financial mechanisms, often facilitated by digital analytics (The Nature Conservancy & Willis Towers Watson, 2021).

In urban areas, companies like The Davey Tree Expert Company are pioneering "Smart Tree Inventory Solutions" using vehicle-mounted LiDAR and machine learning to create 4D digital twins of urban trees, providing objective and precise data for urban forest management (The Davey Tree Expert Company, 2025). This technology helps cities monitor tree health, plan maintenance, and assess ecosystem benefits, contributing to urban sustainability and resilience (The Davey Tree Expert Company, 2025).

Asia and South America: Emerging Digitalisation and Sustainable Practices

While Europe and North America often lead in digital innovation, countries in Asia and South America are rapidly adopting and adapting these technologies, often driven by large-scale forest resources and the imperative for sustainable development.

In **Malaysia**, the Samling Group is actively implementing digital tools for forest management, including GIS and GPS for spatial information, and ERP systems for financial control. They utilize Permanent Sample Plots (PSPs) to monitor plantation forest dynamics and employ Reduced Impact Logging (RIL) systems to minimize environmental damage (Samling Reforestation (Bintulu) Sdn Bhd, 2023). Their commitment to independent sustainability certifications like MTCS and PEFC, supported by digital traceability systems, ensures responsible timber production (Samling Timber Malaysia, 2024). The company also engages in wildlife monitoring using camera trapping, showcasing a blend of traditional ecological practices with modern digital tools (Samling Plywood (Lawas) Sdn Bhd, 2023).

Brazil, with its vast Amazon rainforest, is a critical region for sustainable forestry and digital monitoring. Companies like Valor Florestal are integrating modern cartography with management systems, conducting continuous forest inventories (IFC) and pre-harvest inventories using digital tools, and employing complex optimization models for economic and environmental planning (Valor Florestal, 2018). Precious Woods, operating in the Amazon, was the first timber company in the region to become FSC-certified in 1997, and utilizes GPS-based forest inventory management to track species, size, and location of trees for harvesting (Precious Woods Holding Ltd, 2013). They also generate biomass power from wood waste and sell carbon emission certificates, demonstrating a holistic approach to sustainable forest management and climate action (Precious Woods Holding Ltd, 2013). Research initiatives in Brazil, often in partnership with European institutions, focus on long-term forest dynamics, optimizing forest growth and carbon models, and improving wildlife protection measures (Precious Woods Holding AG, n.d.).

In **India**, the concept of a "Forest Stack" is being conceptualized as a unified Digital Public Infrastructure (DPI) for forest management, aiming to integrate data, technology, and governance to support conservation, enhance biodiversity, and unlock economic opportunities like carbon credits (Bijapurkar et al., 2024). This initiative, a collaboration between the Japan International Cooperation Agency (JICA) and Boston Consulting Group (BCG), highlights a strategic vision for large-scale digital transformation in forest management. Capgemini India has also developed an AI-powered platform that uses hyperspectral drone imagery to detect invasive species and an automated industrial robot for their removal, demonstrating innovative solutions for biodiversity challenges (Capgemini India, 2024).

These regional case studies illustrate that while the core digital technologies are often universal, their application and the specific challenges they address are deeply intertwined with local ecological contexts, economic structures, and policy priorities. The global trend is clearly towards a more data-driven, technologically-enabled approach to forestry, with varying paces and focuses across different geographies.

Critical Knowledge Gaps and Future Outlook

Despite the significant advancements in integrating digitalisation into forestry, several critical knowledge gaps persist, hindering the sector's full potential for sustainable development and climate action. Addressing these gaps is paramount for shaping future research, policy, and innovation pathways, ensuring that technological progress translates into equitable, transparent, and impactful outcomes.

One primary knowledge gap lies in the **standardization and interoperability of data and methodologies**. While numerous digital tools and platforms are emerging for forest monitoring, carbon accounting, and supply chain traceability, there is a notable lack of consensus on common measurement yardsticks for complex environmental metrics, particularly for biodiversity (Ebihara et al., 2023; Hardcastle et al., 2022). Different forestry companies and forest owners often use slightly varying assessment methods, leading to inconsistencies and making it challenging to aggregate data for regional or national-level analysis (Sveaskog, 2024). The absence of harmonized certification standards and the fragmented nature of carbon markets further complicate data collection, verification, and comparability (Hardcastle et al., 2022; Boston Consulting Group, 2024). This fragmentation creates a significant data and compliance burden for businesses, hindering their ability to scale and adapt technological solutions across diverse geographies and regulatory regimes (Prepscius et al., 2025). Future efforts must prioritize the development of universally accepted data standards, open data platforms, and interoperable systems that facilitate seamless information exchange across the entire forest value chain, from forest to consumer.

Another critical area requiring further research is the **long-term ecological and socioeconomic impacts of emerging digital forestry practices**. While technologies like drone-based thinning or AI-driven harvest optimization promise increased efficiency and reduced environmental impact, their long-term effects on forest ecosystems, biodiversity dynamics, and local communities are not yet fully understood. For instance, the scientific complexity of establishing "additionality" in forest carbon projects, and the need for improved mechanisms to mitigate leakage and manage non-permanence risk, remain significant challenges (Kurth et al., 2025). There is also a need for more robust, empirical studies on how specific digital interventions influence factors like soil health, water retention, and species adaptation over extended periods, rather than relying solely on short-term efficiency gains (Choudhry & O'Kelly, 2018). Furthermore, the socioeconomic implications of increased automation and AI in forestry, particularly concerning workforce displacement and the need for digital skill development, require careful consideration and proactive planning (Murray et al., 2020; Habgood & Lys, 2024). Research should explore equitable transition pathways and ensure that technological advancements benefit all stakeholders, including local communities and indigenous peoples whose livelihoods are intimately tied to forest resources (Martinez et al., 2024).

The **governance and ethical dimensions of AI and data in forestry** constitute another significant knowledge gap. As AI systems become more autonomous and data-driven, questions of algorithmic bias, transparency, accountability, and privacy become increasingly pertinent (Deloitte AI Institute, 2021; Booz Allen Hamilton Inc., 2025). Ensuring that AI models are unbiased, their logic is understandable ("explainable AI"), and that data collection and use respect privacy and ethical guidelines is crucial for building trust and ensuring responsible deployment (Deloitte AI Institute, 2021). The inherent "black box" nature of some deep learning networks presents a challenge in providing clear justifications for AI decisions, limiting their use in critical tasks where transparency is paramount (Mayer et al., 2025). Future research needs to focus on developing robust AI governance frameworks tailored to the unique complexities of forest ecosystems and the diverse values associated with them.

Finally, there is a need for more comprehensive understanding and targeted solutions for **underrepresented actors and regions**. While large corporations and well-funded startups often lead in digital adoption, small private forest owners and communities in developing regions may lack the scale, expertise, or capital to access and implement these technologies (Choudhry & O'Kelly, 2018). Obstacles such as poor infrastructure, inadequate credit availability, and lack of clarity around property rights can hinder the adoption of sustainable practices, even when digital solutions exist (Kappen et al., 2020). Future innovation pathways must prioritize the development of affordable, user-friendly, and context-specific digital tools that cater to the needs of these underserved groups, ensuring that the benefits of digitalisation are broadly distributed and contribute to equitable systems change (Oliver Wyman, 2022). This includes exploring alternative funding models, capacity-building programs, and collaborative platforms that empower local communities to leverage digital technologies for their own sustainable development goals.

In conclusion, the future outlook for digitalisation in forestry is promising but contingent upon addressing these critical knowledge gaps. Collaborative efforts involving researchers, policymakers, industry, and civil society are essential to develop standardized data frameworks, understand long-term impacts, establish robust ethical guidelines, and ensure equitable access to digital innovations. By proactively tackling these challenges, the forestry sector can truly harness the power of technology to achieve a more sustainable, resilient, and nature-positive future.

Conclusion

The journey through the vast landscape of forestry and digitalisation reveals a sector in the midst of a profound and necessary transformation. Driven by the urgent imperatives of climate change, biodiversity loss, and the global demand for sustainable resources, digital technologies are no longer merely supplementary tools but fundamental enablers of a more precise, efficient, and environmentally responsible forest management paradigm. From the intricate mapping capabilities of LiDAR and satellite imagery to the predictive power of AI in identifying pest outbreaks and optimizing harvests, and the transparent mechanisms of blockchain in carbon markets, digitalisation is reshaping every facet of how we interact with and manage our forests.

This report has synthesized a wealth of evidence, demonstrating that digital innovations are actively contributing to critical environmental goals. They enable more accurate measurement, reporting, and verification of greenhouse gas emissions and carbon sequestration, providing the necessary data for effective climate change mitigation strategies (Resource Management Service, LLC, 2024; NCX, n.d.). By facilitating early detection of infestations and wildfires, supporting targeted conservation efforts, and enabling the creation of digital twins for comprehensive ecosystem monitoring, these technologies are bolstering biodiversity conservation and enhancing overall ecosystem health (Deloitte Insights, 2023; Capgemini, 2025). Furthermore, digital tools are instrumental in promoting sustainable soil and water management through precision forestry techniques, reduced-impact logging, and smart irrigation systems (Choudhry & O'Kelly, 2018; American Forest Management, 2025). The emergence of nature-based solutions, often underpinned by digital platforms, signifies a growing recognition of the economic value of ecological services, fostering new avenues for sustainable finance and investment (Kurth et al., 2025; Roland Berger GmbH, 2023).

However, the path forward is not without its complexities. The successful integration of digitalisation hinges on overcoming significant adaptation and implementation challenges. These include the persistent issues of data quality, standardization, and interoperability across diverse systems and stakeholders (Hardcastle et al., 2022; PwC, 2025). Infrastructural limitations, particularly in remote forest areas, continue to pose barriers to real-time data flow and technology deployment (Choudhry & O'Kelly, 2018). A critical human dimension involves addressing skills gaps and workforce adaptation, ensuring that forestry professionals are equipped with the necessary digital competencies and that automation is embraced as an opportunity rather than a threat (Murray et al., 2020; Habgood & Lys, 2024). Moreover, the fragmented ownership structures of forests globally, coupled with evolving and sometimes inconsistent regulatory frameworks, demand concerted efforts to foster collaboration and create supportive policy environments (Choudhry & O'Kelly, 2018; Prepscius et al., 2025).

Looking ahead, the future of forestry is undeniably digital. What digitalisation enables is a shift from reactive management to proactive, data-driven stewardship, allowing for more informed decisions that balance economic productivity with ecological integrity. It offers unprecedented transparency across supply chains, empowering consumers and regulators to demand sustainably sourced products. It unlocks new financial mechanisms that incentivize conservation and carbon sequestration, transforming forests into active participants in the global climate economy.

Yet, much still needs to be done for responsible and sustainable advancement. Future research must bridge existing knowledge gaps in data standardization, long-term ecological impacts, and the ethical implications of AI deployment. Policy frameworks need to evolve to support interoperability, incentivize sustainable practices, and ensure equitable access to digital tools for all forest owners, including smallholders and local communities. Investment is required not only in the technologies themselves but also in the human capital and infrastructure necessary for their effective adoption. Ultimately, the true promise of digitalisation in forestry lies in its capacity to foster a symbiotic relationship between human progress and planetary health, ensuring that our forests continue to provide their invaluable services for generations to come. This requires a collective commitment to innovation, collaboration, and a shared vision for a truly sustainable future.

Annex 2: The Trends from the First Horizon Scanning Cycle

The trends below were presented in the 4Growth D3.5 report, here they are updated in the cases, where major changes were observed in the last 12 months.

A.2.1 Glocalisation – Pushed by Geopolitical Tensions

Summary and Key Words[24]

Glocalisation is the phenomenon of an increasing relevance of local and regional business activities addressing bottom-up consumers and stakeholder's needs while still being involved in globalised supply chains and production networks. The rise of glocalisation is being driven by stronger geopolitical tensions, thus limiting trade, and affecting agriculture and forestry. Recent examples of impacts on agriculture and forestry are temporary export restrictions on essential agricultural commodities that aim to counteract the fear of domestic shortfalls. For the next decade, more glocalisation is expected inter alia as part of a de-risking strategy, aiming to reduce the vulnerability of supply chains.

Key words: Global trade / resource dependency / open strategic autonomy / technology dependence / supply chain disruptions

Current and Future Developments of the Trend

Geopolitical tensions driven by wars, terrorism and political disputes and conflicts among states and political actors are rising; recent examples include the Russian war in Ukraine, the Israel Hamas conflict, Houthi attacks on ships in the Red Sea, and US-China trade conflicts, among others (Kaya, 2024; Borges et al., 2024). Currently, far right parties with nationalistic programmes that e.g., favour more inward-looking policies and tend to prioritise domestic interests and markets, are gaining ground in many countries in Europe and globally (WTO, 2023). Nationalist policies also lead to growing ideological divisions across ethnic and religious beliefs and values, with some actors using access to resources to add pressure on importing countries.

For the next decade, more glocalisation is expected as part of a de-risking strategy to address supply chain vulnerability and trade conflicts (Demertzis, 2023). Even if the pendulum swings back from nationalism towards multilateralism, glocalisation can be expected to continue as other drivers favour this development. A main push can be expected from climate policies through which more domestic production is favoured to reduce the environmental footprint of consumption; furthermore, automation and digitalisation can be an enabler for competitive

[24] The summary parts are written without scientific references, respective citations are available in the Current and Future Developments of the Trend parts.

national or regional production (compared with purchasing from global markets) (Gong et al., 2022).

Recent Signals within the Scope of the Trend

Export Limitations for Food Products: India's Rice Export Ban

Resource rich countries can actively influence global food availability through their trade policy, e.g., via trade restrictions and other measures. For example, in 2023 India, the world's top rice exporter, temporarily banned the export of relatively cheap white rice, covering around 75% to 80% of Indian rice exports (Glauber & Mamun, 2023). The aim was to drive down rising domestic prices in the period before the next harvest in preparation for an anticipated crop shortfall due to weather anomalies from the El Nino phenomenon. As India's rice exports are crucial to food security in many Asian and African countries, this had strong repercussions (Glauber & Mamun, 2023). For example, the ban led to a spike in global rice prices, severely affecting low-income countries and consumer groups. However, sudden export restrictions can lead to a perception of India as an unreliable supplier of rice, with importing countries potentially searching for alternative supply options (Biswas, 2023).

Europe's Wood Import Independence – a Reaction to High Russian Export Tariffs in 2008

Russia's invasion of Ukraine in February 2022 led to export bans by the EU and like-minded partners on various products from Russia, including on wood (Vos, 2024). However, the EU's wood supply tensions are not new: Already in 2008, Russia imposed trade tariffs on their wood exports. As a result, the EU's total wood consumption from Russian imports dropped by two thirds during the last 15 years, with Russian wood products accounting for only 2% of total EU consumption already before the war (Nabuurs, 2022). Hence, Europe is highly dependent on its own domestic forest resources. The EU has even managed to become a net exporter of (round-)wood to non-EU countries in the last years[25] (Eurostat, 2023). Relying mainly on domestic resources requires good forest management and a balance between biodiversity, carbons sinks and wood production (Nabuurs, 2022). Wood supply management is a challenging long-term process at the interplay of policy, market side and climate-crises related factors, even with a low import dependence (Eggers et al., 2024).

Fertilizer Dependency due to Russian War in Ukraine

The Russian war in Ukraine led to fertilizer supply disruptions for agrochemicals from Russia and Belarus, due to sanctions introduced in 2022. Both countries are important producers of mineral fertilizers. Resulting supply shortages affected 136 countries, particularly Estonia, Mongolia, Kazakhstan, Brazil, the US, China, and India, while DR Congo, Ethiopia, Egypt, and Pakistan were most vulnerable to such disruptions (Zhang et al., 2023). In addition, China introduced quotas for phosphate fertilizer exports in 2022, halving their exports (WEF, 2023). On top of this, European domestic fertilizer production is also strongly affected due to record

[25] Referring to the statistical period 2018-2022.

high energy price peaks following the Russia-Ukraine war (IEA, 2024). Spiking natural gas prices affect the agrochemical industry, as natural gas is essential to produce nitrogen fertilizers, accounting for 75 to 90% of manufacturing costs. European fertilizer producers reacted with temporary shutdowns of production sites: In the first half of 2023, 40-50% of the EU ammonia industry was temporally closed, and in the first quarter of 2024, 10-20% remained closed (Fertilizers Europe, 2024). Resulting high costs for agricultural fertilizer have led to a reduction in the use of fertilisers; farmers shifted production to crops that require less mineral supplement (Chopra, 2023). In terms of its impacts, high energy and fertilizer prices have been observed to influence food prices more than reduced food imports (Alexander et al., 2023).

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

First and foremost, established and formerly reliable food, feed, fertilizer and energy trade relations, supply chains and routes become more fragile. Therefore, trust in supply providers is reduced, with rising prices affecting poor people the most. Consequently, importing countries tend to seek a greater variety of import sources, try to expand domestic production or attempt to influence consumers to shift their diets and nutrition habits. Digitalisation of farm and forest processes and practices could boom by driving efficiency and productivity of domestic food production through e.g., reducing food waste and wood scrap materials.

With respect to this trend, digitalisation in agriculture and forestry might play out in the following aspects:

- Digitally enabled innovation in agricultural practices can gain relevance by finding ways to boost agricultural and forestry production outputs - while reducing import fertilizer and energy intensive input dependencies.
- Virtual simulations can speed up research and development on substitutes for protein and carbohydrate sources as well as for energy intensive fertilizers.
- Digital food and wood product market modelling might help to identify alternative suppliers and optimise food, feed and other biomaterials imports.
- Tracking of supply chains and food and wood product origins, as well as monitoring of agricultural and forest production is becoming more important for ensuring legality and sustainability of the resources and their origins. Hence, digital tracking and tracing as well as monitoring tools and automated image interpretation are gaining relevance.

A.2.2 Changed Perspectives for Agriculture and Forestry in a Post-war, Enlarged European Union that Includes Ukraine

Summary and Key Words

The Russian war in Ukraine has been significantly affecting global food supplies, due to sanctions, rerouting of trade lanes, land seizures, rising input prices, and destroyed, mined and contaminated land. Additionally, the Russian invasion has accelerated the process of Ukraine joining the EU. A possible EU enlargement, especially including the envisaged future membership of the agricultural powerhouse Ukraine, would affect the competitive landscape in the agri-food and forestry sectors, with enlargement likely to bring about a shift of large players in EU agriculture and forestry. Also, rebuilding Ukraine agriculture and forestry could be a window of opportunity to reinvent and innovate these sectors. Potentially, Ukraine could become a role model for digital agriculture and forestry innovation in Europe, as well as for green and sustainable agriculture. At the same time, regional disparities in a larger EU will likely become wider, while pre-accession support and cohesion policies can counteract this and drive digital infrastructure expansion in peripheral regions.

Key words: EU enlargement / Common Agricultural Policy / Open strategic autonomy / Supply chain disruptions / Post-war Europe

Current and Future Developments of the Trend

The war in Ukraine continues to significantly impact the country's economy, people and environment. Prior to the war, agriculture represented 41% of Ukraine's exports and the country benefited from an estimated 32.7 million hectares of arable land (Albaladejo Román, 2024)[26]. At the end of 2023, estimates placed the damages and losses to the Ukrainian agricultural sector at around €73 billion, with rebuilding expected to cost around €51 billion and demining an additional €29 billion (Albaladejo Román, 2024; Neyter et al., 2024). These figures will likely continue to rise for as long as the war continues. In addition, the continuing war in Ukraine leads to increasing macroeconomic uncertainties, e.g., concerning energy prices, inflation, and geopolitical challenges for the EU, also impacting strongly on the EU Agricultural Outlook to 2035 (EC, 2023c).

Against this backdrop and spurred on by Russia's invasion, Ukraine applied for EU membership in February 2022 and was granted candidate status in June 2022. As of July 2024, EU leaders are welcoming Ukraine's progress in advancing the necessary reforms to fulfil EU membership criteria. By now, the European Council has indicated 2030 as a potential

[26] Current comparisons between Ukraine and the EU agricultural sectors show the size of the potential added value to agriculture of Ukraine joining the EU: The combined 2021 production of the EUs three main crops totalled 30 million tonnes of wheat, 73.5 million tonnes of maize, and 10.3 million tonnes of sunflower. While Ukraine's produced 16.4 million tonnes of sunflower, 10.8 million tonnes of factory sugar beet, 3.5 million tonnes of soya, and 2.9 million tonnes of rapeseed (Albaladejo Román, 2024).

date for Ukraine's membership (European Council, 2023). Reforms to the CAP are likely necessary before Ukraine is admitted to the EU. Both the final shape of the reforms and scale of the war will strongly shape the future of the agricultural sector in an enlarged EU.

Recent Signals within the Scope of the Trend

Militarization and War Alter Biodiversity in Affected Areas

War and military activities have significant consequences for biodiversity, including large-scale habitat alteration, environmental pollution, and contamination (Lawrence et al., 2015). In addition to the environmental consequences of war, the increasing militarization within Europe (including calls for more military training areas to improve defence capabilities) place additional pressure on land available for agriculture and forestry. If such areas are to be converted back to productive farming land once the threat of war has subsided, this will likely require significant investment and time. For example, the costs associated with bringing 80% of the potentially contaminated lands in Ukraine back to normal use are estimated at €29 billion, with the process estimated to take around 10 years (Albaladejo Román, 2024). However, these figures do not take losses in production or human costs into consideration.

Post-War Rebuilding of Ukraine's Agricultural and Forestry Sectors

Next to challenges implied by the sheer scale of the post-war costs associated with rebuilding Ukraine's agricultural sector (estimate assume costs of €80 billion in 2024 for rebuilding and demining (Albaladejo Román, 2024; Neyter et al., 2024)), experts also see a window of opportunity to reinvent the agricultural sector (Adelphi, 2023). They see the potential for Ukraine to become a role model for digital agriculture/forestry innovation in Europe, as well as for green and sustainable agriculture. A 'build back better' approach could modernise Ukrainian agriculture and push the sector to increase its added value, i.e., from predominately low-added-value grains and oilseeds (Albaladejo Román, 2024). The human costs of war, including loss of labour and expertise, could also be a driver for automation and decision support systems, as the skilled workforce will take significantly longer to rebuild.

EU Enlargement to Redefine Common Agricultural Policy

If and when Ukraine joins the EU, significant impacts can be expected for the agricultural and forestry profile of the larger Union. On the one hand, this offers the opportunity to bring Ukraine's legislation into line with EU environmental and agricultural legislation. On the other hand, it brings with it the potential to reform current EU policy, such as the Common Agricultural Policy (CAP). For example, some studies argue that Ukraine's membership would encourage the EU to abrogate area-based agricultural subsides, a move that would favour nature conversation over the current set-up that primarily benefits large landowners and agro-industrial conglomerates (Wolczuk, 2023). Aside from policy implications, with around a third of the world's arable land, Ukraine's accession would strengthen the EU as a dominant agricultural producer and exporter on the world stage, accounting for around 30% of global wheat exports (Albaladejo Román, 2024; Wolczuk, 2023). Furthermore, Ukraine, with a population of over 40 million, would likely become a rapidly growing market for EU agri-food producers and for EU capital and enterprises (Albaladejo Román, 2024).

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

The opportunity to rebuild a better Ukrainian agricultural sector, as well as to redefine the EU's wider agricultural policy (CAP) in the process of accession agreements, has far reaching consequences for Europe's agriculture and forestry sectors, including the possible acceleration of the uptake of digitalisation in relevant areas. With EU enlargement, the EU's agricultural sector would grow significantly, providing ample opportunities to improve productivity and efficiency, as well as to ingrain more sustainable practices, especially as large agricultural enterprises currently dominate the Ukrainian market – with ten companies that cultivate areas of more than 100 000 hectares in control of 71% of the market (Lorenzen & Wetzels, 2023; Albaladejo Román, 2024).

- In newly rebuilt Ukrainian farmland, the digitalisation of farm and forest processes and practices could be implemented on a large scale. This could include, for example, the full automation of agricultural machinery to alleviate effects of probable shortages in workforce.
- Smart and precision farming practices might leapfrog older farming practices, as technology-savvy foreign agricultural players invest in the market, such as the seed conglomerate Bayer-Monsanto or the US grain trader giant Cargill (Lorenzen & Wetzels, 2023).
- Remote sensing could be rapidly adopted to monitor the state of the growth, project yields, identify pest issues, etc. especially in larger farms with access to greater capital.
- Additionally, digitalisation could be adopted in environmental monitoring to enable governments and supervisory authorities to control compliance with newly adopted EU environmental regulation in areas such as water quality, air quality, soil quality, etc.

A.2.3 Increasing Need to Tackle Biodiversity Loss

Summary and Key Words

Biodiversity loss is a major global and European challenge, driven by land use change, overexploitation of species, climate change and pollution. Agriculture and forestry are affected by the decline of ecosystem services such as nature-based pollination, pest control, or soil nutrients. Both sectors are also a driver of biodiversity loss, e.g., through large scale monocultures, expansion of intensive land use, and excessive use of agrochemicals. The adaptation of agricultural and forestry practices can help to restore and protect biodiversity.

Key words: Resource scarcity / Biodiversity loss / Climate change / Cultivation practices / Environmental monitoring

Current and Future Developments of the Trend

Biodiversity is declining around the world due to habitat destruction, overexploitation, pollution and climate change, with one out of eight species threatened with extinction (IPBES, 2019). Many forms of agriculture and commercial forestry are themselves characterized by monocultures and a lack of or adverse effects for biodiversity (Lécuyer et al., 2021). The stress on nature exercised by food production is driven inter alia by growing populations, the economic conditions of farmers, conditions of international trade and a policy environment that rewards intensive farming.

Tackling the biodiversity crises and its conflicts with agriculture requires acknowledging the underlying long-rooted factors under dispute[27], addressing local trade-offs between biodiversity conservation and yield improvement, and implies a need for measurable targets and a new approach of cooperation (Lécuyer et al., 2021). Already today, many global and regional policies are targeting biodiversity loss: For example, the 2022 Kunming-Montreal Global Biodiversity Convention sets out an ambitious pathway for a global vision of living in harmony with nature by 2050 (UNEP, 2022). In Europe, the EU biodiversity strategy for 2030 was transformed into the first continent-wide Nature Restoration Law in June 2024, putting measures in place to restore at least 20% of EU's land and seas by 2030, by requiring EU countries to set up National Restoration Plans (EU, 2024a).

Recent Signals within the Scope of the Trend

Spoonbill Population Threatened by Agricultural Activity

The Eurasian spoonbill all but disappeared from France in the 1500s, only to reappear in the 1970s in Loire Atlantique (EEA, 2020). The wading bird requires wetlands and is an indicator of the overall health of wetland ecosystems (Padmakumar & Shanthakumar 2024). Despite French conservation measures, the status of the protected spoonbill in France is still fragile due to agricultural activity in key sites for the bird. The bird's feeding areas are drained by farmers as well as by power companies, and intensive farming contributes to water pollution that affects wetland habitats. The survival of the bird depends strongly on an effective control of water levels, the protection of flood plains and a continuous monitoring of the vegetation and situation in the wetlands (EEA, 2020). Digital tools for remote sensing could also support in monitoring and tracking harmful behaviour affecting wetland and the bird population.

Farmers Could Grow a Larger Variety of Crops on their Land, Supporting Biodiversity

Although 6,000 food crops are available worldwide, two thirds of our diets depend on only nine crops, with these crops using 90% of all available agricultural land globally (FAO, 2019). To increase the diversity of food crops on the land, researchers and farmers are testing the implementation of strip cultivation by adjusting their production practices (WUR, 2024a). Instead of large monocultures, land is sub-divided into smaller strips where a composition of crops is produced side-by-side to raise the diversity of crops. Main benefits are inter alia

[27] Respective factors are for example land sparing (landscapes specially for food production or biodiversity conservation) and land sharing (integration of conservation into human land-use) (IPBES, 2019).

reduced soil erosion, increased soil fertility, and improved biodiversity (Earthhow, 2024). However, strip farming requires the selection of appropriate crops and different harvesting, storage and processing techniques. This example shows that new cultivation methods can utilize positive ecosystem interactions, increase the variety of crops and contribute to biodiversity.

China’s Ties to Foreign Agricultural Land are Affecting Biodiversity

China undertakes various activities, nationally and abroad, to safeguard its food security (Donnellon-May, 2023). This is driven by concerns about the impact of water scarcity, of droughts and of floodings on its domestic and imported food supply, which is also related to the spread of diseases such as African swine fever (Chang, 2019). To safeguard imports, China rents and buys farmland in Latin America, Central Asia, Eastern Europe, Africa, and even the US (Donnellon-May, 2023). In addition, China concludes free trade and agricultural cooperation agreements mainly with Belt and Road Initiative countries as part of China’s Food Silk Road (Tortajada & Zhang, 2021). Such foreign large scale capital-intensive farming has been criticized for its negative impacts including deforestation, erosion, and loss of biodiversity due to monoculture plantations (Gironde, 2020). Concerning future perspectives, China for example plans to build 25 large scale industrial pig plants in Argentina that produce meat only for export to China, three of which are already in construction (Euromeat, 2023). Here, Argentinean NGOs have raised concerns about possible consequences of deforestation, soil and water pollution, water depletion from plants, and monoculture farming of soy and corn for feed provision, which would heavily affect biodiversity (Koop, 2020).

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

Strip farming is shown as an example of improving biodiversity in agricultural practices. For large applications, specific machineries are needed. It requires innovations in precision agriculture technologies that can manage small but diverse plots for crop production. In contrast to large scale monocultures, precision agriculture machines must perform activities per square meter or per individual animal (WUR, 2024b).

- Respective plant-specific farming includes GPS, sensor technology, Information and Communication Technologies (ICT) and robotics, with sensors recording data on crops and soil, while software identifies deficiencies and needs and can propose location-specific treatments; other software programs define nitrogen application per area (e.g., a strip).
- New types of cultivation approaches can increase the variety of tasks for machines, with e.g., strip farming requiring different machines.
- Robotics, in particular, will rely on cutting edge sensing cameras and adaptive learning and an “understanding” of the high variety of conditions on the field.

Monitoring of the state of biodiversity and understanding what this means for the resilience of the ecosystem, requires strong advancements in remote sensing and automation to assess the degree of vulnerability and to provide information for the prioritisation of conservation activities.

- Remote sensing and monitoring data are needed to control compliance of agriculture and forestry player's actions with respect to environmental regulation and beyond by public authorities. Documented evidence could help to overcome law enforcement deficits to control big and small players (as shown here with Chinese agriculture actors or French farmers activities in bird reserves).
- Specific Biodiversity Data Spaces might be required – beside Agriculture Data Spaces or Forestry ones – for enabling a safe exchange of respective data between various data producers.
- Already today, digital monitoring techniques are used in forestry and agriculture to detect diseases or wildfires at an early stage (Brunori et al. 2021) and to trace food and wood throughout the supply chain. The main reason for monitoring is often economic: to preserve yields in both forestry and agriculture.
- Assessing and interpreting monitoring results requires strong expertise as results in biodiversity are very context sensitive and trade-offs need to be expertly assessed. For example, preventing wildfires and diseases may be beneficial for biodiversity, even though wildfire and disease have a function in the long-term preservation of ecosystems. Hence data analytics need to undergo a steep learning curve and gain critical expert support.
- There are also other monitoring programmes such as Global Forest Watch (Hedberg and Sipka, 2020), in which the European Space Agency ESA launched Φ-sat-1 to collect data on the state of the earth, including the state of vegetation and water quality. Other private-sector initiatives include Google Earth and Microsoft's AI for Earth (ibid.).

A.2.4 Cybersecurity Issues and Network Vulnerability Affect Digitalisation in Agriculture and Forestry

Summary and Key Words

Digital technologies with their sensing, communication and information gathering devices and fixed as well as mobile network infrastructure can be potentially misused as a means of surveillance, espionage, and sabotage. Digital tools in agriculture and forest technologies could become the next frontier in cyberwarfare. The increase in hacking and rising risks of infrastructure failure or malicious attacks of digital agriculture and forestry systems (for the processing industry and for supply chains) also increase the risks for food and biomaterial supply security and safety, which in turn can e.g., increase market prices due to rising costs.

Key words: Vulnerability / Digital divide / Data security / Hacking / Espionage / Sabotage

Current and Future Developments of the Trend

While the expansion of digital infrastructure in Europe is progressing overall, there are still gaps, particularly in rural areas. In 2023, only 56% of households in Europe had fibre-optic connection, and in rural areas this figure was only 41% (EC, 2024e). Furthermore, the rollout of mobile 5G networks is falling short in terms of quality and coverage, due to limited investments (EC, 2024e). Hence, telecommunication networks are subject to age-related failure and are lacking interoperability and scale for the application of the Internet of Things (IoT) in industry, agriculture and forestry (EC, 2024e). At the same time, there are risks posed by the dependency on non-EU providers for components in digital infrastructure, farming and forestry devices and systems, e.g., concerning hacking, espionage and sabotage from various actors (which can be hostile foreign countries, malicious business competitors, terrorists, or activists). However, domestically sourced components are also not immune to such risks. A review of disclosed cybersecurity incidents between mid-2011 and April 2023 showed a rising frequency of cybersecurity threats to the food and agriculture sector globally (Kulkarni et al., 2024).

With the growing numbers and types of digitally connected industry applications and possible entry ways to hacking, incidents of espionage and sabotage are rapidly rising. For example, the IoT platform market alone is expected to grow annually by 29% globally until 2030 (Precision Reports, 2024). The EU is aware of the risks and in February 2024 proposed a collection of measures to address connectivity targets and the resilience of digital systems (EC, 2024f; NIS Cooperation Group, 2024).

Recent Signals within the Scope of the Trend

Espionage Enabling Equipment in Machines and Infrastructure

The involvement of Chinese technology providers in US and European data infrastructure projects in areas such as telecommunication are assessed as high-risk for security threats (EC, 2023d). There are allegations of spying and espionage or possible backdoors, and fears of Chinese state connections with the respective technology providers. Hence, since 2018, Chinese suppliers (including major actors such as Huawei and ZTE) have been banned as technology suppliers to 5G network infrastructure build-up in Japan, the US as well as in several EU countries (Kroet, 2024). A cross-sectoral perspective on evidence for cybersecurity risks appearing in various fields can also sensitise agriculture and forestry actors to widen their risk radar: For example, in early 2024, an investigation by the US Homeland Security on critical infrastructure vulnerabilities raised concerns about espionage and sabotages. Homeland Security identified cellular modems, firewall and networking equipment at several Chinese supplied giant ship-to-shore harbour cranes at US seaports that were not part of the contract nor functional for the machine (Homeland Security, 2024). As military equipment is also handled by these cranes, the US wants to spend €18 billion in replacing the respective cranes (Kuś, 2024). (Semi-)Autonomous machines like self-driving or assisted cars or smart and precision farming devices also include dozens of sensors and can be used as a ubiquitous interface for spies (Eloit, 2021).

Cyberattack on Food Processing Company Exemplifies the Vulnerability of Smart Farming Devices

Data security is a growing concern in the agri-food system, and it can create global repercussions in highly interconnected multinational companies. For example, a ransomware attack in 2021 on the Brazilian meat processing giant (JBS Foods) led to a 5-day production shut down in facilities in the US, Canada, and Australia, causing temporary record-high meat prices (Claughton & Beilharz, 2021). Beside food processing, agricultural and forestry AI also comes with systemic risks for farms, farmers and food security that are often poorly understood and underappreciated (Tzachor et al., 2022): Automatic farm and forestry machines like ag-bots[28], crop sprayers, drones and robotic harvesters and decision support systems can be hacked, data can be stolen, and data and machines can be manipulated. As such, various technical dimensions of Smart Farming and Precision Agriculture can also be attacked: hardware, network and related equipment, data, code and applications, support chains, and other entities like people or institutions (Yazdinejad et al. 2021). These issues can lead to potentially dire implications for global food prices, among other issues.

Connectivity Risks Due to Reliance on Single Networks and Providers

The provision of digital connectivity through infrastructure is at risk to accidents, sabotage, and business interruption. Beside cyber risks, physical threats are particularly pertinent for network infrastructures that are not able to be fully monitored or protected. For example, subsea infrastructure damage of data and energy infrastructure in the Baltic Sea occurred recently multiple times since late 2023. Ships presumably or evidently related to the Russian shadow fleet of oil tankers are accused of sabotage on damaging or cutting subsea data cables, submarine power cables, and gas pipelines, affecting Nordic connectivity and energy security (Brown, 2025). Connectivity is further at risk of becoming commercially unviable for infrastructure providers to invest into infrastructure built-up or maintain services in rural areas and the periphery due to low population and business density and long distances to cover. This causes installation costs with relatively low return on invest (CORA, 2021). Furthermore, dependency on regional monopolies can drive service costs up as well as increase the risk of regions being left behind in terms of infrastructure provision. Overall, the rural digital connectivity gap is constantly declining but persists in Europe – user density and high infrastructure investment costs in rural areas requires public funding for new installations (Arcuri, 2023; De Clercq et al., 2023). Reliability and service continuity of network infrastructure are at stake; however, they are the precondition for using digital agri- and forestry technologies.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for

[28] Autonomous agricultural robots

agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

The reliability of digital infrastructure is a precondition for the functioning of smart and precision farming and forestry applications.

- Digital farmers and forest owners might need back-up solutions or to set-up local data networks to ensure the reliable functioning of digital technologies in their business. Low data solutions that do not need 24/7 internet connectivity and local area data networks might be required here.
- Agri- and forest-technologies could become the next strategic area for espionage. Modern smart farming and forestry machinery, agricultural and forest data spaces, as well as agri-food supply chains and Industry 4.0 food processing plants are possibly subject to hacking, sabotage and espionage. For example, as China increases its activity in the field of green technologies, its influence could strengthen in the European digital agriculture and forestry domain.
- Other respective security threats could be posed by other foreign players, non-state actors and terrorists. Such risks include, for example, the estimation of yields to influence market prices or to gain competitive advantage, the manipulation of sensitive data to influence carbon pricing, fake due diligence by influencing regulatory monitoring, or the sabotage of connected machinery to influence food and bioeconomy product provision and hence influence food and bioeconomy security and safety (Demestichas et al., 2020).

A.2.5 Bio- and Nanotechnologies Can be a Lever for Next Generation Agriculture and Forestry

Summary and Key Words

Technological advancements in bio- and nanotechnologies, omics, and their conversion could help to discover innovative ways for agriculture and forestry to manage challenges like new and invasive pests and the need for climate resistant crops and livestock. Such technologies enable the development of new types of nano-bio-fertilizer which could be highly efficient and have less negative environmental side-effects. Bio-sensors can offer near-real time in-depth understanding of the state of soil, plants, livestock, etc. enabling precision farming that suits the micro-local needs.

Key words: Biotechnology / Nanotechnology / Biomanufacturing / Genetics / Biosensors / Nano-fertiliser

Current and Future Developments of the Trend

The climate crises drive unknown stress factors for plant and livestock growth, such as weather conditions and new diseases and pests, that can lead to decreasing yields and more crop losses. Some agricultural practices, such as forms of factory farming, have in the past led to the resistance of plants and livestock against veterinary pharmaceuticals including antibiotics, pesticides, and herbicides, etc. (Mann et al., 2021; Policy Horizons Canada, 2024). By now, engineering biology, biotechnology and the integration of multiple disciplines have enabled the development of biotechnological approaches and interdisciplinary tools, including genetic engineering, genome sequencing, and genome editing technologies. Use cases are, for example, helping to predict the robustness of species in changing environmental conditions, as well as creating crop cultivars and breeds that meet food and bioeconomy product demands (Aurand et al., 2024; Munaweera et al., 2022; Anderson & Song, 2020). Furthermore, the agricultural biotechnology sector also includes molecular diagnostics, vaccine and veterinary pharmaceuticals, bio-pesticides and bio-fertilizers developments, biofuels developments, etc.

The global market size for agricultural biotechnologies was €110 billion in 2023 and is expected to grow to €270 billion by 2034 (PMI, 2024); and the global market size of agricultural nanotechnologies in 2024 is estimated at €350 billion and may get to €1080 billion by 2034 (PMI, 2024). Despite high public awareness and strong regulation of genetically modified organisms, the EU market is strong in this area, drawing on an innovative and competitive biotech industry. In the next years, Artificial Intelligence is expected to further drive biotech innovations. Concerning future policy conditions, the European Commission has announced a more coordinated approach for biotechnology and biomanufacturing to strengthen the competitiveness of European players and further realise their potential (EC, 2024b).

Recent Signals within the Scope of the Trend

Bio- and Nano Tech for Cultivation of Climate Adaptive Plants and Animals

Numerous efforts are ongoing to advance research around biodesign and gene editing to cultivate plants and animals which are adapted for the ongoing and expected change in climate conditions. Affordable gene sequencing is the basis for compiling a huge gene pool of varieties and breeds from different climate zones, with specific robustness or yield characteristics, and for different eras using natural museum archives and prehistoric finds (Munaweera et al, 2022). The wide gene pool allows researchers to predict the adaptive potential of plants and livestock and to combine and develop possible biodesigns that potentially contain various characteristics and performances (Andersen & Song, 2020). In addition, new genomics approaches in gene editing, RNA interference to regulate gene expression, the application of nanotechnology to genetic manipulation and new interdisciplinary collaboration of ecology, system biology, molecular genetics and conservation agriculture, can help to more systematically cultivate new sorts and breeds for food, feed, biomaterials as well as for biodiversity conservation that are less vulnerable to climate change impacts, diseases and pests (Alexandrova-Stefanova et al., 2023; Munaweera et al, 2022; Aurand et al., 2024; Anderson & Song, 2020). For example, the company Colossal successfully reconstructed the chromosomes structure of a mammoth living 52 000 years ago, that was excavated in 2018 (Leatham, 2024). This is part of a “moonshot mission” to repopulate the Siberian tundra with cold-adapted elephants that involves the ancient genome to contribute to landscape conservation and indirectly prevent melting of the permafrost (Doxzen, 2021).

Biosensor Technologies Enable Real-time Understanding of the State of the Local Environment

New sensor approaches using biosensing based on enzymes, whole cells, antibodies, or DNA offers a new detection principle for on-site monitoring of environmental conditions and developments (Gavrilas, et al. 2022; Huang et al, 2023). Bioelectronic sensing to achieve nearly real-time data about environment and health situation is required for applications like precision farming. For example, by combining synthetic biology and materials engineering, researchers programmed coli bacteria to produce electrical current output within minutes when detecting chemicals like endocrine disruptors[29]. This approach provides a platform for miniature, low-power bioelectronic sensing of various chemicals (Aktinson et al., 2022). Various nano-biosensors offer portable low-cost solutions for assessing plant and soil health, nutritional status, hazardous chemicals, and stress levels of plants in the field. They sense physiological signals at low detection limits and translate them into standardized detectable signals (Mondal et al. 2022). While most of these new sensor types are not yet commercially available, they have a huge potential in sustainable smart and precision agriculture and forestry, environmental monitoring, next generation biomanufacturing and precision medicine (Mondal et al. 2022; Dixon et al. 2021).

Novel Nanomaterials Revolutionise Fertilizers with More Efficiency and Less Negative Side-effects

Today, chemical fertilizers are dominant in global agricultural practices to deliver the necessary nutrients for plant growth. However, their excessive use has negative side effects on soil microflora, environmental contamination, and human health. In contrast, the emerging application of nano and nano-biofertilizers promises high-quality and high-yield food production while limiting ecosystem damage. This new type of nanotechnology enabled biogenic fertilizers increases the efficiency of nutrients uptake. For example, nanoparticles enter plant cells and penetrate leaf interiors at a much higher degree compared to conventional fertilizers (Basavegowda & Baek, 2021). In another case, MIT chemical engineers developed a coating for bacterial cells that make them applicable in large scale agricultural use. The underlying bacteria convert nitrogen gas to ammonia, thus providing nutrients as microbial fertilizer to the plants with the possibility to replace chemical fertilizers (Trafton, 2023).

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

The impacts of novel respective materials for the agriculture and forestry sectors are numerous. Digitalisation plays a major role in the development of resilient organisms, better

[29] chemicals that interfere with human hormones already in extremely small doses in a harmful way

fertilizers and pesticides, by using repositories of material and gene data, and by using insights from new sensor types for next level precision farming and forestry:

- Digitalisation will enable and enhance the potential of synthetic biology as an approach to redesign and engineer organisms that have the potential to make plants and livestock more resilient; this also opens new opportunities for the bioeconomy by replacing fossil-based products and processes (WEF, 2022).
- Advances in deep learning can enable the virtual simulation of cultivation and breeding experiments, as well as the development of new gene based veterinary drugs, fertilisers and pesticides.
- AI-enabled biodesign factories (biofoundaries) could scale up pilot experimentation in biomanufacturing, supporting interdisciplinary research and developments (EC, 2024b)).
- Building up a genomic data infrastructure of gene banks could be used as a pool for genetic variations, with such repositories containing flora and fauna characteristics in standardised passport data type (Munaweera et al., 2022).
- Digital museums and herbarium collections can open new ways of understanding biological responses to climate change in an historical context (Anderson et al., 2020).
- The European Commission (2024b) communication "Building future with nature" highlights the role of AI for biotechnology and biomanufacturing. This includes human health focused action like the 1+ Million Genome initiative and the Virtual Human Twin which could both potentially be applied for environment, plants and livestock gene data infrastructure and to create a 'Virtual Environment Twin'.
- In the future, new types of digitally connected sensors and deep learning on successful growth conditions and vulnerabilities could be the basis to build up a Digital Twin of the field, forest or environment.
- Hence, it could facilitate new forms of smart and precision farming and forestry as well as new ways of providing agriculture, forestry, and environmental policies.

A.2.6 Technology Solutions for Agriculture and Forestry to Deal with Climate Stress

Summary and Key Words

In the open land, geoengineering and microclimate management measures are discussed and tested to mitigate negative impacts of climate change and to manipulate climate and weather at the microlevel, or regionally. Geoengineering includes measures such as atmospheric sulphur spraying that mimic volcano eruptions, or the storage of carbon as greenhouse gas. Also, next generation desalination and irrigation technologies that are extremely energy efficient could overcome water scarcity in coastal regions. These advancements could turn formerly unutilized or abandoned land into areas fit for food production or afforestation. In this context, digitalisation (with e.g., water demand and soil condition monitoring) could enable more efficient use of irrigation, avoiding side-effects like soil salinisation.

Key words: Agricultural practices / Geoengineering / Carbon sequestration / Microclimate management / Water desalination

Current and Future Developments of the Trend

According to the EEA (2023), Europe is not adequately prepared for rapidly growing climate risks, with food production and natural ecosystems including forests both likely to be affected. Respective developments are expected to lead to cascading effects on food security, human and animal health, rural and coastal livelihoods, vulnerable populations, and the wider economy (EEA, 2023). Already today, agriculture and forestry as well as parts of the natural ecosystems are suffering from water stress, in particular in the Mediterranean; in the whole of the EU, 29% of the territory was affected during at least one season in 2019 (EEA, 2023). Climate change, water supply and consumption for populations, energy supply, industry as well as for tourism and agriculture all play a major role for European water resources, with the situation expected to worsen until 2050 (Bisselink et al., 2020).

To mitigate climate change, geoengineering approaches[30] are already being analysed and tested, and forms of agricultural practices are being developed that allow animals, plants and soil to better deal with changing climate and weather conditions. However, according to EEA (2022), the EU food systems policy is not yet strong enough to phase out unsustainable modes of production such as using harmful technologies, substances, and practices. Hence, a growing variety of adaptation methods in agriculture and forestry can be assumed: including conventional practices beside a growing number of innovative sustainability-oriented practices.

Recent Signals within the Scope of the Trend

Geoengineering: Agriculture and Forestry Contributes to e.g. Carbon Storage

Solar geoengineering in the form of solar radiation management is based on the idea of mimicking a volcanic eruption's stratospheric sulphate aerosol emissions that reflect sunlight and hence has cooling effects. Some authors assess that cooling benefits for agricultural productivity might be neutralized by scattered solar radiation (Proctor et al., 2018), others estimate an increase in global crop yield by about 10% (Fan et al., 2021). Other types of geoengineering aim at removing CO_2 from the atmosphere to limit global warming. Here, carbon capture and storage (or utilization) are widely discussed and beginning to scale up and gain momentum with 41 projects in operation and 351 in development globally (Global CCS Institute, 2023). Beside these industrial size installations, agriculture and forestry play a crucial role in carbon sequestration or carbon farming. Here, soil carbon sequestration and biochar are methods to bind CO_2 in the soil that improve soil quality and promote food availability (McDonald et al., 2021; Kortetmäki & Oksanen, 2023; Wani et al., 2021). Also, reafforestation

[30] like reducing solar radiation or binding CO_2 so that it is not released into the atmosphere

is a natural way of binding carbon in trees and drives the expansion of forests[31]. These types of carbon farming in agriculture and forestry are seen by the European Commission as a business model for healthier ecosystems, providing revenues for land managers e.g., by selling carbon credits (EC, 2021d & 2021e).

Microclimate Management: Using Nature-based Solutions to Adapt to the Climate Crisis

Global and regional geoengineering can provide quick fixes to the climate crises, while local microclimate management can manipulate local climatic conditions to optimize agriculture and forest production (Cach-Pérez et al., 2021; Menge et al., 2023). Practices like shading, mulching, applying covers, windbreaks, insect nets, and irrigation systems offer mostly nature-based solutions to improve yields and quality, control pests and diseases, enhance water use efficiency, improve soil health and support climate change adaptation and even increase carbon uptake and storage (Biswas et al., 2023). The European Union supports sustainable practices through its Common Agricultural Policy, and the LULUCUF Regulation (OECD, 2023).

Leaps in Low Energy Consuming Water Desalination Could Open New Opportunities for Agriculture and Land Use

Today, water desalination plays only a minor role in Europe, providing about 3 billion m^3 of desalted water each year (Adamovic et al., 2019). Desalination plants are usually heavily energy consuming; hence, several alternative concepts are under development to find low energy consuming desalted water provision. For example, MIT researchers developed a system of solar powered evaporation and thermohaline convection that provides freshwater cheaper than tap water. However, it is so far just a lab experiment and designed for household size applications (Chu, 2023). Innovative large scale low energy desalination pilots use, for example, forward osmosis filtering that requires less pressure than the dominant reverse osmosis concept (McKee, 2023). Access to clean desalinated water could help to expand agricultural production in coastal areas with irrigation systems without harming groundwater bodies.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

- Carbon farming as a business model requires proofing of the climate service provided. Digitalisation can support reliable monitoring, data analysis and reporting processes.

[31] In contrast, using land for bioenergy carbon capture and storage (BECCS) is seen as problematic as large scale biomass production competes with land and water for food, forests and nature (Kortetmäki & Oksanen, 2023).

Digital sensors could improve the accuracy of measuring carbon uptake and the verification of its long-term carbon sequestration benefits.

- Digital farm administration helps to document cost shares attributed to carbon farming. Market platforms can provide access to clients who want to buy carbon credits (McDonald et al., 2021).
- Smart agriculture devices can support microclimate management. Through using ground sensors and remote sensing data, real-time monitoring can improve microclimate management strategies.
- Irrigation systems that draw on low-cost desalinated water require proper irrigation and humidity monitoring to find ways to manage good crop growth and soil quality, similar to microclimate management.
- Crop simulation models, as well as a Digital Twin of the microclimate conditions on the field, can help to choose the adequate crops and livestock.
- For cultivation strategies and daily management, AI based crop simulation models can provide respective decision support systems to farmers and forest owners, helping to mainstream good microclimate management practices that can be shared with others with less experience.
- Using autonomous agriculture robots in microclimate farming requires innovative machines that better adapt to the variety of cultures on the field.

As such, digitalisation can help climate-smart agriculture applications and practices (Gupta et al., 2022; Pedersen et a., 2024). For example, the Horizon 2020 project Stargate project links microclimate management with climate-smart agriculture approaches and advances respective digital technology solutions (Stargate, 2024).

A.2.7 Intensification of Biological Resource Production in Controlled Environments

Summary and Key Words

The expansion of food production in controlled environments[32] is driven by numerous factors, among them increasingly harsh environmental conditions, increasing safety requirements for food production, a growing need for efficiency improvements and a growing competition for land. Concerning respective solutions, a variety of different approaches exist already, and others are currently in development. Examples include hydroponics in greenhouses or vertical farms, aquaponics that aim at closed nutrient cycles, or the production of food, feed and biomaterials in industrial processes and bioreactors. However, as of today, the application of respective solutions remains limited to certain plants, cells and species, ranging from leafy greens to algae, insects to lab grown meat. With respect to their impact, e.g., algae, insects and other sources produced in controlled environments are regarded as a potential solution

[32] such as greenhouses, vertical farms, or bioreactors

for providing novel protein sources for the growing global population, with much lower resource use than protein sources which are currently commonly consumed.

Key words: Controlled agricultural environment / Vertical farming / Algae farming / Artificial meat / Insects as a protein base

Current and Future Developments of the Trend

For decades, farming in controlled environments, such as greenhouses, has been used to extend the season and to grow plants that would otherwise not grow in outdoor climate conditions. For example, through the extensive use of controlled environments for food production, the Netherlands has become the world's second largest food exporter after the US (Walsh, 2020). In broad terms, the controlled environment agriculture concept covers various areas such as stacked layered vertical farms, aquaponics that integrate fish farming in the nutrient cycle, or production of organisms and cells in bioreactors. This approach works for leafy greens, herbs, certain fruits and vegetables, insects, algae, animal and plant cells, but not for bulk commodities like grain, legume or root vegetables such as potatoes and carrots. For the past 10 years, the innovation rate in this area has been especially high, with respect to new architectural approaches such as vertically stacked layers, or in high tech applications in lighting systems, intra-logistics automation, nutrient recycling, etc. (Wiklund, 2023). Hence, the input of resources can be optimised through an increase in control of the living organisms in the farm, the dosage of pesticides, nutrients, water and light, and the circular recovery of resources. Open-field farming is increasingly under pressure from weather stress, water scarcity and new pests, farmers must take growing efforts to reduce the negative impacts of intensive farming including fertilizer and pesticide washout into water bodies (Devot et al., 2023; Schürings et al., 2024). By reducing external influences and better controlling the flow of nutrients, controlled environment agriculture is becoming one solution for parts of farming, and to a certain amount to forestry (cultivation of seedlings). In addition, consumers request fresh, healthy, and local produce, driving urban farming initiatives including vertical farms (Khan, 2024).

The market for controlled environment agriculture is expected to more than double between 2022 and 2029 to nearly € 200 billion globally (Petruk, 2024). However, the start-up market that rose over the last 10 years is currently in a highly competitive transition phase in what is called "the valley of disillusion" with some start-ups filing bankruptcy (Wiklund, 2023). Nevertheless, controlled environment agriculture is regarded as being at the verge of a new upswing through innovations in energy solutions, circularity, and integration in urban planning (Gordon-Smith, 2024). Countries with limited agricultural space, like Singapore, are strategically deploying vertical farming to achieve local food production of 30% by 2030 and to reduce foreign dependency on food supply (Gordon-Smith, 2024), while the European Union aims at strategically exploiting algae as bioeconomy resource (EC, 2022).

Recent Signals within the Scope of the Trend

Giant Vertical Farm Project GigaFarms in Construction in Dubai

In 2024, the construction of the world's largest vertical farm began in the United Arabic Emirates. Dubbed 'GigaFarm', it operates as a closed loop circular waste-to-value system. Starting at a size of 80 000 m^2 and 12-meters high, it aims to grow 3 million kilograms of leafy greens, herbs, and vegetables by 2026 and to reduce the UAEs food imports (ReFarm TM, 2023). The project is also expected to limit freshwater and external pesticide use in its controlled environment, and to replace fertilizer by onsite compost and nutrients from wastewater recycling, thus also contributing to national decarbonization efforts. GigaFarm plans to also grow mangrove seedlings for reforestation efforts (IGS, 2023). Other comparable concepts integrate fish tanks into the farm to produce food integrated in the nutrient cycle (Santosh et al., 2024). Large scale vertical farms are ideal for data-driven farming practices, and AI driven automation; however, the technology learning curve needs to cut down costs for automation solutions for their application in smaller farms (Campbell, 2024).

Advancements in Controlled Environment Production of Alternative Proteins

Meat and dairy production accounts for at least 11% of global greenhouse gas emissions[33] (Blaustein-Rejto & Gambino, 2023). Today, several plant-based substitutes for meat-based protein are already available on the mass market, while insect-based proteins are used mainly for feedstock, with a small quantity marketed for human consumption for a mainly Asian food market. However, global insect production – carried out in partly innovative vertical farms[34] – is expected to grow from an estimated 100 kilotons in 2024 to 700 kilotons annually by 2030 (Schafer, 2024); insect farms are scaling up, with big players located in Europe (Fantom, 2022).

In a related technology field, bioreactors are closed systems for cell growth in a controlled environment. Here, the market viability of lab grown or cultivated meat is progressing. In 2023, the first company applied for authorization to sell lab grown meat in Europe, while the market of less than 20 companies across Europe is currently in its infancy (Stummer, 2024). Although lab-based cell growth is a standard process in the pharmaceutical industry, the challenge here lies in scaling-up production sizes to large quantities, requiring reactors that are 10-times larger than today's largest reactor in the pharma sector (Alwahaidi, 2024; Ching et al., 2022). The other major challenge is finding animal free substitutes for the required nutrient base for muscle growth. Today, cost-intensive bovine serum from calf foetuses is the major nutrient base for cell cultivation, making up 50% to 95% of the production costs of nearly all artificial meat products. Cell meat start-ups and biotech companies are searching for alternative proteins that can stimulate the division of the cultivated muscle cells (TransGen, 2024).

[33] Other studies estimate the share up to 19.6% (Blaustein-Rejto & Gambino, 2023).

[34] Vertical insects farms follow similar design principles and processes like vertical farms for plants.

European Commission Highlights the Role of Algae as Underexplored Bioeconomy Resource

Algae grow around 10 times faster than traditional crops, they do not compete with other crops for land, do not require freshwater, and require much less fertilizer (Kite-Powell, 2018). They can be used for multiple purposes, for example as a resource for biofuels, as feed for livestock farming, directly as food or nutritional supplements, as a biostimulant in support of the uptake of fertilizer by plants, or as an additive to construction materials (EC, 2022; Transparency Market Research, 2022). In 2022, the European Commission highlighted the role of algae as an alternative but relatively untapped protein source and identified action needs to upscale algae cultivation and production (EC, 2022). Research also confirmed that about 20 million km^2 (about twice the area of Canada) of the ocean is suitable for macroalgae or seaweed farming, and that there is a rich farming potential in the North Sea (Liu et al., 2023). While macroalgae grow in open oceans and in off- and onshore aquacultures, micro-algae can also be mass-cultivated in photobioreactors in industrial processes (EC, 2022); aquacultures and bioreactors are both form of controlled environment farming practices.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

- A controlled environment allows relatively easy digitalisation and automation, as external influences (as are present in the natural environment) are limited. This makes it easier for automated machines to treat and harvest plants and to manage processes like watering, fertilizer supply, etc.
- Digitalisation is a key prerequisite for implementing more controlled environments and drives innovation through continuous real-time learnings, e.g., on improving growing conditions by regulating light, temperature, wind, etc., adjusting robotics for harvesting, understanding impacts of plant maintenance, improving circular nutrition and waste cycles, etc. (Wiklund, 2023).
- Specifically, highly automated vertical plant and insect farms are strongly dependent on automated internal logistics processes as well as on monitoring and maintaining growth conditions and the state of the plants.
- Concerning the production of cultivated meat and microalgae in bioreactors, this is comparable to pharmaceutical and food chemical processes. Industry 4.0 approaches[35] based on digitalisation can help to improve these processes and their efficiency, enable supply chain transparency, etc. (Kamalapuram & Choudhury, 2024; Wydra et al., 2023).

[35] Industry 4.0 refers to the Industrial Internet of Things. It integrates intelligent digital technologies into physical manufacturing processes and goods and in agriculture biological realms enabling digital automation in systems, processes (Kamalapuram & Choudhury, 2024).

- For algae farming in the open ocean, digitalisation can play a crucial role as well, especially concerning monitoring algae stocks and their growth, or to enable transparency of sourcing, for managing sustainable harvesting approaches, etc. Furthermore, controlled environment agriculture could be seen as a “sandbox” for digital and automated agricultural technologies to gain experiences with complex outdoor applications.

A.2.8 Next Level Decision Making Enabled by Digital Data Management and Spaces

Summary and Key Words

The global data base from agricultural and forestry machines, remote sensing, sensors, market data, etc. is massively growing. In addition, expected advancements in AI enabled data analytics will make the use of data management in farms and in forestry management simpler and more meaningful for the user by providing hands-on support for business processes. Thereby, agricultural data spaces provide platforms, infrastructure, and tools for safe use of data for farmers and forest owners. Internal and external farm and forestry data are used for increasingly automated analysis for decision support, for communication with business partners, consumers, public authorities, and others. However, trust and clear added value is important to engage in data sharing. Public authorities are increasingly using data spaces to combine data to get an overview on the state of agriculture and forestry and to inform policymaking and execute legislation. Agricultural data spaces are part of investments of the EU into European Data Spaces.

Key words: EU Data Act / Agricultural Data Spaces / Smart farming / Precision farming / Decision support systems

Current and Future Developments of the Trend

Beside skills, experience and traded knowledge (e.g., about land, crops and livestock), farm and forest businesses need systematic data collection for planning, resource management, sales, certifications, and for gaining access to CAP subsidies and taxes. Agricultural and forestry machinery can provide information on field data, machine data, and executed tasks (crop care, milking, tree harvesting). However, these domains are often not connected, lack interoperability, and are isolated in several (sub-)ecosystems of different machines and service providers (Kalmar et al., 2022). Data Spaces are an ecosystem of data repositories and software to share, exchange, access and generate knowledge for the user to understand the status quo. Through the combination of multiple data sources and advancements in data analytics as well as in generative AI, data can be translated into decision support systems output, providing advice to farmers and forestry managers or directly to autonomous agri- or forestry robots (Rose et al., 2016; Iakovidis, et al. 2024). Already today, the EU is investing in the development of European data spaces in several sectors, including agriculture, to improve the industry’s competitiveness based on a vibrant data market and enable better decisions based on a sound evidence base (EC, 2024f). In addition, the EU is currently leading in data policies and contributes to improved regulation of data spaces with regulations such as the EU Data Act (EU, 2023). These policy frameworks are important as they increase trust in the market players that share their data and ensure cross-border and cross-system interoperability.

Overall, the field of data spaces is developing dynamically, as visible in increases in the number of different data sources, partners, and application fields (EC, 2024f). With the European partnership of 'Agriculture of Data' providing research and development funding for tools to enhance sustainable production, the resilience and competitiveness of the sector as well as strengthen policy monitoring, the European data spaces and decision support tools will further develop innovative solutions and improve their uptake (European Partnership 'Agriculture of Data', 2023).

Recent Signals within the Scope of the Trend

On-Farm Data Spaces for Decision Making and Automation

On-farm agricultural data spaces are advanced farm management systems that gather data from various sources such as machinery, sensors, and external sources like marketplaces and weather data. Farmers can choose which data to share (Brunori et al, 2025; Kalmar et al., 2022). This data can be used for decision support, moving from understanding current events to predicting future outcomes and enabling self-optimization (Fraunhofer, 2020). This integrated knowledge supports smart and precision farming, considering factors like market conditions and quality requirements. Digital Twins, representing the farm's state and activities in real-time, can enable remote control and simulation testing for better decision-making in the future (Verdouw et al., 2021, see in another sector Empson, 2023).

Corporate Companies Driving Agricultural Data Spaces

Big agricultural suppliers like Bayer, Syngenta, Claas, and John Deere are heavily involved in digital farming solutions: they offer software and platforms that integrate field data, provide crop analyses, and offer suggestions for optimizing planting and fertility management. These include software like Climate FieldView or Cropwise that incorporate field data and interactions with crops and soil, real-time data integration for field activities, and platforms for carbon quantification and agronomic advice using generative AI expert systems (Climate, 2024; Claas, 2024; Syngenta, 2024; Bayer, 2024). The goal is to optimise planting, fertility management, and precision farming practices. Critics raise concerns about the potential monopoly power of these companies in controlling farm data, dominating digital tools, and driving sales of their own products (Atik, 2022; Davidson, 2018; van Woensel, 2016).

Data Spaces for Policymaking and Reduction of Bureaucratic Burden

Governments use farm and forestry data to inform policy making, monitor policy effectiveness, and enforce regulations. In this processes, digital data can streamline procedures for authorities, farmers, and forest owners (Finck & Mueller, 2023; Kotsev et al., 2021). Recently, nine EU Member States joined forces to realise an integrated administration and control system for CAP governance (EC, 2021f). One prime use case of the joint action simplifies the control of specific CAP requirements for environmental sustainability in the agriculture sector (here specifically to maintain the land in good environmental conditions through defined mowing practices): In Estonia, companies developed the SATIKAS system using Copernicus satellite-based information to monitor mowing practices on agricultural grasslands, which reduced the need for field inspections (Copernicus, 2024; NEREUS et al, 2018). Hence, digital data spaces have the potential to reduce the bureaucratic burden on farmers and public authorities.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

- Functioning agricultural data spaces that use the full potential of gathering intelligence and learning across the sector require an increasing number of actors to participate in data sharing initiatives. Here, trust-building among partners that are exchanging potentially sensitive company information is crucial.
- In agricultural data spaces, traditional suppliers representing industrial agricultural practices are the leading actors in providing data platforms, software and decision support systems. The risk of data lock-in with a decision for a farm software and data space are driving lack of trust by farmers (Atik, 2022). It is important that decision support systems promoting sustainability in agriculture and forestry are not controlled solely by big agricultural companies but by organisations with more neutral or balanced interests.
- To promote collaboration, business models need to be developed that are attractive for all partners (Deero et al., 2023). With farm suppliers that are already dominant in agrochemicals, seeds or machinery domain providing data management solutions, the fairness of business models for data software and platforms are key to avoid one-sided dependencies.
- The EU Data Act aims to regulate the data economy to create a fair data market and support compatible European data spaces, specifically in the agriculture sector (EU, 2023). However, building trust relies on functioning law enforcement and the experience of individuals and organisations.
- Several EU projects had been carried out recently, including AgriDataSpace and Demeter[36] that both aim to build a framework for the digital transformation of the EU's agri-food sector by collecting experience with various concepts and approaches to learn from good (and bad) practice.
- The EU is acknowledged by a recent OECD study as leading the way in the digital traceability of food supply chains, enabled under alia by agricultural data spaces (Charlebois et al., 2024; Tay, 2024).

[36] See https://agridataspace-csa.eu and https://h2020-demeter.eu

A.2.9 Rising Regulatory and Consumer Demand for Higher Food Quality, Safety, and Sustainability

Summary and Key Words

Food safety, quality, and sustainability are key concerns in European agri- and aquaculture. The EU's Farm to Fork Strategy as well as new consumption patterns further drive this trend, with consumers increasingly demanding high food safety and quality – which in turn promotes sustainable, local, and transparent farming practices. In this context, the way food is produced and consumed is becoming increasingly relevant to one's social status. At the same time, individualized nutrition that addresses specific health needs and value criteria, is playing an increasingly significant role for some consumer groups. This leads to rising requirements for more transparent and traceable food chain controls and more comprehensive information on quality, health, and value dimensions.

Key words: Food safety, quality and sustainability / Supply chain transparency / Individualized nutrition

Current and Future Developments of the Trend

High-quality, safe and sustainable food are core concerns of the EU and its citizens. Poor food quality and unhealthy diets significantly impact public health, contributing to illnesses, such as obesity, non-communicable diseases, and deaths (Hau & Lange, 2023). Furthermore, a growing public awareness of sustainability, environmental issues and of animal welfare leads to demands for increasingly higher standards, including organic food and fair-trade products (Chiripuci et al. 2022). In response to these concerns, the EU's 2020 Farm to Fork Strategy seeks to develop a sustainable food architecture by minimizing environmental impact, ensuring food security, and encouraging healthy eating habits. The strategy also links to the EU's Green Deal, CAP, and the biodiversity strategy, and it is related to the 2021-2027 Organic Action Plan, which aims to promote organic production and demand. This initiative, amongst others, has led to an expansion of over 0.8 million hectares of organic farmland in the EU from 2021 to 2022, resulting in organic agriculture covering 10.4% of the agricultural area within the EU by 2022 (IFOAM, 2024).

Recent Signals within the Scope of the Trend

Healthy, Organic, Home-cooked Food Trending on Social Media

Food has long been a prominent topic on social media, significantly shaping users' shopping, eating, and cooking behaviours. A variety of platforms offer extensive information on diets, nutrition, and recipes, with a notable impact on younger, digitally native audiences (Simeone & Scarpato, 2020). The trend towards healthy, organic, and home-cooked food is particularly pronounced (Pilar et al., 2021). An analysis of the #healthyfood hashtag on Twitter (now X) from 2019 to 2020 reveals that users link healthy food with a balanced lifestyle, diet, fitness, and concepts such as veganism, homemade, and organic options (Pilar et al., 2021). Similarly, social media has increasingly elevated food to a status symbol and lifestyle indicator (Simeone & Scarpato, 2020). From YouTuber 'Freelee the Banana Girl' gaining fame in the 2010s with her raw vegan diet to TikTok star Nara Smith's rise in late 2023 with her "home cooking from scratch" content, food choices are increasingly seen as reflections of lifestyle and personal values (Butler, 2024; Lundahl, 2018). Hence, healthy, organic, and partially home-cooked content is likely to shape future food preferences, mirroring broader trends in individual approaches to diet and well-being.

Rising Number of Food Supply Chain Management Start-ups

A rising number of tech start-ups are enhancing transparency in supply chain management by enabling real-time monitoring and digitising food information from farm to fork (StartUs Insights, 2021). Key technologies driving these advancements include IoT and blockchain, that provide information to producers, retailers, consumers, and other stakeholders across various industries from crop and animal farming to seafood (StartUs Insights, 2021). For example, the French start-up Connecting Food uses blockchain to trace supply chains and provides solutions for a range of stakeholders, including consumers, by sharing production information through QR codes on packaging (Connecting Foods, 2024). Another example is Clear Farm, which employs smart farming technology to improve animal welfare in pig and dairy cattle production chains, offering data on welfare, economic, and environmental sustainability (Clear Farm, 2024). As another example, the Canadian start-up Sedna Technologies offers a seafood traceability ecosystem using IoT sensors, radio-frequency identification, and back-office digitization to enhance transparency in seafood manufacturing (Sedna Technologies, 2024). Consequently, these digital innovations enable food processors, retailers, consumers and other stakeholders to make informed decisions along the supply chain based on reliable and traceable information.

Food Watch Demands EU-wide Mandatory Front-of-pack Nutrition Labelling "Nutri-Score"

The NGO Food Watch advocates for the EU-wide adoption of a standardized nutrition label called Nutri-Score, aiming to help consumers make more informed decisions and improve their dietary habits and health (Food Watch, 2024a). As of 2023, seven European countries have voluntarily adopted the Nutri-Score label (Hau & Lange, 2023). In an open letter to the European Commission, Food Watch has called for its mandatory implementation across the EU (Food Watch, 2024a). While the effectiveness of the Nutri-Score once harmonized and adopted remains to be seen, it could be a relatively straightforward initial step towards enabling improved consumer decision-making (Hau & Lange, 2023). The advocacy around the Nutri-Score reflects both growing consumer concern over nutrition data and personalized nutrition (Chaudhary et al., 2021) as well as the powerful opposition of the agri-food industry in the European political arena over the past two decades (Food Watch, 2024b)[37]. Enabled by

[37] The European Commission proposal on mandatory Nutri-Score systems is as of April 2025 not in the Commission's work programme (Foodchain ID, 2025)

digital supply chain traceability and transparency, food-related consumer information systems are generally expected to continue to increase and evolve. However, already traditional package labelling – like highlighted here with the example of Nutri-Score – shows the difficulties and hurdles faced, such as the different interests of the food industry and consumer protection representatives, varying assessment of health, environmental impacts and their integration into one simple label design. These hurdles need to be overcome for a successful market dissemination of new food quality and health related product information that may come with digitally enabled supply chain transparency and increased traceability.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

- Digital solutions increasingly enable higher standards through innovative methods, from enhancing traceability in supply chains to optimising various aspects of production.
- Digital tools and platforms can provide comprehensive insights into food production processes from farm to fork, enabling more effective communication with business partners and end customers.
- Advances in technology allow for the collection, utilization, and analysis of vast amounts of data across the entire value chain, potentially disrupting traditional business models and significantly reducing transaction costs (Schroeder et al., 2021).
- For instance, it is expected that by 2050, an average farm will generate around 4.1 million data points per day, up from 190,000 data points per day in 2014 (Schroeder et al., 2021). Agrifood producers may increasingly be urged by the food processing industry or by retail partners to adopt tracking technologies along the supply chain to gain a competitive edge.
- Solutions from digital platforms dedicated to providing detailed supply chain data, such as the start-up Connecting Foods, may also be complemented by social media as a marketing tool for farmers and agribusinesses (Jurado et al., 2019).

A.2.10 Shift in Market Power in Agri-food and Forest Systems

Summary and Key Words

The market structure in agri-food systems is driven by market concentration in agribusinesses and in farms. In agriculture, small farms are decreasing, and the number and size of large farms are increasing. Consequently, new business models are required for small players, with rewards for environmental and climate services being one option. While in the forest sector the market structure has been relatively stable, the sector is also characterized by a high degree of diversity of players, which can make dissemination of innovation difficult. Recent developments also show that large farms and forests are more prone to integrate digital tech options, and that powerful supply chain partners and transparency and traceability requirements are driving digitalisation in farms and forests.

Key words: Agriculture market concentration / Market power balance / Carbon farming

Current and Future Developments of the Trend

The market structure in European farms is changing, while in forestry structures are more stable. Since 2005, the number of farms in Europe has decreased by 37% amounting to a loss of more the 5 million – mainly small – farms. In parallel, the largest farms (more than 100-hectare size) have been growing through land acquisition and mergers (Eurostat, 2022). This development is expected to continue, by 2040 the EU could potentially lose an estimated further 6 million farms (Schuh et al., 2022). Generational changes and operational handover play a role, as well as higher market pressure from concentration in the agribusiness and food industry. The ownership structure of European forests is different: these are owned by 16 million private (60%) and public (40%) entities with a wide variety of property sizes, almost 90% of private forests have a size of less than 10 hectares. The EU forestry ownership structure is more stable compared to farms, only the restitution of nationalised land to its former owner in some Eastern European countries is an ongoing change. Perseverance in the ownership structures is expected to continue largely unchanged. State and industrial owners actively manage their forest in line with political and business objectives, while private small-scale forests vary from altruistic motives to active management. European forests resources are growing, only 75% of annual growth is felled (Mauser, 2022).

Recent Signals within the Scope of the Trend

Concentrated Agribusiness Sector Limiting Farm Supply Choices and Sale Options – Small Farms Decline

The European Parliament sees the need to strengthen farmers' bargaining power with wholesale and retail companies, and to rebalance power in the food system (EP, 2021). Corporate concentrations in the global agri-seed and pesticide market led to only four big players (ChemChina/Syngenta Group, Bayer, Corteva Agriscience, BASF) controlling 62% of the global agricultural seed segment and 51% of the agrochemical market in 2022 (ETC Group, 2022; Omar & Thorsøe, 2023). By offering digital data platforms and expert advice systems, these corporations can potentially directly influence farmer's strategies and purchasing decisions. Also, on the downstream side of buyers of farm products, medium to high concentration in the food industry and retail sector is accelerating. Therefore, the market power of farmers is often limited (Hernandes et al., 2023). Thus, farmers are often under pressure to follow the food industry and retail partner's sales price, quality, certification, and other criteria. In addition, the key agribusiness actors maintain close relationships with governments, possibly allowing them to influence policymaking: the Farm to Fork strategy could manifest their market power according to Omar & Thorsøe (2023) – in contrast to the European Parliament's claims (EP, 2021). With small farms under pressure, both upstream and downstream, large-scale farms are likely to further grow as market structures favour intensive production and accelerate farm concentration processes (Schuh et al., 2022). Economic pressure, consumer focus on sustainability and changing business models thus drive the need for European farmers to adopt digital technologies, particularly those with large farms (i.e., larger than 800-hectares) (Fiocco et al., 2023).

Vertically Integrated Forest Companies are Lead Appliers and Developers of Digital Precision Solutions

Companies with vertically integrated operations spanning forestry to secondary wood-based products are unique, as they are large forest owners with a direct impact on forest management, and they integrate forestry into a complex value chain. Three such European companies are Stora Enso, a Finnish timber company that is one of the world's largest private forest owners, Holmen and Svenska Cellulosa, both Swedish timber companies that together own around 3 million hectares of forests in Sweden (Charrey, 2023). Their integrated value chains cover downstream activities, including the manufacturing of wood products for construction and paper and packaging. Hence, they are well-positioned to measure the carbon flows across their value chain, from carbon sequestration in their forests to product storage, providing insights into the net carbon impact of their diversified businesses in forestry (Charrey, 2023). In addition, these large integrated companies can more easily adopt digital solutions: they use digitalisation strategically in their industry manufacturing processes and must manage vast forest land; therefore, they often are more open, more capable and have a high need to use technology and digitalisation in their forest management (Holmström, 2020; Feng & Audy, 2020). For example, Stora Enso uses satellite imagery, drones, LiDAR[38] and on-ground sensing to have detailed insights into the health of their forests; furthermore, they use forest's Digital Twin for precision forestry and co-develop specific solutions for forest management (Stora Enso, 2023).

Increasing Influence of Food Companies and Fossil Fuel Energy Companies on Farms through Carbon Markets

Carbon farming is seen by the EU as a business model for farmers and land managers for implementing defined land management options (EC, 2021e). On the one hand, farmers and forest owners can receive area-based CAP payments for climate commitments, on the other hand they can receive results-based incentives for carbon stored in the soil and in plants by earning marketable carbon credits (EC, 2021d & 2021e). In recent years, there is increasing competition for carbon credits among different sectors, particularly between agriculture and fossil fuel industries, and agribusinesses are advocating for preferential access to agriculture and forestry carbon farming credits, aiming to ensure they can meet their emissions reduction targets without being outbid by other industries (Scherger, 2022). Energy utilities, particularly those in fossil fuel sectors, have already been strategically investing in carbon farming projects as part of their corporate social responsibility (CSR) strategies or sustainability initiatives and

[38] LiDAR is Light Detection and Ranging is an active remote sensing technology like radar, but using light and laser technology instead of radio or microwaves. It allows detailed 3D mapping of forest structure and height, tracking health. It can be used on the ground and in the air, e.g. using drones as well as on satellites.

to offset their carbon emissions from their core business. Energy utilities often collaborate with agribusinesses and other stakeholders to develop carbon farming initiatives (Scherger, 2022).[39] Hence, farmers and forestry owners can benefit from cooperation with big corporations, like monetising climate mitigation outcomes, or getting access to carbon certification schemes, but can also be put under pressure regarding how and what to do on their land.

Implications for Digitalisation of Agriculture and Forestry in Europe

What impacts do these developments and signals have on the agriculture and forestry sectors and their digital transformation? Drawing from past experiences, the following implications for agriculture and forestry and digitalisation in the sectors could also be expected in the mid- to long-term future.

- With large farms and forests, there is a higher need to use digital tools in farm management to enable a better overview of the health of crops, livestock and forests (Fiocco et al., 2023). Furthermore, large farms tend to have a higher degree of specialization in the workforce and can employ highly trained specialists in charge of introducing and maintaining digital technologies and training colleagues (McFadden et al., 2022).
- While Europe and North America are leaders in digital agriculture technologies adoption (Fiocco et al., 2023), in Europe, 62% of farmers are currently, as of 2023, using or planning to use digital agriculture technologies in the following two years[40], according to a McKinsey survey from 2022 (Fiocco et al., 2023).
- The strong market pressure from up- and downstream agribusiness market partners – upstream suppliers offer digital data sensing and software in their products and services, and downstream customers demand specific information that defines the criteria for traceability and transparency of products – can drive the application of digital technologies to provide supply chain transparency, provide certification requirements for specific farming practices or quality standards, and enter market platforms to increase customer relationships.
- Small farms need to be highly innovative and diversify their business model to survive the market shakeout. Digital tools can help to communicate and sell directly to consumers and offer non-food products and services.

[39] For example, The World Economic Forum launched in 2021 its ‘Carbon+ Farming Coalition’ – which is no more visible in 2024 – advocating for climate-smart farming with partners from agribusiness, energy and insurance corporations and some others (World Economic Forum, 2022; DeSmog, 2022).
[40] mainly farm management software and remote sensing

Annex 3: Cross-cutting trend implications for digitalisation

Table 3 : Overview of cross-cutting trend implications for digitalisation compared with the state of play and market estimates (Source: Future Impacts)

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
Digital solutions for monitoring Includes: • Monitoring of agricultural and forestry production • Monitoring of risks for agricultural and forestry production (pest control, diseases, wildfires, etc.) • Monitoring of environmental status and ecosystem challenges	• Adapting agricultural practices to sustain yields and competitiveness requires **reliable, multi-scale monitoring** (linked to trends[43] such as *Glocalisation, Trade, Tech to deal with climate stress, Land scarcities, Controlled environments*)**.** This includes both large-scale and site specific, combining long-term data (e.g., climate trends, forest stock) with short-term metrics (e.g., soil moisture). • **Early warning systems** - incorporating wildfire warning, pest and disease monitoring or drought forecasts - are increasingly essential to address emerging environmental threats (as reflected in trends such as *Land scarcity, Biodiversity loss, Controlled environment, Forestry and digitalisation*). • **Monitoring is vital for identifying and validating sustainable land-use opportunities**, such as carbon farming, nature restoration, and eco-friendly practices (reflected in trends such as *Future of CAP, Biodiversity loss,*	• **Policy frameworks mandate monitoring for funding and sustainable management** e.g., CAP policies require monitoring and performance tracking; EU and national forest strategies call for remote sensing and forest mapping. • Monitoring technologies and data sources are essential for forest monitoring and climate risk assessment. • EU land managers rely on a **diverse set of monitoring data sources**, including e.g., satellite and drone imagery, LiDAR data, IoT sensor data outputs, climate data and spatial information.	The use of **recoding / mapping technologies** (remote and ground sensing in agriculture) is expected to grow from 3% penetration rate in 2025 to 13% in 2040. The subcategories remote sensing hardware and ground sensing software are both expected to reach 35% market penetration by 2040. The use of **remote sensing technologies** in forestry is expected to grow in hardware like drones and UAVs from 4% today to 17% in 2040 and in

[41] This table refers to the Chapter 3
[42] Indicator used is the penetration rate, defined as the proportion of the market that has been realised, i.e. how much of the addressable market is covered by the installed base.
[43] Trend names mentioned in italics are short titles, Table 3 gives an overview of short and long titles.

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
	Consumer demand, Market power shifts, Forestry and digitalisation). • Effective and equitable use of **monitoring data depends on quality, interpretation, and access and requires specialized tools and skills** such as data validity proofing, developing of data interfaces and geographical sensemaking and interpretation.		the remote sensing software from 5% today to 35% in 2040. The use of **field survey** technologies in forestry is expected to grow in hardware like soil, moisture, weather sensors from 6% today 29% in 2040 and for GIS software from 5% today to 23% in 2040.
Simulation and prediction Includes: • Market modelling • Virtual simulations for farms, forests and operational processes (Digital twins) • Virtual simulation and experimenting in research and development • Predictive maintenance of machines	• **Simulation and prediction are increasingly vital to anticipate developments** in food and wood markets, as well as supplier markets for agrochemicals, seeds and feed (as reflected in trends such as *Glocalisation, Trade, Market power shift, Tech alliances, Generative AI, Post-war enlarged EU, Forestry and digitalisation*). • **Predictive insights** for growth cycles and adaptation needs like **crop simulation models** that account for micro-climate conditions are gaining importance due to changing climate conditions, extreme events, and emerging pests and diseases (see the trends *Land scarcity, Tech to deal with climate stress, Legal subjects, Forestry and digitalisation, Controlled environment, Data spaces*). • **Virtual simulations** of farms and forests (digital twins) based on monitoring and operational data—are emerging,	• AI-driven analytics are widely applied, with yield prediction, disease detection, forest growth modelling, and supply chain optimisation among the most common digital solutions. • **Crop modelling, combined with precision agriculture tools**, is increasingly used to optimise fertilizer and pesticide management. • Digitalisation significantly **enhances innovation capacities**, including the development of new tools and services and smart	There is no specific 4Growth technology category related to this function; they are covered by the digital solutions that translate the findings for decision making (FMIS, DSS)

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
	but **broader use requires better data quality and system understanding.** • Research and development is accelerating through computer models **that simulate laboratory experiments**, enabling faster and more efficient innovation. For example, breeding experiments using genetic databases and **AI-enabled biodesign** are advancing synthetic biology and speeding up development processes. There is a growing need for plants and livestock adapted to changing climates and capable of withstanding extreme events. • Reliable machineries are essential, as operating windows depend on growth cycles and weather conditions (see trends Market power shifts, Tech alliances, Alternatives to market driven models, Data spaces, Land scarcity, Biodiversity loss, Forestry and digitalisation etc.). **Predictive maintenance of connected machinery supports business continuity**.	specialization strategies based on predictive analytics to better align production with market demands.	
Decision support for management of agricultural and forestry systems Includes: • Operational decision support for precision farming & forestry	• **Decision support and planning tools** powered by IoT and AI enhance efficiency by reducing fertilizer use, improving yields through optimized cultivation, and supporting climate-smart practices (reflected in trends such as *Glocalisation, Trade, Market power shift, Tech alliances, Tech to deal with climate stress, Post-war enlarged EU, Forestry and digitalisation, Alternatives to market driven models, Processing industry innovation, Consumer demands, Gender equality*). Industry 4.0 technologies, already used in controlled environment farms and bioreactors, hold potential for **wider application in outdoor farming and forestry.**	• **Farm management records** are among the types of data most frequently used by European farmers and forestry operators, next to monitoring data. • Farmers and forestry operators see the benefit in **data-driven decision support tools that enable yield and quality improvements**. They support enhanced crop planning, enable	The use of **Farm Management Information Systems** is expected to grow from 2% penetration rate in 2025 to 10% in 2040. The use of **Decision Support Systems** in forestry is expected to grow from 10% today to 65% in 2040.

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
• Improve operational and administrative processes • Decision support to innovate practices, transform the business	• Digitalisation of farm administration is increasingly essential for **automated documentation and reporting,** ensuring legal compliance and supply chain transparency for clients and consumers. • **Supply chain tracking** is becoming crucial for quality assurance in sensitive sectors like infant nutrition, elderly care, pharmaceuticals, and specialised construction materials (highlighted by trends such as *Future of CAP, New subjects in legislation, Processing industry innovation, Market power shifts, Consumer demands*). It demands **reliable recording and tracing of input quality, composition, and management of production and logistics.** • **Inter-firm and cross-area learning**, based on shared data of farm and forestry processes, can accelerate innovation and improve practices. However, to avoid focusing only on industrialised methods, it's important to address potential biases that overlook less digitalised smallholders, specialised crops, and agroecological approaches.	timely interventions, and optimise harvest scheduling. • AI-driven decision support platforms are increasingly used to raise productivity, sustainability and climate resilience. • Cloud and blockchain technologies are used for **data traceability, transparency and secure exchange in agricultural value chains**, as well as AI-driven analytics for supply chain optimisation.	
Automation & robotics Includes: • Automation for more efficient processes • Automation to simulate ecological functions	• **Precision farming and forestry are increasingly important to optimise reduce use—**water, fertilizer, pesticides—reducing costs, import dependence, and environmental impact (driven by the *Glocalisation, Trade, Market power shift, Tech alliances, Tech to deal with climate stress, Post-war enlarged EU, Forestry and digitalisation, Alternatives to market driven models, Processing industry innovation, Consumer demands, Gender equality*).	• **Precision agriculture tools** are among the most commonly and actively used, delivering co**st reduction, resource optimisation,** higher yields, and labour efficiencies. **Automation and robotics** are especially common in dairy and horticulture to **support labour savings**.	The use of **Variable Rate Technologies (VRT)** is expected to grow from 2% penetration rate in 2025 to 6% in 2040; the subcategory **map-based VRT** performs better: respective hardware will reach 10% and of software 16% penetration by 2040.

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
• Automation to support & enhance workforce and substitute workforce gaps	• **Autonomous machines inspired by nature**— such as soft robots, swarm robots like robot bees, and bat-like drones for insect control— are emerging. They support manual work and reduce pesticide use by enabling targeted weed identification and automated weeding (driven by trends like *Forestry & Digitalisation, Tech alliances, Tech to deal with climate stress, Consumer demands, Gender equality)*. • **Sensors and actuators tailored for crops and livestock** are rapidly advancing, enabling support or substitution of labour in tasks like planting, pest control, growth monitoring, and harvesting. **Augmented Reality** can assist untrained workers with agricultural tasks and basic maintenance of machinery software and hardware (as highlighted in the trends *Post-war enlarged EU, Market power shifts, Alternatives to market driven models*). • **Precision farming** must evolve from managing uniform environments to **adapting multifaceted, multifunctional fields and forests.** Climate-smart, biodiversity-friendly practices on healthy soils will increasingly involve multipurpose uses like strip farming, agrivoltaics, forest pastures, and nature-based solutions (as highlighted in the trends *Biodiversity loss, Gender equality, Land scarcity, Forestry & digitalisation)*.	• **Precision field data from sensors are crucial but often proprietary**, leading to limited data sharing by farmers and forestry operators. • Observatories recognise that **streamlined data access and improved sharing** are essential to unlock full benefits like precision input management.	The use of **Guidance and Controlled Traffic Farming** is expected to grow from 10% penetration rate in 2025 to 56% in 2040 The use of **Robotics and Smart Machines** is expected to grow from 3% penetration rate in 2025 to 25% in 2040; milking robots are expected to reach 90%, planting robots 50% and harvesting robots 42% market penetration by 2040.
Communication and Market Integration Includes:	• **Direct sales platforms** are expanding, allowing farmers and forestry operators to connect directly with consumers and market partners. This also enables producers to **tailor their output to specific demands (**as reflected in *Market*	• **Strong incentives for data sharing** include regulatory compliance, supply chain optimisation, and faster innovation	There is no specific 4Growth technology category related to this function, they are covered by FMIS and DSS

Technology Functions	Cross-cutting[41] Trend Implications for Digitalisation of Agriculture and Forestry in Europe up to 2040	State of play of using digital solutions in European agriculture and forestry: Results from the Observatories	State of technology use today (in 2025[42]) and baseline estimations for 2040 in EU 27 (market penetration - MMFT results)
• Supply chain communication • Sales and supply platforms • Sharing platforms • Knowledge sharing & innovation	*power shifts, Glocalisation, Trade, consumer demand, Gender equality, Alternatives to market driven models, Processing industry innovation)*. • Direct consumer access crates **new business opportunities like community-based farming, with new forms of co-production** and an intensified level of customer loyalty and interaction (as mentioned in the trends *Future of CAP, Tech to deal with climate stress, Market power shift*). Carbon markets enable collaboration between agriculture, forestry, energy providers, and energy intensive industries, etc.	acceleration. **Barriers** such as technical integration issues and lack of trust limit widespread data exchange. • Observatories suggest the promotion of open innovation ecosystems and clear data sharing norms. • Digital technologies catalyse innovations, like new service models, research collaborations, and agritech entrepreneurship.	

References

Abbas, F., & Taeihagh, A. (2024). Unmasking deepfakes: A systematic review of deepfake detection and generation techniques using artificial intelligence. Expert Systems With Applications, 252, 124260. https://doi.org/10.1016/j.eswa.2024.124260

Accenture. (2018). Artificial Intelligence, Genuine Impact: Public Services in the Era of Artificial Intelligence. Accenture. https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-additional-pages-1/pdf/pdf-75/accenture-ai-genuineimpact-pov-final-uk.pdf

Accenture. (2025). A Data-driven Approach to Global Reforestation. Accenture. https://www.accenture.com/us-en/case-studies/cloud/a-data-driven-approach-to-global-reforestation

Adamovic, M., Bisselink, B., De Felice, M., De Roo, A., Dorati, C., Ganora, D., Medarac, H., Pistocchi, A., Van De Bund, W. & Vanham, D. (2019). Water - Energy Nexus in Europe. https://10.2760/968197

Adelphi. (2023). Rebuilding Ukraine: A green post-war recovery. https://adelphi.de/en/news/rebuilding-ukraine-a-green-post-war-recovery

Adkins, M., & Potey, V. (2020). Decarbonizing Shipping: A Digital Approach. Roland Berger. https://www.rolandberger.com/en/Insights/Publications/Sustainable-Shipping.html

Agarwal, M., Madsen, R., & Malivert, L. (2022). ZS in Pune switches to 100% renewable energy. ZS. https://www.zs.com/life-at-zs-insights/zs-in-pune-switches-to-100-renewable-energy

agrathaer GmbH & Leibniz Centre for Agricultural Landscape Research (2017). Alternative Netzwerke zur Nahrungsmittelversorgung an der Schnittstelle zwischen Stadt und Land, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccv/2017/FutureFoodCommons-Alternative-Netzwerke-zur-Nahrungsmittelversorgung.pdf&ved=2ahUKEwit3OS46cqNAxUdSvEDHbO6MMQQFnoECBUQAw&usg=AOvVaw0DBdbd7T4Bruz9xBqczTVB

Agrawal, A., Khavkin, M., & Slonim, J. (2020). Bringing a real-world edge to forecasting. McKinsey & Company. https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/bringing-a-real-world-edge-to-forecasting

Albaladejo Román, A. (2024). Ukrainian agriculture: From Russian invasion to EU integration. Briefing. Members' Research Service, PE 760.432 – April 2024. European Parliamentary Research Service (EPRS). https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/760432/EPRS_BRI(2024)760432_EN.pdf

Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S., & Rounsevell, M. D. A. (2023). High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. Nature Food, 4(1), 84–95. https://doi.org/10.1038/s43016-022-00659-9

Alexandrova-Stefanova, N., Mroczek, Z.K., Nosarzewski, K., Audouin, S., Djamen, P., Kolos, N. & Wan, J. (2023). Harvesting change: Harnessing emerging technologies and innovations for agrifood systems transformation – Global foresight synthesis report. Rome. FAO and Cirad. https://doi.org/10.4060/cc8498en

Ali, B. (2025). Where do Trump's tariffs leave global ag markets? Agri Investor. https://www.agriinvestor.com/where-do-trumps-tariffs-leave-global-ag-markets/

Alwahaidi, K. (2024, February 22). Lab-grown meat could be the future of food — but possibly not in our lifetimes: experts. CBC. https://www.cbc.ca/radio/thecurrent/lab-grown-meat-could-be-the-future-of-food-but-possibly-not-in-our-lifetimes-experts-1.7121578

American Forest Management. (2025). Best Management Practices in Forestry | Protecting Water & Soil. American Forest Management. https://www.americanforestmanagement.com/news/what-are-best-management-practices

American Forest Management. (2025). Complete Land Management Plans & Services | AFM. American Forest Management. https://www.americanforestmanagement.com/services/land-management

American Forest Management. (2025). Forest Carbon Management Services. American Forest Management. https://www.americanforestmanagement.com/services/forest-carbon

American Forest Management. (2025). Forest Certification Support | American Forest Management. American Forest Management.https://www.americanforestmanagement.com/services/forest-certification

American Forest Management. (2025). New Opportunities for Landowners in the Forest Carbon Market. American Forest Management. https://www.americanforestmanagement.com/news/new-opportunities-for-landowners-in-the-forest-carbon-market

Amplify (2025). Autonomous Agriculture: How AI and Robotics Are Transforming Food Production. https://amplyfi.com/blog/autonomous-agriculture-how-ai-and-robotics-are-transforming-food-production/

Anderson, J. T., & Song, B. (2020). Plant adaptation to climate change—Where are we? Journal of Systematics and Evolution/Journal of Systematics and Evolution, 58(5), 533–545. https://doi.org/10.1111/jse.12649

Araújo, R., & Koessler, L. (2021). The rise of the constitutional protection of future generations. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3933683

Arcadis. (2021). The Arcadis Global Sustainability Strategy 2021-2023. https://www.arcadis.com/-/media/project/arcadiscom/com/investors/2020/strategy-update-and-capital-markets-day-2020/1arcadis-2021-2023-sustainability-strategy.pdf

Arcadis. (2025). Urban forests in Paris. https://www.arcadis.com/en-ca/projects/europe/france/forets-urbaines-a-paris

Arcuri, S. (2023). Digitalisation in rural areas. SHERPA Position Paper. DOI: 10.5281/zenodo.7773476

Astill, J., Dara, R. A., Campbell, M., Farber, J. M., Fraser, E. D., Sharif, S., & Yada, R. Y. (2019). Transparency in food supply chains: A review of enabling technology solutions. Trends in Food Science & Technology, 91, 240–247. https://doi.org/10.1016/j.tifs.2019.07.024

Atik, C. (2022). Towards comprehensive European agricultural data governance: Moving beyond the "data ownership" debate. IIC-International Review of Intellectual Property and Competition Law, 53(5), 701-742. https://doi.org/10.1007/s40319-022-01191-w

Atkinson, J. T., Su, L., Zhang, X., Bennett, G. N., Silberg, J. J., & Ajo-Franklin, C. M. (2022). Real-time bioelectronic sensing of environmental contaminants. Nature, 611(7936), 548–553. https://doi.org/10.1038/s41586-022-05356-y

Aurand, E. R., Moon, T. S., Buan, N. R., Solomon, K. V., & Köpke, M. (2024). Addressing the climate crisis through engineering biology. Npj Climate Action, 3(1). https://doi.org/10.1038/s44168-023-00089-8

Aznar Cano, I. (2024). The EU Deforestation Regulation: Getting started now. PwC. https://www.pwc.com/gx/en/issues/esg/eu-deforestation-regulation.html

Bailey, R., Davis, J., & Liu, L. (2022). Now For Nature: The Decade of Delivery. Oliver Wyman & CDP. https://www.oliverwyman.com/our-expertise/insights/2022/mar/now-for-nature.html

Barabanova, Y. & Krzysztofowicz, M. (2023). Digital Transition: Long-term Implications for EU Farmers and Rural Communities. doi:10.2760/286916

Barrett, C. B., Beaudreault, A. R., Meinke, H., Ash, A., Ghezae, N., Kadiyala, S., Nigussie, M., Smith, A. G., & Torrance, L. (2021). Foresight and trade-off analyses: Tools for science strategy development in agriculture and food systems research. Q Open, 1(1). https://doi.org/10.1093/qopen/qoaa002

Basavegowda, N., & Baek, K. (2021). Current and future perspectives on the use of nanofertilizers for sustainable agriculture: the case of phosphorus nanofertilizer. 3 Biotech, 11(7). https://doi.org/10.1007/s13205-021-02907-4

Bayer. (2023). Bayer demonstrates digital technologies as a key enabler for regenerative agriculture. https://www.bayer.com/media/en-us/bayer-demonstrates-digital-technologies-as-a-key-enabler-for-regenerative-agriculture/

Bayer. (2024). Bayer Pilots Unique Generative AI Tool for Agriculture. Global AgTech Initiative. https://www.globalagtechinitiative.com/digital-farming/bayer-pilots-unique-generative-ai-tool-for-agriculture/

Behounek, J. (2018). Technology in Urban Forestry. The Davey Tree Expert Company. https://www.davey.com/environmental-consulting-services/resources-news/technology-in-urban-forestry/

Bertelsmann Stiftung. (ed.), Daheim, C., Jöster-Morisse, C., Störmer, E., Trier, E., Wintermann, B. & Wintermann, O. (2025). Advancing the Circular Economy in Germany and the EU: Policies, Perspectives and Pathways. DOI: 10.11586/2025003. https://www.bertelsmann-stiftung.de/en/publications/publication/did/advancing-the-circular-economy-in-germany-and-the-eu-policies-perspectives-and-pathways

Bijapurkar, A., Vasudevan, S., Naik, H., Kunte, H., Adhia, V., Nagano, Y., Suematsu, T., Natsumi, K., Hirari, S., & Suzuki, S. (2024). Forest Stack: Transforming Forest Conservation and Management Through Digital Public Infrastructure. Boston Consulting Group & Japan

International Cooperation Agency. https://www.bcg.com/publications/2024/india-forest-stack-digitally-transforming-forest-management

Bishop, P. (2009). Horizon Scanning. Why is it so hard? https://law.uh.edu/faculty/thester/courses/Emerging%20Tech%202011/Horizon%20Scanning.pdf

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., Feyen, L., & de Roo, A. (2020). Climate change and Europe's water resources. https://doi.org/10.2760/15553

Biswas, P., Mondal, S., Maji, S., Mondal, A., & Bandopadhyay, P. (2023). Microclimate Modification in Field Crops: A way toward Climate-Resilience. In Springer eBooks (pp. 647–666). https://doi.org/10.1007/978-3-031-37424-1_29

Biswas, S. (2023). Why India's rice ban could trigger a global food crisis. BBC. https://www.bbc.com/news/world-asia-india-66360064

Blaustein-Rejto, D. & Gambino, C. (2023, March 21). Livestock don't contribute 14.5% of global greenhouse gas emissions. The Breakthrough Institute. https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions

Borges, C., Gupta, K & Palazzi, A.L. (2024). Geoeconomics Bi-Weekly: Geopolitical Tensions Continue to Shape Global Trade. CSIS.https://www.csis.org/analysis/geoeconomics-bi-weekly-geopolitical-tensions-continue-shape-global-trade

Bradley, C., Chui, M., Russel, K., Ellingrud, K. Birshan, M., & Chettih, S. (2024). The next big arenas of competition. https://www.mckinsey.com/mgi/our-research/the-next-big-arenas-of-competition#ai-software-and-services

Bredehöft, C. & Zimmermann, J. (2022). Machinery rings – an innovative approach to mechanising Kenyan agriculture. Rural21. https://www.rural21.com/english/news/detail/article/machinery-rings-an-innovative-approach-to-mechanising-kenyan-agriculture.html

Brennan, S., Bravo Gonzalez, R., Puzniak-Holford, M., Kilsby, R., Subramoni, A., & Haka, E. (2025). EU 2025 Sustainability Regulation Outlook: Unlocking competitiveness and growth. Deloitte Insights. https://www2.deloitte.com/us/en/insights/environmental-social-governance/eu-2025-sustainability-regulation-outlook.html

Bria, F. Timmers, P., Gernone, F. (2025). EuroStack – A European Alternative for Digital Sovereignty. Bertelsmann Stiftung. Gütersloh. https://www.bertelsmann-stiftung.de/en/publications/publication/did/eurostack-a-european-alternative-for-digital-sovereignty

British Broadcasting Corporation (BBC). (2014). Algorithm appointed board director. https://www.bbc.com/news/technology-27426942

Bromfield, P., Highfield, C., & McGrath, G. (2024). Will Consolidation in Landscaping Services Take Root? Executive Insights. L.E.K. Consulting. https://www.lek.com/sites/default/files/insights/pdf-attachments/will-consolidation.pdf

Brown, E. (2025). The Baltic Sea at a Boil: Connecting the Shadow Fleet and Episodes of Subsea Infrastructure Sabotage. https://carnegieendowment.org/research/2025/06/baltic-russia-maritime-cable-sabotage

Brunori, A., Brunori, G., Casares, B. & Nieto, E., (2021). Key digital game changers shaping the future of forestry in 2040. Desira. https://sisef.org/wp-content/uploads/2021/09/DESIRA_LTVRA_Forestry_fv.pdf

Brunori, G., Bacco, M., Puerta-Piñero, C., Borzacchiello, M. T., & Stormer, E. (2025). Agri-Food Data Spaces: highlighting the Need for a Farm-Centered Strategy. Data in Brief, 59, 111388. https://doi.org/10.1016/j.dib.2025.111388

BSI, Federal Office for Information Security. (2025). Generative AI Models. Opportunities and Risks for Industry and Authorities. https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/KI/Generative_AI_Models.html

Budzyńska, A. & Durakiewicz, M. (2024). The role of food trade in the European Single Market in the years 2000-2022. Agronomy Science. 79. 101-112. 10.24326/as.2024.5295.

Business Wire. (2024). Syngenta Group Adds Cutting-Edge Generative Artificial Intelligence (GenAI) to Cropwise. https://siliconcanals.com/syngenta-group-adds-cutting-edge-generative-artificial-intelligence-genai-to-cropwise/

Butler, S. (2024). Who is Nara Smith and why are her recipes going viral? Indy100.https://www.indy100.com/tiktok/nara-smith-tiktok-recipes

Buxel, H. (2024). My Food – Personalisation and Nutrition. DLG Study Part 1: Personalised Food. https://www.dlg.org/en/mediacenter/alle-publikationen/dlg-studien/my-food-personalisation-and-nutrition/my-food-personalisation-and-nutrition-study-part-1

Cach-Pérez, M. J., López, G. V., Gamboa, J. a. A., Toral, J. N., & Lugo, F. C. (2021). Microclimate management: From traditional agriculture to livestock systems in tropical environments. In Springer eBooks (pp. 1–29). https://doi.org/10.1007/978-3-030-71571-7_1

Cagnin, C., Muench, S., Scapolo, F., Stoermer, E., & Vesnic Alujevic, L. (2021). Shaping and securing the EU`s Open Strategic Autonomy by 2040 and beyond, https://dx.doi.org/10.2760/414963

Campbell, C. (2024). Navigating the Future of Controlled Environment Agriculture (CEA). The Food Institute. https://foodinstitute.com/focus/navigating-the-future-of-controlled-environment-agriculture-cea/

Capgemini India. (2024). Solving biodiversity challenges with AI-powered platform. Capgemini. https://www.capgemini.com/in-en/news/inside-stories/solving-biodiversity-challenges-with-ai-powered-platform/

Capgemini Invent. (2025). Deforestation, meet transparency: How regulation is reshaping global markets. Capgemini. https://www.capgemini.com/fi-en/wp-content/uploads/sites/26/2025/03/EUDR-Deforestation-meets-Transparency-Report.pdf

Capgemini Sweden. (2025). The TREEADS project: innovation and technology for forest fire prevention, detection, and restoration. Capgemini. https://www.capgemini.com/se-en/news/treeads-project-innovation-and-technology-for-forest-fire-prevention-detection-and-restoration/

Capgemini. (2020). Capgemini supports the European Space Agency in the exploration of forest biomass from space. Capgemini. https://www.capgemini.com/news/press-releases/capgemini-supports-the-european-space-agency-in-the-exploration-of-forest-biomass-from-space/

Capgemini. (2021). AI 4 Environment - Towards Sustainable Territories: How can Artificial Intelligence help achieve Environmental Goals?. Capgemini. https://www.capgemini.com/wp-content/uploads/2022/08/AI4Environment_Brochure.pdf

Capgemini. (2025). Discussion: AI for Good – let's protect our forests. Capgemini. https://www.capgemini.com/insights/research-library/ai-for-good-lets-protect-our-forests/

Capgemini. (2025). Sogeti Sweden leverage AI to hunt spruce bark beetles. Capgemini. https://www.capgemini.com/news/client-stories/sogeti-sweden-leverage-ai-to-hunt-spruce-bark-beetles/

Capgemini. (2025). Tech for growing urban forests: Using data to increase biodiversity and combat climate change. Capgemini. https://www.capgemini.com/news/inside-stories/tech-for-growing-urban-forests/

Center for Democratic and Environmental Rights. (2025). Rights of Nature Law Library. https://www.centerforenvironmentalrights.org/rights-of-nature-law-library

Chang, F.K. (2019). Pork Apocalypse: African Swine Fever and the U.S.-China Trade War. https://www.fpri.org/article/2019/12/pork-apocalypse-african-swine-fever-and-the-u-s-china-trade-war/

Charlebois, S., Latif, N., Ilahi, I., Sarker, B., Music, J., & Vezeau, J. (2024). Digital traceability in Agri-Food Supply Chains: A Comparative analysis of OECD member countries. Foods, 13(7), 1075. https://doi.org/10.3390/foods13071075

Charrey, S. (2023). Sector Fundamentals – Integrated Forestry and Wood-Based Product Manufacturers. https://timberfinance.ch/en/sector-fundamentals-integrated-forestry/

Chatham House. (2023). The emerging global crisis of land use. Report Environment and Society Centre. November 2023. https://www.chathamhouse.org/sites/default/files/2023-11/2023-11-22-emerging-global-crisis-land-use-king-et-al.pdf

Chaudhary, N., Kumar, V., Sangwan, P., Pant, N. C., Saxena, A., Joshi, S., & Yadav, A. N. (2021). Personalized Nutrition and -Omics. In Elsevier eBooks (pp. 495–507). https://doi.org/10.1016/b978-0-08-100596-5.22880-1

Ching, X. L., Zainal, N. a. a. B., Luang-In, V., & Ling, N., MA. (2022). Lab-based meat the future food. Environmental Advances, 10, 100315. https://doi.org/10.1016/j.envadv.2022.100315

Chiripuci, B., Popescu, M., & Marius, C. (2022). The European consumers' preferences for organic food in the context of the European Green Deal. Amfiteatru Economic Journal, 24(60), 361–378. https://doi.org/10.24818/EA/2022/60/361

Chlouveraki, E. & Kasimati, A. (2025a). D2.3: Analysis of the state-of-the-art - Draft. (forthcoming)

Chlouveraki, E. & Kasimati, A. (2025b). D4.13 – Framework Conditions and Impact Analysis – Draft. (forthcoming)

Chopra, N. (2023). Fuel, food, and fertilizer: The Interwoven Impacts of the Russia-Ukraine War. Kleinman Center for Energy Policy. https://kleinmanenergy.upenn.edu/news-insights/fuel-food-and-fertilizer-the-interwoven-impacts-of-the-russia-ukraine-war/

Choudhry, H., & O'Kelly, G. (2018). Precision forestry: A revolution in the woods. McKinsey & Company. https://www.mckinsey.com/industries/packaging-and-paper/our-insights/precision-forestry-a-revolution-in-the-woods

Chu, J. (2023). Desalination system could produce freshwater that is cheaper than tap water. MIT News. https://news.mit.edu/2023/desalination-system-could-produce-freshwater-cheaper-0927

Chui, M., Hazan, E., Roberts, R,. Singla, A., Smaje, K., Sukharevsy, A., Yee, L., & Zemmel, R. (2023). The economic potential of generative AI. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-economic-potential-of-generative-ai-the-next-productivity-frontier#/

Ciruela-Lorenzo, A. M., Del-Aguila-Obra, A. R., Padilla-Meléndez, A., & Plaza-Angulo, J. J. (2020). Digitalization of Agri-Cooperatives in the Smart Agriculture Context. Proposal of a Digital Diagnosis Tool. Sustainability, 12(4), 1325. https://doi.org/10.3390/su12041325

Claas. (2024). DataConnect. https://international-hrc.claas.com/cl-pw-en/products/digital-solutions/data-management/data-connect

Claughton, D. & Beilharz, N. (2021). JBS Foods pays $14.2 million ransom to end cyber attack on its global operations, ABC. https://www.abc.net.au/news/rural/2021-06-10/jbs-foods-pays-14million-ransom-cyber-attack/100204240

Clear Farm. (2024). https://www.clearfarm.eu/the-project/

Climate. (2024). Climate FieldView. https://climate.com

Confederation of European Paper Industries (CEPI) (2024). Key Statistic 2023. European pulp & paper industry. https://www.cepi.org/wp-content/uploads/2024/09/Key-Statistics-2023-FINAL-2.pdf

Connecting Foods. (2024). https://connecting-food.com/

Convention on Biological Diversity (2022). Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Copernicus. (2023). OBSERVER: How Copernicus helps implement the CAP. https://www.copernicus.eu/en/news/news/observer-how-copernicus-helps-implement-cap

CORA. (2021). Boosting the Delivery of Digital Infrastructures in Rural Areas. https://ruraldigital.eu/wp-content/uploads/2021/12/211201_CORA_Policy-Brief_2.pdf

Cornago, E. (2025). The EU budget in a larger Union: Key issues and open questions. CER Insight. https://www.cer.eu/insights/eu-budget-larger-union-key-issues-and-open-questions

Costenaro, A. (2025). FieldView: scale without selling the software. Lessons from Agtech. https://www.linkedin.com/pulse/fieldview-scale-without-selling-software-andré-costenaro-5cbsf/

Cuhls, K. E. (2019). Horizon Scanning in Foresight – Why Horizon Scanning is only a part of the game. Futures & Foresight Science, 2(1). https://doi.org/10.1002/ffo2.23

Darvas, Z. & Mejino-Lopez, J. (2024). What enlargement could imply for the European Union's budget. Bruegel. https://www.bruegel.org/analysis/what-enlargement-could-imply-european-unions-budget

Davidson, J. (2018). Bayer, Monsanto and Big Data: Who will control our food system in the era of digital agriculture and mega-mergers? Friends of the Earth. https://foe.org/blog/bayer-monsanto-digital-agriculture/

De Clercq, M., D'Haese, M., & Buysse, J. (2023). Economic growth and broadband access: The European urban-rural digital divide. Telecommunications Policy, 47(6), 102579. https://doi.org/10.1016/j.telpol.2023.102579

Deero, E. & Maes, E. (2023). D1.1: Up-to-date online inventory. AgriDataspace. https://agridataspace-csa.eu/wp-content/uploads/2024/07/AgriDataSpaceDeliverable_D1.1_Reviewed_V1.pdf

Deloitte AI Institute. (2021). Seeing the forest for the trees, and the forests beyond: The future of AI. Deloitte AI Institute. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/process-and-operations/us-ai-institute-future-of-ai.pdf

Deloitte Insights. (2023). Stora Enso fosters sustainability through digital transformation. Deloitte Insights. https://www2.deloitte.com/us/en/insights/focus/tech-trends/2023/digitalization-and-sustainability.html

Deloitte, World Economic Forum & NTT Data. (2024). Climate-smart and regenerative agriculture: Transitioning towards sustainable farming. Deloitte US. https://www2.deloitte.com/us/en/insights/focus/climate-and-sustainability/climate-smart-agriculture-sustainable-farming.html

Demertzis, M. (2023). De-risking as an economic strategy. https://www.bruegel.org/comment/de-risking-economic-strategy

Demestichas K, Peppes N, & Alexakis T. (2020). Survey on Security Threats in Agricultural IoT and Smart Farming. Sensors. 2020; 20(22):6458. https://doi.org/10.3390/s20226458

DeSmog. (2022). European Carbon+ Farming Coalition. https://www.desmog.com/european-carbon-farming-coalition/

Devot, A., Royer, L., Arvis B., Deryng, D., Caron Giauffret, E., Giraud, L., Ayral, V., & Rouillard, J. (2023). Research for AGRI Committee – The impact of extreme climate events on agriculture production in the EU, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733115/IPOL_STU(2023)733115_EN.pdf

Dixon, T. A., Williams, T. C., & Pretorius, I. S. (2021). Sensing the future of bio-informational engineering. Nature Communications, 12(1). https://doi.org/10.1038/s41467-020-20764-2

Donellon-May, G. (2023). China's food dilemma; The push for a "Food Silk Road" is telling of the superpower's vulnerability – environmental and geopolitical. The Interpreter, 29 May 2023. https://www.lowyinstitute.org/the-interpreter/china-s-food-dilemma

Doriane, A. (2023). Innovations in Timber Products and Processing. J Biodivers Manage Forestry 12:4. https://www.scitechnol.com/peer-review/innovations-in-timber-products-and-processing-yxrK.php?article_id=24656

Doxzen, K. (2021). How engineering animals and plants could help fight climate change. https://www.weforum.org/agenda/2021/10/deextinction-genetic-engineering-climate-change/

Dragt, E. (2023). How to Research Trends. Revised edition. ISBN: 9789063696825

Earthhow. (2024). Strip Cropping: The Benefits of Green Stripes. https://earthhow.com/strip-cropping

Eastlake, D. (2025). Gut health: What consumers want in 2025. https://www.foodnavigator.com/Article/2025/02/03/gut-health-what-consumers-want-in-2025/

Ebihara, J., Takahashi, M., Saito, R. R., Shibahara, N., Sugimoto, M., Sakata, Y., & Kasai, T. (2023). Business Risk and Opportunity on Biodiversity: TNFD case study with Location analysis - Kao Corporation. Accenture Japan Ltd. & Kao Corporation. https://www.accenture.com/content/dam/accenture/final/accenture-com/document/Accenture-Biodiversity-TNFD-Executive-Summary-EN.pdf

EEA (2021). Land take and land degradation in functional urban area. EEA Report 17/2021. https://www.eea.europa.eu/en/analysis/publications/land-take-and-land-degradation

Eggers, C., Grima, N., Kleine, M. & Radosavljevic, M. (eds., 2024). Europe's wood supply in disruptive times. An evidence-based synthesis report. IUFRO World Series, Volume 42. https://www.iufro.org/fileadmin/material/publications/iufro-series/ws42/ws42.pdf

Elofsson, E., Nordbø, E., & Rutigliano, M. (2023). The Paper and Packaging Industry Faces a Biodiversity Crisis. Bain & Company. https://www.bain.com/insights/the-paper-and-packaging-industry-faces-a-biodiversity-crisis/

Eloit, L. (2021). Serious Concerns That AI Self-Driving Cars Cybersecurity Will Be A Hacker Leak Like An Open Sieve. https://www.forbes.com/sites/lanceeliot/2021/08/25/serious-concerns-that-ai-self-driving-cars-cybersecurity-will-be-a-hacker-leak-like-an-open-sieve/

Emerson M. (2023). The Potential Impact of Ukrainian Accession on the EU's Budget – and the Importance of Control Valves. ICDS. https://icds.ee/en/the-potential-impact-of-ukrainian-accession-on-the-eus-budget-and-the-importance-of-control-valves/

Empson, C. (2023). Unleashing the Potential of Digital Twins for Informed Decision-Making. techUK. https://www.techuk.org/resource/guest-blog-unleashing-the-potential-of-digital-twins-for-informed-decision-making.html

Ess Team. (2025). Personalised nutrition drives innovation in functional food formulation. https://essfeed.com/personalized-nutrition-drives-innovation-in-functional-food-formulation-personalized-nutrition-drives-innovation-in-functional-food-formulation/

ETC Group. (Action Group on Erosion, Technology and Concentration). (2022). Food Barons 2022. Crisis Profiteering, Digitalization and Shifting Power. https://www.etcgroup.org/files/files/food-barons-2022-full_sectors-final_16_sept.pdf

EU CAP Network. (2024). Promoting gender equality in European agriculture and rural areas. https://eu-cap-network.ec.europa.eu/publications/promoting-gender-equality-european-agriculture-and-rural-areas_en

EU DG AGRI. (European Union Directorate General for Agriculture and Rural Development (2023). FLIARA, GRASS CEILING & SWIFT: Supporting women-led innovation in rural areas, https://rural-vision.europa.eu/news/news/fliara-grass-ceiling-swift-supporting-women-led-innovation-rural-areas-2023-04-11_en

Euractiv. (2023a). Ukraine's EU membership will trigger a rewriting of CAP, says Kyiv official. https://www.euractiv.com/section/agriculture-food/news/ukraines-eu-membership-will-trigger-a-rewriting-of-cap-says-kyiv-official/

Euractiv. (2023b). The Brief – The price of enlargement. https://www.euractiv.com/section/global-europe/opinion/the-brief-the-price-of-enlargement/

Euromeat. (2023). China builds three large swine farm units in Argentina. https://euromeatnews.com/Article-China-builds-three-large-swine-farm-units-in-Argentina/4258

European Commission (EC) (2019). The European Green Deal (COM(2019) 640 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640

European Commission (EC) (2020a). A European Strategy for Data (COM(2020) 66 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0066

European Commission (EC) (2020b). 2020 Strategic Foresight Report. https://commission.europa.eu/strategy-and-policy/strategic-foresight/2020-strategic-foresight-report_en

European Commission (EC) (2021a). Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery (COM(2021) 350 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0350

European Commission (EC) (2021b). The new Common Agricultural Policy: 2023–2027 – Policy Overview. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en

European Commission (EC) (2021c). Connectivity: key to revitalising rural areas. https://digital-strategy.ec.europa.eu/en/news/connectivity-key-revitalising-rural-areas

European Commission (EC). (2021d) Sustainable Carbon Cycles. COM(2021) 800 final. https://climate.ec.europa.eu/system/files/2021-12/com_2021_800_en_0.pdf

European Commission (EC). (2021e). Sustainable carbon cycles – Carbon farming. SWD(2021) 450 final. https://climate.ec.europa.eu/document/download/d3529f84-0f18-40ee-ab72-124ba786fb5a_en

European Commission (EC). (2021f). A New IACS Vision in Action. https://cordis.europa.eu/project/id/842009/reporting

European Commission (EC). (2022b). Blue Bioeconomy. Towards a strong and sustainable EU algae sector. SWD(2022) 361 final. https://oceans-and-fisheries.ec.europa.eu/document/download/d2b345d5-9c66-4eca-aa43-6b135293bac8_en?filename=swd-2022-361_en.pdf

European Commission (EC). (2023a). Digitalisation of agriculture and rural areas in the EU. https://agriculture.ec.europa.eu/sustainability/digitalisation_en

European Commission (EC). (2023b). EU support to rural revitalisation through broadband roll-out and smart solutions. Retrieved from https://digital-strategy.ec.europa.eu/en/news/eu-support-rural-revitalisation-through-broadband-roll-out-and-smart-solutions

European Commission (EC). (2023c). EU Agricultural Outlook for markets 2023-2035. https://agriculture.ec.europa.eu/data-and-analysis/markets/outlook/medium-term_en

European Commission (EC). (2023d). Commission announces next steps on cybersecurity of 5G networks in complement to latest progress report by Member states. Press Release. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3309

European Commission (EC). (2024a). EU agricultural outlook, 2024-2035. European Commission, DG Agriculture and Rural Development, Brussels. https://agriculture.ec.europa.eu/data-and-analysis/markets/outlook/medium-term_en

European Commission (EC). (2024b). Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU. COM(2024) 137 final. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52024DC0137

European Commission (EC). (2024c). EU-MERCOSUR Partnership Agreement. https://ec.europa.eu/commission/presscorner/api/files/attachment/880027/Factsheet%20EU-Mercosur%20Trade%20Agreement%20-%20Agriculture.pdf

European Commission (EC). (2024d). New reports highlight CAP's role in strengthening rural areas. https://agriculture.ec.europa.eu/media/news/new-reports-highlight-caps-role-strengthening-rural-areas-2024-07-04_en

European Commission (EC). (2024e). White Paper - How to master Europe's digital infrastructure needs? COM(2024) 81 final. https://digital-strategy.ec.europa.eu/en/library/white-paper-how-master-europes-digital-infrastructure-needs

European Commission (EC). (2024f). Commission Staff Working Document on Common European Data Spaces. SWD(2024) 21 final. https://digital-strategy.ec.europa.eu/en/library/second-staff-working-document-data-spaces

European Commission (EC). (2025a). A Vision for Agriculture and Food: Shaping together an attractive farming and agri-food sector for future generations. COM (2025) 75 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0075

European Commission (EC). (2025b). Glenn Micallef. Commissioner (2024-2029). Intergenerational Fairness, Youth, Culture and Sport. https://commission.europa.eu/about/organisation/college-commissioners/glenn-micallef_en

European Commission (EC). (2025c). AI Act. https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

European Commission (EC). (2025d). CAP Strategic Plans. https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en%20p.30

European Commission (EC). (2025e). Food Safety. https://food.ec.europa.eu/index_en

European Commission (EC) & Daheim, C. (2023). Mutual learning exercise – R&I foresight – An introduction to the current state of play – Thematic report. https://data.europa.eu/doi/10.2777/528500

European Commission Joint Research Centre (EC JRC). (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. doi:10.2760/171121. https://joint-research-centre.ec.europa.eu/document/download/68960967-4846-47c2-8818-533906ab9539_en

European Commission Joint Research Centre (EC JRC). (2024a). Peering into the Future: How Horizon Scanning can help shape EU Policy. https://policy-lab.ec.europa.eu/news/spotting-future-how-horizon-scanning-can-help-shape-eu-policy-2024-01-19_en

European Commission Joint Research Centre (EC JRC). (2024b). The State of Soils in Europe, Arias Navarro, C., Baritz, R. and Jones, A. editor(s), Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/7007291, JRC137600 page 24

European Commission Joint Research Centre (EC JRC). (2024c). Bailey, G., Farinha, J., Mochan, A. & Polvora, A. (2024). Eyes on the Future - Signals from recent reports on emerging technologies and breakthrough innovations to support European Innovation Council strategic intelligence - Volume 1. https://op.europa.eu/s/zN81

European Commission Joint Research Centre (EC JRC). (2025). Paving the way for an EU Intergenerational Fairness Strategy. EU Policy Lab. https://policy-lab.ec.europa.eu/news/paving-way-eu-intergenerational-fairness-strategy-2025-02-25_en

European Council (2023). Remarks by President Charles Michel following his meeting with President of Ukraine Volodymyr Zelenskyy and President of Moldova Maia Sandu. Press Release, 21 November 2023. https://www.consilium.europa.eu/en/press/press-releases/2023/11/21/remarks-by-president-charles-michel-following-his-meeting-with-president-of-ukraine-volodymyr-zelenskyy-and-president-of-moldova-maia-sandu/

European Court of Auditors (ECA). (2018). Combating desertification in the EU: a growing threat in need of more action. Special Report 33 2018. https://op.europa.eu/webpub/eca/special-reports/desertification-33-2018/en/

European Court of Auditors (ECA). (2021). Special Report: CAP Performance Reporting. https://op.europa.eu/webpub/eca/special-reports/cap-and-climate-16-2021/en/

European Economic and Social Committee (EESC). (2021). Territorial development of rural areas: the CAP alone cannot make it happen, says the EESC. https://www.eesc.europa.eu/en/news-media/news/territorial-development-rural-areas-cap-alone-cannot-make-it-happen-says-eesc

European Environment Agency (EEA). (2020). State of nature in the EU Results from reporting under the nature directives 2013-2018. EEA Report 10/2020.

European Environmental Agency (EEA). (2023). Water scarcity conditions in Europe (Water exploitation index plus). https://www.eea.europa.eu/en/analysis/indicators/use-of-freshwater-resources-in-europe-1

European Environment Agency (EEA) (2020). State of nature in the EU Results from reporting under the nature directives 2013-2018. EEA Report 10/2020

European Environmental Agency (EEA) & European Environment Information and Observation Network (EIONET). (2023). Horizon Scanning – tips and tricks. https://www.eea.europa.eu/publications/horizon-scanning-tips

European Environmental Agency (EEA). (2022). Transforming Europe's food system: Assessing the EU Policy Mix. https://www.eea.europa.eu/publications/transforming-europes-food-system

European Foresight Platform (EFP). (2016). Megatrend / Trend / Driver / Issue. http://foresight-platform.eu/community/forlearn/how-to-do-foresight/methods/analysis/megatrend-trend-driver-issue/

European Parliament (EP) (2021). Report on a farm to fork strategy for a fair, healthy and environmentally-friendly food system. Report - A9-0271/2021. https://www.europarl.europa.eu/doceo/document/A-9-2021-0271_EN.html

European Parliament (EP) (2024). The future of agriculture and the post-2027 common agricultural policy. https://www.europarl.europa.eu/committees/en/the-future-of-agriculture-and-the-post-2/product-details/20250508WKS06322

European Parliamentary Research Service (EPRS) (2025). Military drone systems in the EU and global context: Types, capabilities and regulatory frameworks. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2025)772885

European Partnership "Agriculture of Data". (2023). Unlocking the potential of sustainable agriculture. Strategic Research and Innovation Agenda. https://research-and-innovation.ec.europa.eu/system/files/2023-08/AgData%20SRIA%20final_version.pdf

European Union (EU) (2021). Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the Common Agricultural Policy. https://eur-lex.europa.eu/eli/reg/2021/2115/oj

European Union (EU). (2023). Regulation (EU) 2023/2854 of the European Parliament and of the Council of 13 December 2023 on harmonised rules on fair access to and use of data and amending Regulation (EU) 2017/2394 and Directive (EU) 2020/1828 (Data Act). http://data.europa.eu/eli/reg/2023/2854/oj

European Union (EU). (2024a). Regulation Of The European Parliament and of the Council on nature restoration and amending Regulation (EU) 2022/869. https://data.consilium.europa.eu/doc/document/PE-74-2023-INIT/en/pdf

European Union (EU). (2024b). Directive (EU) 2024/1203 Of The European Parliament and of the Council on the protection of the environment through criminal law. http://data.europa.eu/eli/dir/2024/1203/oj

European Union (EU). (2024c). Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods. http://data.europa.eu/eli/dir/2024/1799/oj

European Union (EU) (2024d). Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence. http://data.europa.eu/eli/reg/2024/1689/oj

European Union (EU). (n.d.). The EU rural vision. https://rural-vision.europa.eu/rural-vision_en

Eurostat. (2020). Age classes of farm managers, by gender (% of all farm managers, EU, 2020). https://webtools.europa.eu/rest/charts/export/html/

Eurostat. (2022). Farms and farmland in the European Union – statistics. (ef_lus_main). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farms_and_farmland_in_the_European_Union_-_statistics#The_evolution_of_farms_and_farmland_between_2005_and_2020

Eurostat. (2023). Wood products – production and trade. (online data code: for_remov). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_-_production_and_trade

Eurostat. (2024). Key Figures in the European Food Chain: 2024 Edition. https://ec.europa.eu/eurostat/documents/15216629/20555393/KS-01-24-000-EN-N.pdf/937addab-5089-aa08-3b95-bf0fa0beee3d?version=4.1&t=1741695672920

Ewing-Chow, D. (2025). The latest AI trends transforming the food industry. Forbes. https://www.forbes.com/sites/daphneewingchow/2025/03/18/these-are-the-latest-ai-trends-transforming-the-food-industry/

EY Global. (2024). EU Deforestation Regulation | Insights into proposed changes and latest guidance. EY Global. https://www.ey.com/en_gl/technical/tax-alerts/eu-deforestation-regulation-insights-into-proposed-changes-and-latest-guidance

Fan, Y., Tjiputra, J., Muri, H., Lombardozzi, D., Park, C., Wu, S., & Keith, D. (2021). Solar geoengineering can alleviate climate change pressures on crop yields. Nature Food, 2(5), 373–381. https://doi.org/10.1038/s43016-021-00278-w

Fantom, L. (2022). Insect Farms are Scaling Up—and Crossing the Atlantic—in a Play for Sustainable Protein. Civil Eats. https://civileats.com/2022/12/20/insect-farms-scaling-up-sustainable-protein-innovafeed-adm-cargill-protix-black-soldier-fly-livestock-aquaculture/

Farmonaut (2025). Autonomous Drone Military: 7 Precision Ag Innovations. https://farmonaut.com/precision-farming/autonomous-drone-military-7-precision-ag-innovations#:~:text=Conclusion,productivity%20and%20environmental%20stewardship%20worldwide.

Farooq, M. A., Gao, S., Hassan, M. A., Huang, Z., Rasheed, A., Hearne, S., Prasanna, B., Li, X., & Li, H. (2024). Artificial intelligence in plant breeding. Trends in Genetics, 40(10), 891–908. https://doi.org/10.1016/j.tig.2024.07.001

Feng, Y., & Audy, J. (2020). Forestry 4.0: a framework for the forest supply chain toward Industry 4.0. Gestão & Produção, 27(4). https://doi.org/10.1590/0104-530x5677-20

Fertilizers Europe. (2024). Beyond Gas. The Risks of Fertilizer Dependence for EU. https://www.fertilizerseurope.com/beyond-gas-the-risks-of-fertilizer-dependence-for-eu

Finck, M., & Mueller, M. S. (2023). Access to Data for Environmental Purposes: Setting the Scene and Evaluating Recent Changes in EU Data Law. Journal of Environmental Law, 35(1), 109-131

Fiocco, D., Ganesan, V., Garcia de la Serrana, M., & Sharifi, H. (2023). Agtech: Breaking down the farmer adoption dilemma. https://www.mckinsey.com/industries/agriculture/our-insights/agtech-breaking-down-the-farmer-adoption-dilemma#/

FLIARA. (2025). Female-Led Innovation in Agriculture and Rural Areas, https://fliara.eu

Flytkjaer, R., Dunn, E, Miller, L., Ladher, R., & Profanter, M. (2025). D3.2 – 4Growth Market Monitoring and Forecasting Tool (MMFT). (forthcoming)

Food 4 Future. (2024) Personalised Nutrition: How Technology is Transforming Food. https://www.expofoodtech.com/personalized-nutrition-technology-transforming-food/

Food and Agriculture Organisation (FAO). (2019). The State of the World's Biodiversity for Food and Agriculture. http://www.fao.org/3/CA3129EN/CA3129EN.pdf

Food and Agriculture Organisation (FAO). (2024). In Brief to The State of Agricultural Commodity Markets 2024 – Trade and nutrition: Policy coherence for healthy diets. Rome

Food Standards Agency (FSA). (2023). The Evolution of Personalised Nutrition: Key findings. https://www.food.gov.uk/research/the-evolution-of-personalised-nutrition-key-findings

Food Watch. (2023). Food speculation: What are we talking about again? https://www.foodwatch.org/en/food-speculation-what-are-we-talking-about-again

Food Watch. (2024a). Open letter calling for action on nutritional aspects of food. https://www.foodwatch.org/fileadmin/-INT/food_politcs/240319_Letter_Commission_and_BE_Presidency.pdf

Food Watch. (2024b). Strategies used by the agro-industrial lobby against a mandatory Nutri-Score. https://www.foodwatch.org/en/strategies-used-by-the-agro-industrial-lobby-against-a-mandatory-nutri-score

Foodchain ID. (2025). Nutri-Score or Not? A European Union Analysis and Global Overview. https://www.foodchainid.com/resources/nutri-score-or-not-a-european-union-analysis-and-global-overview/

Foodwatch. (2023) Food speculation: What are we talking about again? https://www.foodwatch.org/en/food-speculation-what-are-we-talking-about-again

FORSight Resources, LLC. (2005). The FORSight Resource, Volume 2, Issue 1. FORSight Resources, LLC. https://www.forsightresources.com/archive/FORSightResource_v2n1.pdf

FORSight Resources, LLC. (2009). Forest Inventory—The FIA Program. The FORSight Resource, Volume 6, Issue 2, October 2009. FORSight Resources, LLC. https://www.forsightresources.com/archive/FORSightResource_v6n2.pdf

FORSight Resources, LLC. (2025). Harvest Scheduling and Forest Planning. FORSight Resources. http://www.forsightresources.com/planning.htm

Fraunhofer. (2020). Agricultural Data Space (ADS). Whitepaper. https://www.iese.fraunhofer.de/content/dam/iese/publication/agricultural-data-space-cognac-fraunhofer-iese.pdf

FTSG. (2025). 2025 Tech Trends Report. 18th edition. https://ftsg.com/wp-content/uploads/2025/03/FTSG_2025_TR_FINAL_LINKED.pdf

Future Farming. (2021). Bayer and Microsoft partner to develop digital farming tools. https://www.futurefarming.com/smart-farming/bayer-and-microsoft-partner-to-develop-digital-farming-tools/

Future Generations Commissioner for Wales (2025). Well-being of Future Generations Act 2015. https://futuregenerations.wales/discover/about-future-generations-commissioner/future-generations-act-2015/

Future Impacts & European Monitoring Agency for Drugs and Addiction (EMCDDA). (2022). How to run a trends workshop. A foresight toolkit by the EMCDDA for the drugs field. https://www.euda.europa.eu/publications/manuals-and-guidelines/how-run-trends-workshop-emcdda-foresight-toolkit-drugs-field_en

Futurepolicy.org (2021). Well-being of Future Generations (Wales) Act. https://www.futurepolicy.org/guardians/wales-well-being-of-future-generations-act/

Garnett, P., Doherty, B. & Heron, T. (2020). Vulnerability of the United Kingdom's food supply chains exposed by COVID-19. Nat Food 1, 315–318. https://doi.org/10.1038/s43016-020-0097-7

Gavrilaș, S., Ursachi, C. Ș., Perța-Crișan, S., & Munteanu, F. (2022). Recent trends in biosensors for environmental quality monitoring. Sensors, 22(4), 1513. https://doi.org/10.3390/s22041513

Gemüse Syndikat. (2025). Regionales Gemüse aus enkeltauglichem Anbau zum solidarischen Preis, https://gemuese-syndikat.de

General Kinematics. (2024). Wood processing: From forest to finished. https://www.generalkinematics.com/blog/wood-processing/

GFI Europe. (2023). Over 50% of Europeans are eating less meat, but taste and price remain biggest barriers to plant-based uptake. https://gfieurope.org/blog/over-50-of-europeans-are-eating-less-meat-but-taste-and-price-remain-biggest-barriers-to-plant-based-uptake/

Ghalandarzadeh, S., Kurti, A., Unell, C., Hallborg, A., Kastrati, Z. & Sjökvist, T. (2025). Community-based business models for agricultural and forestry data ecosystems: A systematic literature review, Smart Agricultural Technology, Volume 11,100958, https://doi.org/10.1016/j.atech.2025.100958

Gironde, C. (2020). Land Grabs, Big Business and Large-Scale Damages. CIES Research Brief 4. https://www.graduateinstitute.ch/sites/internet/files/2020-11/Research%20brief%204.pdf

Glauber, J. & Mamun, A (2023). India's new ban on rice exports: Potential threats to global supply, prices, and food security. IFPRI Blog: Issue Post Markets, Trade, and Institutions. https://www.ifpri.org/blog/indias-new-ban-rice-exports-potential-threats-global-supply-prices-and-food-security/

Glauber, J., Piñeiro, V. & Gianatiempo, J.P. (2025). How ‘reciprocal tariffs’ harm agricultural trade. IFPRI Blog. https://www.ifpri.org/blog/how-reciprocal-tariffs-harm-agricultural-trade/

Glazebrook, T., Noll, S., Opoku, E. (2020). Gender Matters: Climate Change, Gender Bias, and Women´s Farming in the Global South and North, Agriculture 2020, 10(7), 267, https://doi.org/10.3390/agriculture10070267

Global CCS Institute. (2023). Global Status of CCS 2023. Scaling up through 2030. https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf

Global Market Insight (GMI). (2025). Functional Foods Market Size - Industry Analysis Report, Regional Outlook, Growth Potential, Competitive Market Share & Forecast, 2025 - 2034. https://www.gminsights.com/industry-analysis/functional-foods-market

Godshall, L., & Weick, M. (2023). How the nature-related regulatory disclosure landscape is evolving. Ernst & Young LLP. https://www.ey.com/en_us/insights/climate-change-sustainability-services/the-nature-related-disclosure-landscape

Gong, H., Hassink, R., Foster, C., Hess, M., & Garretsen, H. (2022). Globalisation in reverse? Reconfiguring the geographies of value chains and production networks. Cambridge Journal of Regions Economy and Society, 15(2), 165–181. https://doi.org/10.1093/cjres/rsac012

Gordon-Smith, H. (2024). Column: The Decline of Vertical Farming is a Prelude to Innovation and Profitability - The Food Institute. The Food Institute. https://foodinstitute.com/focus/column-the-decline-of-vertical-farming-is-a-prelude-to-innovation-and-profitability/

Grain. (2021). Digital control: how Big Tech moves into food and farming (and what it means). https://grain.org/en/article/6595-digital-control-how-big-tech-moves-into-food-and-farming-and-what-it-means

GRASS CEILING. (2025). Gender Equality in Rural and Agricultural Innovation Systems, https://www.grassceiling.eu

Gupta, Debaditya & Gujre, Nihal & Singha, Siddhartha & Mitra, Sudip. (2022). Role of existing and emerging technologies in advancing climate-smart agriculture through modeling: A review. Ecological Informatics. 71. 101805. 10.1016/j.ecoinf.2022.101805.

Guyomard, H., Stickel, M., Détang-Dessendre, C., Soler, L.-G., Aubert, P.-M., Carpentier, A., Catallo, A., Dupraz, P., Gaigné, C., Régnier, E., Thoyer, S. (2024). Research for AGRI Committee – The next reform of the CAP: The variables in the equation. European Parliament, Policy Department of Directorate for Regional Development, Agriculture and Fisheries Policies, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2025/759316/CASP_STU(2025)759316_EN.pdf

Haas, C., Burgers, L. & Putzer, A. (2025). Introducing Rights of Nature in Europe. https://www.boell.de/en/2025/02/03/introducing-rights-nature-europe

Habgood, J., & Lys, T. (2024). The Future of Work in the Age of AI. McKinsey & Company. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-future-of-work-in-the-age-of-ai

Hanacek, A. (2025). The Time for Digitalization in Food & Beverage is Now. https://www.foodprocessing.com/on-the-plant-floor/technology/article/55280735/the-time-for-digitalization-in-food-beverage-is-now

Hardcastle, D., & Felenbok, R. (2020). Making the Hidden Visible: Preparing for the Satellites in Your Sustainable Future. Bain & Company. https://www.bain.com/insights/making-the-hidden-visible/

Hardcastle, D., Kulkarni, V., Fries, G., & Huenteler, H. (2022). Nature: The New Asset Class. Bain & Company. https://www.bain.com/insights/nature-the-new-asset-class/

Hau, R. C., & Lange, K. W. (2023). Can the 5-colour nutrition label "Nutri-Score" improve the health value of food? Journal of Future Foods, 3(4), 306–311. https://doi.org/10.1016/j.jfutfo.2023.03.002

Hedberg, A. & Šipka, S. (2020). Improving biodiversity: How can digitalisation help? EPO, discussion paper.

Hendricks, D. (2021). Future factors. https://www.iftf.org/insights/what-is-the-future-factors-platform/

Hernandes, M.A., Espinosa, A, Berrospi, M.L., Deconinck, K., Swinnen, J., & Vos, R. (2023). The role of Market Concentration in the Agrifood Industry. IFFPRI Discussion Paper 02168. https://cgspace.cgiar.org/server/api/core/bitstreams/a6616f26-7df9-4614-9c03-9a537ad0724a/content

Herold, A., Antony, F., Böttcher, H., Scheffler, M., Teufel, J., von Vittorelli, L. & Wiegmann, K. (2024). Land-use transition – Strategies and solutions for sustainable land use. Policy Brief. https://www.oeko.de/en/blog/land-use-transition-strategies-and-solutions-for-sustainable-land-use/

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., Barrett, C. B., Benton, T. G., Hall, A., Pikaar, I., Bogard, J. R., Bonnett, G. D., Bryan, B. A., Campbell, B. M., Christensen, S., Clark, M., Fanzo, J., Godde, C. M., Jarvis, A., . . . Rockström, J. (2021). Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health, 5(1), e50–e62. https://doi.org/10.1016/s2542-5196(20)30277-1

Hines, P., Yu, L. H., Guy, R. H., Brand, A., & Papaluca-Amati, M. (2019). Scanning the horizon: a systematic literature review of methodologies. BMJ Open, 9(5), e026764. https://doi.org/10.1136/bmjopen-2018-026764

Holmström, J. (2020). Digital Transformation of the Swedish Forestry Value chain: Key Bottlenecks and Pathways Forward. https://wwwmistradigital.cdn.triggerfish.cloud/uploads/2020/04/jh-wp0-digital-transformation-of-the-swedish-forestry-value-chain.pdf

Holopainen, M., & Toivonen, M. (2012). Weak signals: Ansoff today. Futures, 44(3), 198–205. https://doi.org/10.1016/j.futures.2011.10.002

Homeland Security. (2024). Wtas: Joint Investigation Into CCP-Backed Company Supplying Cranes To U.S. Ports Reveals Shocking Findings. https://homeland.house.gov/2024/03/12/wtas-joint-investigation-intoccp-backed-company-supplying-cranes-to-u-s-ports-reveals-shocking-findings/

Hosseini, S., & Seilani, H. (2025). The Role of Agentic AI in Shaping a Smart Future: A Systematic review. Array, 100399. https://doi.org/10.1016/j.array.2025.100399

Huang, C., Lin, C., Nguyen, M. K., Hussain, A., Bui, X., & Ngo, H. H. (2023). A review of biosensor for environmental monitoring: principle, application, and corresponding achievement of sustainable development goals. Bioengineered, 14(1), 58–80. https://doi.org/10.1080/21655979.2022.2095089

Huang, L. (2025). The Digital Agricultural Revolution: Shaping a New Era of Global Farming Innovation. AgNews. https://news.agropages.com/news/NewsDetail---53245.htm

Hyöky, R., & Virranta, J. (2023). How can technology fast-track your journey to robust ESG reporting?. EY Finland. https://www.ey.com/en_fi/insights/consulting/how-can-technology-augment-sustainability-reporting

Hyöky, R., Piipari, R., & Korri, K. (2023). How can the forestry industry transform ERP?. EY Finland. https://www.ey.com/en_fi/insights/consulting/how-can-the-forestry-industry-transform-erp

Iakovidis, D., Gadanakis, Y., Campos-Gonzalez, J., & Park, J. (2024). Optimising decision support tools for the agricultural sector. Environment Development and Sustainability. https://doi.org/10.1007/s10668-024-04743-x

IBM. (2020). IBM Services: Cloud Migration and Modernization Approach. IBM. https://www.ibm.com/services/resources/transform-your-traditional-it/

Ibounig, E., Saarela, L., Belt, A., Inovaara, S., Wilkko, W., Kangas, O., Kaskinen, T., & Turkki, J. (2023). Finland's Moonshots for Green Growth: Maximizing Finland's Growth and Handprint in the Green Transition. Boston Consulting Group. https://www.bcg.com/publications/2023/moonshots-for-green-economy-in-finland

Inayatullah, S. (2013). Futures Studies: theories and methods. In Fernando Gutierrez Junquera. (ed.).. There's a Future: Visions for a better world. 36-66. https://www.bbvaopenmind.com/en/articles/futures-studies-theories-and-methods/

Innova Market Insights. (2024). Top 10 Global Food and Beverage Trends 2025. https://www.innovamarketinsights.com/trends/top-food-trends-2025/

Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE). (2020). The role of European agriculture in world trade by 2050. https://www.inrae.fr/en/actualites/agricultures-europeennes-horizon-2050

Intelligent Growth Solutions (IGS). (2023). GigaFarm announcement at COP28, Dubai | IGS, Vertical Farming. https://www.intelligentgrowthsolutions.com/press-release/gigafarm-announcement-in-dubai

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.009

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3553579

International Environmental Agency (IEA). (2024). Analysing the impacts of Russia's invasion of Ukraine on energy markets and energy security. https://www.iea.org/topics/russias-war-on-ukraine

International Federation of Organic Agriculture Movement (IFOAM). (2024). Organic in Europe - Browse latest production and market data. https://www.organicseurope.bio/about-us/organic-in-europe/

International Network for Community Based Agriculture (URGENCI). (2016). Overview of Community Supported Agriculture in Europe. European CSA Research Group, https://urgenci.net/wp-content/uploads/2016/05/Overview-of-Community-Supported-Agriculture-in-Europe-F.pdf

Isermeyer, F. (2022). Photovoltaics on agricultural land – for a rapid energy turnaround. https://www.thuenen.de/en/thuenen-topics/long-term-policy-concepts/photovoltaics-on-agricultural-land-for-a-rapid-energy-turnaround

Jagtap, S., Kumar, A., Trollmann, H., & Hassoun, A. (2024). Digital Transformation in Food Processing: From Industry 4.0 to Industry 5.0. Journal of Food Quality. https://onlinelibrary.wiley.com/doi/toc/10.1155/6095.si.650822

Jagtap, S., Trollman, H., & Woolley, E. (2025). Guest editorial: Digitising food supply chains: a path to ensuring food security. International Journal of Industrial Engineering and Operations Management, 7(2), 97–99. https://doi.org/10.1108/ijieom-04-2025-083

Javaid, M., Haleem, A., Khan, I. H., & Suman, R. (2022). Understanding the potential applications of Artificial Intelligence in Agriculture Sector. Advanced Agrochem, 2(1), 15–30. https://doi.org/10.1016/j.aac.2022.10.001

Jha, A., Pathania, D., Sonu, N., Damathia, B., Raizada, P., Rustagi, S., Singh, P., Rani, G. M., & Chaudhary, V. (2023). Panorama of biogenic nano-fertilizers: A road to sustainable agriculture. Environmental Research, 235, 116456. https://doi.org/10.1016/j.envres.2023.116456

Jia, N., Xia, Z., Li, Y., Yu, X., Wu, X., Li, Y., Su, R., Wang, M., Chen, R., & Liu, J. (2024). The Russia-Ukraine war reduced food production and exports with a disparate geographical impact worldwide. Communications Earth & Environment, 5(1). https://doi.org/10.1038/s43247-024-01915-5

Jorge-Vázquez, J., Chivite-Cebolla, M. P., & Salinas-Ramos, F. (2021). The Digitalization of the European Agri-Food Cooperative Sector. Determining Factors to Embrace Information and Communication Technologies. Agriculture, 11(6), 514. https://doi.org/10.3390/agriculture11060514

Jurado, E. B., Uclés, D. F., Moral, A. M., & Viruel, M. J. M. (2019). Agri-food companies in the social media: A comparison of organic and non-organic firms. Economic Research-Ekonomska Istraživanja, 32(1), 321–334. https://doi.org/10.1080/1331677x.2018.1547203

Kalmar, R., Rauch, B., Dörr, J., & Liggesmeyer, P. (2022). Agricultural Data space. In Springer eBooks (pp. 279–290). https://doi.org/10.1007/978-3-030-93975-5_17

Kamalapuram, S. K., & Choudhury, D. (2024). Industry 4.0 technologies for cultivated meat manufacturing. Food Bioengineering. https://doi.org/10.1002/fbe2.12080

Kappen, G., Kastner, E., Kurth, T., Puetz, J., Reinhardt, A., & Soininen, J. (2020). The Staggering Value of Forests—and How to Save Them. Boston Consulting Group. https://www.bcg.com/publications/2020/the-staggering-value-of-forests-and-how-to-save-them

Kaya, A. (2024). How are geopolitical risks affecting the world economy? Economics Obervatory. https://www.economicsobservatory.com/how-are-geopolitical-risks-affecting-the-world-economy

Khan, M. H. U., Wang, S., Wang, J., Ahmar, S., Saeed, S., Khan, S. U., Xu, X., Chen, H., Bhat, J. A., & Feng, X. (2022). Applications of Artificial Intelligence in Climate-Resilient Smart-Crop breeding. International Journal of Molecular Sciences, 23(19), 11156. https://doi.org/10.3390/ijms231911156

Khan, S. (2024). Vertical Farming and the Revival of Local Food Economies. https://green.org/2024/01/30/vertical-farming-and-the-revival-of-local-food-economies/

Khodakivska, O., Pugachov, M., Pugachov, V., Mamchur, V., & Yurchenko, I. (2022). Farm Size and Technology Implementation: A Comparison between Canada and Ukraine. Naukovì Gorizonti, 25(7). https://doi.org/10.48077/scihor.25(7).2022.74-81

Kite-Powell, J. (2018). See how algae could change our world. Forbes. https://www.forbes.com/sites/jenniferhicks/2018/06/15/see-how-algae-could-change-our-world/

Koop, F. (2020). Chinese pork investment sparks criticism in Argentina. Dialogue Earth. https://dialogue.earth/en/business/37359-chinese-pork-investment-sparks-criticism-in-argentina/

Kornher, L., von Braun, J. & Algieri, B. (2022). Speculation risks in food commodity markets in the context of the 2022 price spikes - Implications for policy. ZEW Policy Brief No. 40. https://www.zef.de/fileadmin/user_upload/ZEF_Policy_Brief_40_eng-_27_4_2022.pdf

Kortetmäki, T., & Oksanen, M. (2023). Right to food and geoengineering. Journal of Agricultural and Environmental Ethics, 36(1). https://doi.org/10.1007/s10806-023-09898-7

Kotsev A., Minghini M., Cetl V., Penninga F., Robbrecht J., & Lutz M. (2021). INSPIRE – A Public Sector Contribution to the European Green Deal Data Space. A vision for the technological evolution of Europe's Spatial Data Infrastructures for 2030. doi:10.2760/8563

Kroet, C. (2024). Most EU members not implementing Huawei, ZTE 5G ban, data shows. Euronews. https://www.euronews.com/next/2024/02/12/most-eu-members-not-implementing-huawei-zte-5g-ban-data-shows#

Kulkarni, A., Wang, Y., Gopinath, M., Sobien, D., & Rahman, A. (2024). A Review of Cybersecurity Incidents in the Food and Agriculture Sector. https://arxiv.org/pdf/240

Kurth, T., Barnes, W., Murray, L., Coad, L., Wegener, J., Truitt, N., Riley, L., Cadigan, C., & Tran, C. (2025). How Forests Can Revitalize Carbon Markets. Boston Consulting Group. https://www.bcg.com/publications/2025/how-forests-can-revitalize-carbon-markets

Kuś, Ł. (2024). US government wants to replace Chinese STS cranes in ports. https://intermodalnews.eu/2024/02/23/us-government-wants-to-replace-chinese-sts-cranes-in-ports/

La Mela, M. (2014). Property rights in conflict: wild berry-picking and the Nordic tradition of allemansrätt. Scandinavian Economic History Review. 62. 10.1080/03585522.2013.876928.

Larsson-Stern, M. (2016). Hänsyn till forn- och kulturlämningar i skogsbruket: Branschgemensamma riktlinjer. Skogforsk. https://www.mellanskog.se/wp-content/uploads/2025/03/branschgemensamma-riktlinjer-for-hansyn-till-forn-och-kulturlamningar.pdf

Lawrence, A., Gatto, P., Bogataj, N. & Lidestav, N. (2020). Forests in common: Learning from diversity of community forest arrangements in Europe. Ambio 50, 448–464 (2021). https://doi.org/10.1007/s13280-020-01377-x

Lawrence, M. J., Stemberger, H. L. J., Zolderdo, A. J., Struthers, D., P., and Cooke, S., J. (2015). The effects of modern war and military activities on biodiversity and the environment. Environmental Reviews; Volume 23, Number 4, December 2015. https://cdnsciencepub.com/doi/full/10.1139/er-2015-0039

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockstöm, J., Renn, O., & Donges, J. F. (2024). Global Polycrisis: The causal mechanisms of crisis entanglement. Global Sustainability, 1–36. https://doi.org/10.1017/sus.2024.1

Lawrence, P. (2022). Justifying representation of future generations and nature: contradictory or mutually supporting values? Transnational Environmental Law, 11(3), 553–579. https://doi.org/10.1017/s2047102522000176

Leatham, X. (2024). De-extinction of the woolly mammoth takes a major step forward. https://colossal.com/de-extinction-of-the-woolly-mammoth/

Lécuyer, L., Alard, D., Calla, S., Coolsaet, B., Fickel, T., Heinsoo, K., Henle, K., Herzon, I., Hodgson, I., Quétier, F., Mccracken, D., Mcmahon, B., Melts, I., Sands, D., Skrimizea, E., Watt, A., White, R., & Young, J. (2021). Conflicts between agriculture and biodiversity conservation in Europe: Looking to the future by learning from the past. In Advances in ecological research/Advances in Ecological Research (pp. 3–56). https://doi.org/10.1016/bs.aecr.2021.10.005

Lindner, J., Nguyen, T., & Hansum, R. (2023). What does it cost? Financial implications of the next enlargement. Delors Centre. https://www.delorscentre.eu/en/publications/financial-implications-of-the-next-enlargement

Liu, Y., Cao, L., Cheung, W. W. L., & Sumaila, U. R. (2023). Global estimates of suitable areas for marine algae farming. Environmental Research Letters, 18(6), 064028. https://doi.org/10.1088/1748-9326/acd398

Lloyds (2022). From farm to fork. Rethinking food and drink supply chains. https://assets.lloyds.com/media/60e7d0b6-3702-4cf6-a819-2ba10d68f4d4/Lloyds-Futureset_From-farm-to-fork_The-food-and-drink-industry_Part-2.pdf

Loi, A., Gentile, M, Bardley, D., Christodoulou, M., Bracken, J., Knuuttila, M., Niemi, J. & Wejberg, H. (2024). Research for AGRI Committee – The dependency of the EU's food system on inputs and their sources, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels https://www.europarl.europa.eu/RegData/etudes/STUD/2024/747272/IPOL_STU(2024)747272_EN.pdf

Lorenzen, H. & Wetzels, H. (2023). Ukraine joining the EU - an elephant in the room. Agricultural and Rural Convention. https://www.arc2020.eu/ukraine-joining-the-eu-an-elephant-in-the-room/

Lundahl, O. (2018). Dynamics of positive deviance in destigmatisation: Celebrities and the media in the rise of veganism. Consumption Markets & Culture, 23(3), 241–271. https://doi.org/10.1080/10253866.2018.1512492

Madre Brava. (2024). Europe's top supermarkets race towards plant-rich diets – but the finish line is far. https://madrebrava.org/media/pages/insight/11fd194bc7-1724333852/madre_brava_briefing_proteintransition_race_retailer_eng.pdf

Mallakpour, S., Sirous, F., & Hussain, C. M. (2021). Sawdust, a versatile, inexpensive, readily available bio-waste: From mother earth to valuable materials for sustainable remediation technologies. Advances in Colloid and Interface Science, 295, 102492. https://doi.org/10.1016/j.cis.2021.102492

Mann, A., Nehra, K., Rana, J., & Dahiya, T. (2021). Antibiotic resistance in agriculture: Perspectives on upcoming strategies to overcome upsurge in resistance. Current Research in Microbial Sciences, 2, 100030. https://doi.org/10.1016/j.crmicr.2021.100030

Manogna, R.L., & Kulkarni, N. (2024). Does the financialization of agricultural commodities impact food security? An empirical investigation. Borsa Istanbul Review, 24(2), 280–291. https://doi.org/10.1016/j.bir.2024.01.001

Marquart, A. (2022): Exclusive: Musk's SpaceX says it can no longer pay for critical satellite services in Ukraine, asks Pentagon to pick up the tab. CNN. https://edition.cnn.com/2022/10/13/politics/elon-musk-spacex-starlink-ukraine/index.html

Marson, M., & Saccone, D. (2025). The effect of food price upsurges on income inequality: The richest win and the poorest lose. Food Policy, 131, 102830. https://doi.org/10.1016/j.foodpol.2025.102830

Martinez, L., Garcia, R., & Sanchez, M. (2024). Indigenous Communities and Forest Management: The Role of Technology.

Matthews, A. (2022). Implications of the European Green Deal for agrifood trade with developing countries, Brussels, European Landowners' Organization. https://europeanlandowners.org/wp-content/uploads/2023/09/Matthews_ELO_paper_23_May_2022_1.pdf

Mauser, H. (ed). (2021). Key questions on forests in the EU. Knowledge to Action 4. European Forest Institute. https://doi.org/10.36333/k2a04

Max Planck Institute for Comparative and International Private Law. (2022). Rights of nature on the upswing. Private Law Gazette. https://www.mpipriv.de/1593744/2022-2-rechte-der-natur-im-aufwind

Mayer, H., Yee, L., Chui, M., & Roberts, R. (2025). Superagency in the workplace: Empowering people to unlock AI's full potential. McKinsey & Company. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/superagency-in-the-workplace-empowering-people-to-unlock-ais-full-potential-at-work

McDonald, H., Frelih-Larsen, A., Lóránt, A., Duin, L., Pyndt Andersen, S., Costa, G., & Bradley, H. (2021). Carbon farming – Making agriculture fit for 2030. Study for the committee on Environment, Public Health and Food Safety (ENVI). European Parliament. https://www.europarl.europa.eu/RegData/etudes/STUD/2021/695482/IPOL_STU(2021)695482_EN.pdf

McFadden, J., Casalini, F., Griffin, T., & Antón, J. (2022). The Digitalisation of Agriculture. A Literature Review and Emerging Policy Issues. https://eulacfoundation.org/system/files/digital_library/2023-07/285cc27d-en.pdf

McKee, C (2023). New Mexico Tech touts breakthrough water filtration invention. https://www.krqe.com/news/new-mexico/new-mexico-tech-touts-breakthrough-water-filtration-invention/

McKinsey. (2020). Agriculture's connected future: How technology can yield new growth. https://www.mckinsey.com/industries/agriculture/our-insights/agricultures-connected-future-how-technology-can-yield-new-growth#/

McKinsey. (2023). Land: A crucial resource for the energy transition. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/land-a-crucial-resource-for-the-energy-transition

McKinsey (2023b) What's the future of generative AI? https://www.mckinsey.com/featured-insights/mckinsey-explainers/whats-the-future-of-generative-ai-an-early-view-in-15-charts#/

Mellanskog. (2023). Medlemsapp. Mellanskog. https://www.mellanskog.se/medlem/digitala-hjalpmedel/medlemsapp/

Mellanskog. (2024). Nu lanseras Skogstorget till 77 000 skogsägare!. Mellanskog. https://www.mellanskog.se/nyheter/nu-lanseras-skogstorget-till-77-000-skogsagare/

Mellanskog. (2025). Ajourhållning i Skogstorget – håll din skog uppdaterad!. Mellanskog. https://www.mellanskog.se/nyheter/nyhet-ajourhallning-i-skogstorget-hall-din-skog-uppdaterad/

Mellentin, B. (2024). Key trends in Functional Foods for 2025. https://www.nutraceuticalsworld.com/key-trends-in-functional-foods-for-2025

Menge, J. H., Magdon, P., Wöllauer, S., & Ehbrecht, M. (2023). Impacts of forest management on stand and landscape-level microclimate heterogeneity of European beech forests. Landscape Ecology, 38(4), 903–917. https://doi.org/10.1007/s10980-023-01596-z

Mercer LLC. (2024). Nature-based Investments: Exploring the Opportunities. Mercer LLC. https://www.mercer.com/en-gb/insights/investments/investing-sustainably/nature-based-investments-exploring-opportunities/

Möller, M. (2025). Three Steps to Digitalised Food Production. https://www.anugafoodtec.com/magazine/three-steps-to-digitalised-food-production.php

Mondal, R., Dam, P., Chakraborty, J., Paret, M. L., Katı, A., Altuntas, S., Sarkar, R., Ghorai, S., Gangopadhyay, D., Mandal, A. K., & Husen, A. (2022). Potential of nanobiosensor in sustainable agriculture: the state-of-art. Heliyon, 8(12), e12207. https://doi.org/10.1016/j.heliyon.2022.e12207

Morgenstern, E.K. (2007). The origin and early application of the principle of sustainable forest management. The Forestry Chronicle VOL. 83, No. 4, P 485-489

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M. & Scapolo, F. (2022). Towards a green and digital future. https://dx.doi.org/10.2760/977331

Munaweera, T. I. K., Jayawardana, N. U., Rajaratnam, R., & Dissanayake, N. (2022). Modern plant biotechnology as a strategy in addressing climate change and attaining food security. Agriculture & Food Security, 11(1). https://doi.org/10.1186/s40066-022-00369-2

Murray, L., Clos, R., & Engdar, F. (2020). How to make disruption an advantage in the forest products industry. Accenture. https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-123/accenture-reinventing-forest-products-industry.pdf

Nabuurs, G. J. (2022). Does the EU depend on Russia for its wood? https://www.wur.nl/en/research-results/research-institutes/environmental-research/show-wenr/does-the-eu-depend-on-russia-for-its-wood.htm

NCX. (2022). Integrating Remote Sensing Datasets for Accurate, High Resolution Forest Carbon Accounting. NCX. https://info.ncx.com/integrating-remote-sensing-datasets-for-accurate-high-resolution-forest-carbon-accounting-recording

NCX. (n.d.). How NCX Calculates Business-as-Usual (BAU). NCX. https://info.ncx.com/fws-how-ncx-calculates-bau-recording

NCX. (n.d.). The NCX Methodology and Vision for the Future. NCX. https://info.ncx.com/fws-methodology-and-vision-on-demand

NCX. (n.d.). Transparency Drives Trust in Carbon Credit Quality: Announcing the NCX Next Generation Harvest Deferral Methodology. NCX. https://info.ncx.com/next-generation-methodology

Nendel, C., Reckling, M., Debaeke, P., Schulz, S., Berg-Mohnicke, M., Constantin, J., Fronzek, S., Hoffmann, M., Jakšić, S., Kersebaum, K., Klimek-Kopyra, A., Raynal, H., Schoving, C., Stella, T., & Battisti, R. (2022). Future area expansion outweighs increasing drought risk for soybean in Europe. Global Change Biology, 29(5), 1340–1358. https://doi.org/10.1111/gcb.16562

NEREUS, European Space Agency & European Commission (2018). The ever growing use of Copernicus across Europe's regions. https://indd.adobe.com/view/5352a668-e4d4-4696-924d-364a358ff650

Netzwerk Solidarische Landwirtschaft e.V. (2025). Bestehende Solawis und Solawis in Gründung, https://www.solidarische-landwirtschaft.org/solawis-finden/auflistung/solawis/

Neyter R., Zorya S. and Muliar O. (2024). Agricultural War Damages, Losses, and Needs Review. KSE Center for Food and Land Use Research. https://kse.ua/agricultural-war-damages-review/

Nhokovedzo, S, (2024). A comparative analysis of Delphi Method and Horizon Scanning. Journal of Futures Studies. https://jfsdigital.org/a-comparative-analysis-of-delphi-method-and-horizon-scanning/

NIS Cooperation Group. (2024). Cybersecurity and resiliency of Europe's communications infrastructures and networks. https://digital-strategy.ec.europa.eu/en/library/report-cybersecurity-and-resiliency-eu-communications-infrastructures-and-networks.

Nuscheler, D., Fiocco, D., Prabhala, P., Perdur, RS M,. Breenan, T. & Gautam Y. (2024). From bytes to bushels; How gen AI can shape the future of agriculture. https://www.mckinsey.com/industries/agriculture/our-insights/from-bytes-to-bushels-how-gen-ai-can-shape-the-future-of-agriculture

Oliver Wyman. (2022). GROWTrees Initiative: Reforestation for Climate and Community. Oliver Wyman. https://www.oliverwyman.com/our-expertise/insights/2022/mar/growtrees-initiative-reforestation-for-climate-and-community.html

Omar, A., & Thorsøe, M. H. (2023). Rebalance power and strengthen farmers' position in the EU food system? A CDA of the Farm to Fork Strategy. Agriculture and Human Values, 41(2), 631–646. https://doi.org/10.1007/s10460-023-10508-5

Organisation for Economic Co-operation and Development (OECD). (2023). Policies for the Future of Farming and Food in the European Union. OECD Agriculture and Food Policy Reviews. https://doi.org/10.1787/32810cf6-en.

Oyedijo, A. & Akenroye, T. (2024). Here's how we make the $9 trillion global food supply chain sustainable. https://www.weforum.org/stories/2024/08/food-supply-chain-networks-why-sustainable-practices-fail-and-approaches-to-improve-them/

PAC Network. (2024). The European Union assesses the role of the CAP and the LEADER approach in rural development. https://redpac.es/en/news/european-union-assesses-role-cap-and-leader-approach-rural-development

Padmakumar V & Shanthakumar M. (2024). Ecological factors shaping the evolution and behavior of spoonbills: insights for conservation and management. Int J Avian & Wildlife Biol. 2024;8(2):72–75. https://medcraveonline.com/IJAWB/ecological-factors-shaping-the-evolution-and-behavior-of-spoonbills-insights-for-conservation-and-management.html

Pallottino, F., Violino, S., Figorilli, S., Pane, C., Aguzzi, J., Colle, G., Nemmi, E. N., Montaghi, A., Chatzievangelou, D., Antonucci, F., Moscovini, L., Mei, A., Costa, C., & Ortenzi, L. (2025). Applications and perspectives of Generative Artificial Intelligence in agriculture. Computers and Electronics in Agriculture, 230, 109919. https://doi.org/10.1016/j.compag.2025.109919

Pedersen, S. M., Erekalo, K. T., Christensen, T., Denver, S., Gemtou, M., Fountas, S., Isakhanyan, G., Rosemarin, A., Ekane, N., Puggaard, L., Nertinger, M., Brinks, H., Puško, D., & Adrián, J. B. (2024). Drivers and Barriers to Climate-Smart Agricultural Practices and Technologies Adoption: Insights from stakeholders of Five European Food Supply Chains. Smart Agricultural Technology, 100478. https://doi.org/10.1016/j.atech.2024.100478

Pellegrini, M. (2024). Adapting to Changing Consumer Preferences: Trends and Strategies. Food Industry Executive. https://foodindustryexecutive.com/2024/12/adapting-to-changing-consumer-preferences-trends-and-strategies/

Pells, R. (2023). How France became the unlikely home of the insect-farming industry. Nature. https://doi.org/10.1038/d41586-023-00290-z

Peters, K. (2024). A healthier planet for healthier people: Inside ZS's strategy to reduce Scope 3 emissions. ZS. https://www.zs.com/life-at-zs-insights/a-healthier-planet-for-healthier-people-zs-scope-3-strategy

Petruk, I. (2024). The potential of controlled environment agriculture. Infopulse. https://www.infopulse.com/blog/pros-and-cons-of-cea

Pfenning-Butterworth, A., Buckley, L. B., Drake, J. M., Farner, J. E., Farrell, M. J., Gehman, A. M., Mordecai, M., E. A., Stephens, P. R., Gittleman, J. L., & Davies, T. J. (2024). Interconnecting global threats: climate change, biodiversity loss, and infectious diseases. The Lancet Planetary Health, 8(4), e270–e283. https://doi.org/10.1016/s2542-5196(24)00021-4

Pilar, L., Stanislavská, L. K., & Kvasnička, R. (2021). Healthy food on the Twitter social network: Vegan, homemade, and organic food. International Journal of Environmental Research and Public Health, 18(7), 3815. https://doi.org/10.3390/ijerph18073815

Planet Labs PBC. (2025). Satellite Imagery for Deforestation Monitoring. Planet Labs PBC. https://www.planet.com/solutions/deforestation-monitoring/

Policy Horizons Canada. (2024). Disruptions on the horizon. https://horizons.service.canada.ca/en/2024/disruptions/index.shtml

Precedence Research. (2024). Agricultural Biotechnology Market Size, Share, and Trends 2024 to 2034. https://www.precedenceresearch.com/agricultural-biotechnology-market

Precious Woods Holding Ltd. (2013). Precious Woods: Sustainable management of tropical forests. Innovative market performance. Precious Woods Holding Ltd. https://www.preciouswoods.com/domains/preciouswoods_com/data/free_docs/PW_Broschuere_EN_digital_2.pdf

Precious Woods Holding Ltd. (2020). Precious Woods Online Half-Year Report 2020. Precious Woods. https://www.preciouswoods.com/pt/home

Precision Reports (2024). Iot Platforms Market Outlook: Anticipated Growth Trends and Strategies for 2032 and Beyond. https://www.linkedin.com/pulse/iot-platforms-market-outlook-anticipated-growth-trends-strategies-bsmae/

Preiss, M., Vogt, J. H., Dreher, C., & Schreiner, M. (2022). Trends shaping Western European agrifood systems of the future. Sustainability, 14(21), 1976. https://doi.org/10.3390/su142113976

Prepscius, J., Buysing Damsté, C., & de Vos van Steenwijk, A. (2025). Navigating EU Deforestation Regulation: from guidelines to best practices. PwC. https://www.pwc.com/gx/en/services/tax/esg-tax/navigating-eu-deforestation-regulation.html

Proctor, J., Hsiang, S., Burney, J., Burke, M., & Schlenker, W. (2018). Estimating global agricultural effects of geoengineering using volcanic eruptions. Nature, 560(7719), 480–483. https://doi.org/10.1038/s41586-018-0417-3

Prophecy Market Insights (PMI). (2024). Agricultural Nanotechnology Market Size, Share, by Type. https://www.prophecymarketinsights.com/market_insight/agricultural-nanotechnology-market-5534

Przetacznik J. and Stanicek B. (2023). Enlargement policy: Reforms and challenges ahead. EPRS, European Parliament. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)757575

PwC. (2024). Nature & biodiversity: Creating nature positivity. https://www.pwc.com/gx/en/issues/esg/nature-and-biodiversity.html

PwC. (2025). 2025 State of Decarbonization: Sector Insights. https://www.pwc.com/us/en/services/esg/library/decarbonization-strategic-plan/sector-insights.html

Rashidinejad, A. (2024b). The road ahead for functional foods: Promising opportunities amidst industry challenges. Future Postharvest and Food, 1(2), 266–273. https://doi.org/10.1002/fpf2.12022

ReFarm. (2023). “GigaFarm” capable of replacing 1% of UAE food imports set for construction in Dubai Food Tech Valley. GlobeNewswire. https://www.globenewswire.com/en/news-release/2023/12/06/2791780/0/en/GigaFarm-capable-of-replacing-1-of-UAE-food-imports-set-for-construction-in-Dubai-Food-Tech-Valley.html

Resource Management Service, LLC. (2024). RMS GHG Inventory Methodology: Greenhouse Gas Inventory Methodology (Report Version 2.0). Resource Management Service, LLC. https://resourcemgt.com/wp-content/uploads/RMS-Greenhouse-Gas-Inventory-Methodology-v2.0.pdf

Rights of Future Generations. (2023). The Maastricht Principles on the Human Rights of Future Generations. https://www.rightsoffuturegenerations.org/

Roland Berger GmbH. (2023). Biodiversity valuation: How measuring the value of biodiversity can help avoid an ecological collapse and fight climate change. Roland Berger GmbH. https://www.rolandberger.com/publications/publication_pdf/23_2165_STU_Biodiversity_valuation-03.pdf

Roos, A., Blomquist, M., Bhatia, R., Ekegren, K., Rönnberg, J., Torfgård, L., & Tunberg, M. (2021). The digitalisation of the Nordic bioeconomy and its effect on gender equality. Scandinavian Journal of Forest Research, 36(7–8), 639–654. https://doi.org/10.1080/02827581.2021.1996629

Rose, D. C., Sutherland, W. J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., & Dicks, L. V. (2016). Decision support tools for agriculture: Towards effective design and delivery. Agricultural Systems, 149, 165–174. https://doi.org/10.1016/j.agsy.2016.09.009

RPS Group. (2025). Aerial LiDAR Spatial Data Capture, Processing and Insights. RPS Group. https://www.rpsgroup.com/media/n2hb1e4f/lidar_brochure.pdf

Samling Plywood. (Lawas) Sdn Bhd. (2023). Public Summary for Forest Management Plan for Layun Forest Management Unit (T/0405) for the period 2021 to 2030. Samling Group of Companies. https://www.samling.com/wp-content/uploads/2024/11/Layun-Public-Summary-20230531.pdf

Samling Reforestation. (Bintulu) Sdn Bhd. (2023). Forest Plantation Management Plan for the MTCS Area within PAONG LPF/0021: Public Summary (1 January 2023 to 31 December

2032). Samling Group of Companies. https://www.samling.com/wp-content/uploads/2024/11/Paong-LPF-0021-30-May-23.pdf

Samling Timber Malaysia. (2024). Upstream Timber Operations. Samling Timber Malaysia. https://www.samling.com/upstream-timber-operations/

Santos, F. J., Guzmán, C. & Ahumada, P. (2024). Assessing the digital transformation in agri-food cooperatives and its determinants, Journal of Rural Studies, Volume 105, https://doi.org/10.1016/j.jrurstud.2023.103168

Santosh, D.T. & Shukla, Chitra. (2024). Innovations in Aquaponics: Components, Operations, and Economic Viability. In: Sairam, M., Santosh, DT., Gaikwad, D.J. & Maitra, S. (eds.) Advances in modern agricultural practices. https://www.researchgate.net/publication/378496706_Innovations_in_Aquaponics_Components_Operations_and_Economic_Viability

Sai, S., Kumar, S., Gaur, A., Goyal, S., Chamola, V., & Hussain, A. (2025). Unleashing the power of generative AI in agriculture 4.0 for smart and sustainable farming. Cognitive Computation, 17(1). https://doi.org/10.1007/s12559-025-10420-6

Sauvagerd, M., Mayer, M., & Hartmann, M. (2024). Digital platforms in the agricultural sector: Dynamics of oligopolistic platformisation. Big Data & Society, 11(4). https://doi.org/10.1177/20539517241306365 (Original work published 2024)

Sawano, T. (2024). Ingredient Informatics: The future of food development – R&D Innovations co-created by AI. https://www.mitsui.com/mgssi/en/report/detail/__icsFiles/afieldfile/2024/03/18/2401report_4_sawano_e.pdf

Schafer, E. (2024). Predictions for the future insect protein market. Feed Mill of the Future. https://www.feedmillofthefuture.com/protein-of-the-future/article/15663697/predictions-for-the-future-insect-protein-market

Scherger, S. (2022) Carbon Farming: How big corporations are driving the EU's carbon removals agenda. https://www.iatp.org/big-corporations-driving-eus-carbon-farming-agenda

Schiavo, M., Le Mouël, C., Poux, X., & Aubert, P.-M. (2021). An agroecological Europe by 2050: What impact on land use, trade and global food security? https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Etude/202107-ST0821_TYFA%20World_1.pdf

Schlemminger, M., Lohr, C., Peterssen, F., Bredemeier, D., Niepelt, R., Bensmann, A., Hanke-Rauschenbach, R., Breitner, M. H., & Brendel, R. (2024). Land competition and its impact on decarbonized energy systems: A case study for Germany. Energy Strategy Reviews, 55, 101502. https://doi.org/10.1016/j.esr.2024.101502

Schroeder, K., Lampietti, J., & Elabed, G. (2021). What's cooking: Digital transformation of the agrifood system. World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/417641615957226621/whats-cooking-digital-transformation-of-the-agrifood-system

Schuh, B. et al. (2022). Research for AGRI Committee – The Future of the European Farming Model: Socio-economic and territorial implications of the decline in the number of farms and farmers in the EU. European Parliament, Policy Department for Structural and Cohesion Policies. https://www.europarl.europa.eu/RegData/etudes/STUD/2022/699620/IPOL_STU(2022)699620_EN.pdf

Schürings, C., Globevnik, L., Lemm, J. U., Psomas, A., Snoj, L., Hering, D., & Birk, S. (2024). River ecological status is shaped by agricultural land use intensity across Europe. Water Research, 251, 121136. https://doi.org/10.1016/j.watres.2024.121136

Sedna Technologies. (2024). https://www.sednatech.io/

Sharma, N., Colucci-Gray, L., Lakeman-Fraser, P., Robinson, A., Newman, J., Van Der Wal, R., Rueger, S., & Siddharthan, A. (2024). Image Recognition as a "Dialogic AI Partner" Within Biodiversity Citizen Science—an empirical investigation. *Citizen Science Theory and Practice*, *9*(1). https://doi.org/10.5334/cstp.735

Shelton, D. (2023). Stockholm Declaration (1972) and Rio Declaration (1992). Oxford Public International Law. https://opil.ouplaw.com/display/10.1093/law:epil/9780199231690/law-9780199231690-e1608

Simeone, M., & Scarpato, D. (2020). Sustainable consumption: How does social media affect food choices? Journal of Cleaner Production, 277, 124036. https://doi.org/10.1016/j.jclepro.2020.124036

Sitra. (2019). Start here – Trends and signals. https://www.sitra.fi/en/cases/start-here-trends-and-signals

Sloan, A.E. (2020). The Top 10 Functional Food Trends. https://realriskap.com/helados/wp-content/uploads/2020/10/The-Top-10-Functional-Food-Trends-IFT.pdf

Squire, H. J., Tomatz, S., Voke, E., González-Grandío, E., & Landry, M. (2023). The emerging role of nanotechnology in plant genetic engineering. Nature Reviews Bioengineering, 1(5), 314–328. https://doi.org/10.1038/s44222-023-00037-5

Stargate. (2024). Resilient Farming by Adaptive Microclimate Management. https://www.stargate-h2020.eu

StartUs Insights. (2021). 5 Top Food Tech Startups increasing Transparency. https://www.startus-insights.com/innovators-guide/5-top-food-tech-startups-increasing-transparency/

Stora Enso. (2023). Annual Report 2022. https://www.storaenso.com/-/media/documents/download-center/documents/annual-reports/2022/storaenso_annual_report_2022.pdf

Störmer, E., Bontoux, L., Krzysztofowicz, M., Florescu, E., Bock, A., & Scapolo, F. (2020). Foresight – using science and evidence to anticipate and shape the future. In Elsevier eBooks (pp. 128–142). https://doi.org/10.1016/b978-0-12-822596-7.00012-7

Stummer, H. (2024). Schnitzel out of the Reactor. Popchop. https://popchop.at/zukunft/schnitzel-out-of-the-reactor/

Sukharevsky, A., Kerr, D., Hjartar, K., Hämäläinen, L., Bout, S., Di Leo, V. & Dagorret, G. (2025). Seizing the agentic AI advantage.

https://www.mckinsey.com/capabilities/quantumblack/our-insights/seizing-the-agentic-ai-advantage

Sustainability Directory. (2025). Personalised Nutrition in Climate-Controlled Environments. https://prism.sustainability-directory.com/scenario/personalized-nutrition-in-climate-controlled-environments/

Sutherland, L. A. (2023). Who do we want our 'new generation' of farmers to be? The need for demographic reform in European agriculture. Agric Econ 11, 3, https://doi.org/10.1186/s40100-023-00244

Sutherland, L. A., Monllor, N., Pinto-Correira, T. (2015). New entrants into farming: lessons to foster innovation and entrepreneurship. Minipaper: Gender issues among new entrants. https://ec.europa.eu/eip/agriculture/sites/agrieip/files/fg14_03_minipaper_gender_.pdf

Sveaskog. (2019). Sveaskog tidigt ute med digital leveransavisering. Sveaskog. https://www.sveaskog.se/skogen-pa-djupet/digitalisering-och-teknik/sveaskog-tidigt-ute-med-digital-leveransavisering/

Sveaskog. (2022). Sveaskog och ForestX lanserar KingPin – ett nytt AI-verktyg som ökar skogens värde. Sveaskog. https://www.sveaskog.se/press/2022/sveaskog-och-forestx-lanserar-kingpin--ett-nytt-ai-verktyg-som-okar-skogens-varde/

Sveaskog. (2023). Green bond framework 2023. Sveaskog AB. https://www.sveaskog.se/globalassets/om-sveaskog/finansiering/sveaskog_vart_grona_ramverk_2023.pdf

Sveaskog. (2023). Sveaskog deltar i projekt med fokus på elektrifiering av skogsbrukets vägtransporter. Sveaskog. https://www.sveaskog.se/press/2023/sveaskog-deltar-i-projekt-med-fokus-pa-elektrifiering-av-skogsbrukets-vagtransporter/

Sveaskog. (2023). Sveaskog investerar i AI-bolag – blir delägare i Nordic Forestry Automation. Sveaskog. https://www.sveaskog.se/press/2023/sveaskog-investerar-i-ai-bolag--blir-delagare-i-nordic-forestry-automation/

Sveaskog. (2024). Sveaskog nature value assessments. Sveaskog. https://www.sveaskog.se/en/vart-skogsbruk/att-forvalta-skogslandskapet/sveaskog-nature-value-assessments/

Sveaskog. (2024). Sveaskog och AirForestry stärker sitt partnerskap. Sveaskog. https://www.sveaskog.se/skogen-pa-djupet/digitalisering-och-teknik/sveaskog-och-airforestry-starker-sitt-partnerskap/

Syarikat Samling Timber Sdn Bhd. (2024). Forest Management Plan for Forest Management Unit (T/0294) Ravenscourt Sdn Bhd for the period 2016 to 2025 (Edition 10, July 2024). Samling Group of Companies. https://www.samling.com/wp-content/uploads/2025/02/Ravenscourt-FMU-Public-Summary-Ed.-10-v2-1.pdf

Syngenta. (2024). Syngenta Integrates Cool Farm Tool Into the Cropwise Sustainability Application. Global AgTech Initiative. https://www.globalagtechinitiative.com/digital-farming/analytics/syngenta-integrates-cool-farm-tool-into-the-cropwise-sustainability-application/

Taran S. and Lausberg P. (2024). Economic security: The strategic argument for Ukraine's EU membership. European Policy Centre. https://www.epc.eu/en/Publications/Economic-security-The-strategic-argument-for-Ukraines-EU-membership%7E57c2cc

Tay, C.M. (2024). Global ag-food digital traceability needs greater inclusivity and collaboration to progress. https://www.agtechnavigator.com/Article/2024/05/30/global-ag-food-digital-traceability-needs-greater-inclusivity-and-collaboration-to-progress

The Davey Tree Expert Company. (2023). Create a Digital Urban Forest with New Technology. The Davey Tree Expert Company. https://www.davey.com/environmental-consulting-services/resources-news/create-a-digital-urban-forest-with-new-technology/

The Davey Tree Expert Company. (2023). DRG and greehill partner to deliver digital tree inventory to US cities. The Davey Tree Expert Company. https://www.davey.com/about/newsroom/drg-and-greehill-partner-to-deliver-digital-tree-inventory-to-us-cities/

The Davey Tree Expert Company. (2025). iTree Tree Benefits Tool. The Davey Tree Expert Company. https://www.davey.com/about/davey-institute/itree/

The Davey Tree Expert Company. (2025). Smart Urban Forestry With Smart Tree Inventory. The Davey Tree Expert Company. https://www.davey.com/environmental-consulting-services/smart-tree-inventory/

The Davey Tree Expert Company. (2025). Urban Tree Canopy Assessment. Davey Resource Group, The Davey Tree Expert Company. https://www.davey.com/environmental-consulting-services/urban-community-forestry/urban-tree-canopy-assessment/

The Nature Conservancy & Willis Towers Watson. (2021). Willis and The Nature Conservancy Launch First-of-its-Kind Wildfire Resilience Insurance. WTW. https://www.wtwco.com/en-se/news/2025/04/willis-and-the-nature-conservancy-launch-first-of-its-kind-wildfire-resilience-insurance

Think Tank EUROPA. (2023). High-level Insights: Food Systems in an Age of Polycrisis, https://thinkeuropa.dk/brief/2023-09-high-level-insights-food-systems-in-an-age-of-polycrisis

Tortajada, C. & Zhang, H. (2021). When food meets BRI: China's emerging Food Silk Road, Global Food Security, Volume 29, 100518, https://doi.org/10.1016/j.gfs.2021.100518.

Trafton, A. (2023). MIT’s Green Revolution: Transforming agriculture with microbial fertilizers. SciTechDaily. https://scitechdaily.com/mits-green-revolution-transforming-agriculture-with-microbial-fertilizers.

TransGEN. (2024). Ohne Tiere, aber mit viel High-Biotech: Fleisch aus Zellkultur kommt auf den Markt. https://www.transgen.de/lebensmittel/2700.fleisch-zellkultur-biotechnologie.html

Transparency Market Research. (2022). Algae Market. https://www.transparencymarketresearch.com/algae-market.html

Trendov, N. M., Varas, S., & Zeng, M. (2019). Digital technologies in agriculture and rural areas. Food and Agriculture Organisation. https://openknowledge.fao.org/items/ba78b670-0947-4e73-ad10-091009c0dfc3

Tunberg, M. (2022). Digital transformation can improve gender equality in the bioeconomy, but it will not happen automatically. https://www.analysysmason.com/contentassets/2b8c645498f747bbb93bcbe3ccdcd1fb/analysys_mason_gender_imbalance_bioeconomy_jan2022.pdf

Tzachor, A., Devare, M., King, B., Avin, S., & Héigeartaigh, S. Ó. (2022). Responsible artificial intelligence in agriculture requires systemic understanding of risks and externalities. Nature Machine Intelligence, 4(2), 104–109. https://doi.org/10.1038/s42256-022-00440-4

Unay-Gailhard, I. & Bojnec, S. (2021). Gender and the environmental concerns of young farmers: Do young women farmers make a difference on family farms?, Journal of Rural Studies, Volume 88, pp. 71-82, https://doi.org/10.1016/j.jrurstud.2021.09.027

United Nations Department of Economic and Social Affairs (UN DESA). (2024). The 17 Goals. https://sdgs.un.org/goals

United Nations Development Programme (UNDP). (2018). Foresight Manual. Empowered Futures for the 2030 Agenda. Global Centre for Public Service Excellence. https://www.undp.org/sites/g/files/zskgke326/files/publications/UNDP_ForesightManual_2018.pdf

United Nations Environment Programme (UNEP). (2019). Environmental Rule of Law: First Global Report. https://www.unep.org/resources/assessment/environmental-rule-law-first-global-report

United Nations Environment Programme (UNEP). (2022). Convention on Biological Diversity. DECISION ADOPTED BY THE CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY. 15/4. Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

United Nations General Assembly (UNGA). (2024). The Pact for the Future. Resolution adopted by the General Assembly on 22 September 2024. A/RES/79/1. https://docs.un.org/en/A/RES/79/1

Vaccaro, I., Oriol, B. & Del Mármol, C. (2023). Reimagining modern politics in the European mountains: confronting the traditional commons with the neo-rural conception of the common good. Theory and Society. 53. 1-21. 10.1007/s11186-023-09528-1.

Valor Florestal. (2018). Gestão – Valor Florestal. Valor Florestal. https://www.valorflorestal.com.br/gestaoflorestal-2/

Van der Velde, E., Kretz, D., Lecluyse, L., Kincsö, I., Markianidou, P., & Moreno, C. (2023). Monitoring the twin transition of industrial ecosystems. AGRI-FOOD Analytical report. https://monitor-industrial-ecosystems.ec.europa.eu/sites/default/files/2023-12/EMI%20Agrifood%20industrial%20ecosystem%20report.pdf

Van Woensel, L., Kurrer, C., Tarlton, J., Schrijver, R., Poppe, K., Daheim, C., Bol, E., & Hartog – De Wilde, S. D. (2016). Precision agriculture and the future of farming in Europe. In European Parliament & Science and Technology Options Assessment (STOA) Panel, Scientific Foresight Study. European Union. https://doi.org/10.2861/020809

Vasile, M. (2019). Forest and pasture commons in Romania: Territories of life, potential iccas: country report, https://www.iccaconsortium.org/wp-content/uploads/2019/07/CommonsRomaniaPotentialICCAS2019.pdf

Venkataraman, H., Westerhof, K., & Olson, S. (2019). The Digital Transformation of the Food Industry. https://web.luxresearchinc.com/hubfs/Press%20Release%20Assets/Lux%20Research%20-%20The%20Digital%20Transformation%20of%20the%20Food%20Industry.pdf

Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. Agricultural Systems, 189, 103046. https://doi.org/10.1016/j.agsy.2020.103046

Vesnic Alujevic, L., Muench, S. & Stoermer, E. (2023). Reference foresight scenarios: Scenarios on the global standing of the EU in 2040. doi:10.2760/11879

Von der Leyen, U. (2023). 2023 State of the Union Address. https://ec.europa.eu/commission/presscorner/detail/en/speech_23_4426

Vos, R. (2024). The war in Ukraine continues to undermine the food security of millions. IFPRI Blog: Issue Post Markets, Trade, and Institutions. https://www.ifpri.org/blog/war-ukraine-continues-undermine-food-security-millions/

Vujović, D. (2024). Generative AI: Riding the new general purpose technology storm. Ekonomika Preduzeca, 72(1–2), 125–136. https://doi.org/10.5937/ekopre2402125v

Wageningen University and Research (WUR). (2024a). Biodiversity, agriculture and food. https://www.wur.nl/en/research-results/themes/biodiversity/biodiversity-agriculture-and-food.htm

Wageningen University and Research (WUR). (2024b). Precision agriculture – Smart farming. https://www.wur.nl/en/research-results/dossiers/file/dossier-precision-agriculture.htm

Walsh, N. P. (2022). How the Dutch Use Architecture to Feed the World. ArchDaily. https://www.archdaily.com/932301/how-the-dutch-use-architecture-to-feed-the-world

Wang, G. G., Lu, D., Gao, T., Zhang, J., Sun, Y., Teng, D., Yu, F., & Zhu, J. (2024). Climate-smart forestry: an AI-enabled sustainable forest management solution for climate change adaptation and mitigation. Journal of Forestry Research, 36(1). https://doi.org/10.1007/s11676-024-01802-x

Wani, I., Ramola, S., Garg, A., & Kushvaha, V. (2021). Critical review of biochar applications in geoengineering infrastructure: moving beyond agricultural and environmental perspectives. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-01346-8

Weinand, J. M., Pelser, T., Kleinebrahm, M., & Stolten, D. (2025). Countries across the world use more land for golf courses than wind or solar energy. Environmental Research Communications. https://doi.org/10.1088/2515-7620/adb7bd

Weller, C. (2017). A robot has just been granted citizenship of Saudi Arabia. https://www.weforum.org/stories/2017/10/a-robot-has-just-been-granted-citizenship-of-saudi-arabia/

Weyerhaeuser Company. (n.d.). How We Do It. Weyerhaeuser Company. https://www.weyerhaeuser.com/sustainability/how-we-do-it/

Wiklund, J. (2023). Growing Up - CEA & the Future of Indoor Farming - The Food Institute. The Food Institute. https://foodinstitute.com/focus/growing-up-cea-the-future-of-indoor-farming/

Wilkinson, A. (2017). Strategic foresight primer. European Political Strategy Center. https://data.europa.eu/doi/10.2872/71492

Willis Limited / Willis Re Inc. (2018). Willis Re Wildfire Hazard Score. Willis Limited / Willis Re Inc. https://www.wtwco.com/-/media/wtw/solutions/services/willis-re-wildfire-hazard-score---one-pager.pdf?modified=20190422195412

Wolczuk, K. (2023). Overcoming EU Accession Challenges in Eastern Europe: Avoiding Purgatory. Carnegie Europe. https://carnegieendowment.org/research/2023/06/overcoming-eu-accession-challenges-in-eastern-europe-avoiding-purgatory?lang=en&center=europe

World Economic Forum (WEF). (2022). Transforming Food Systems with Farmers. A Pathway for the EU. https://www3.weforum.org/docs/WEF_Transforming_Food_Systems_with_Farmers_A_Pathway_for_the_EU_2022.pdf

World Economic Forum (WEF). (2023). This is how war in Europe is disrupting fertilizer supplies and threatening global food security. https://www.weforum.org/agenda/2023/03/ukraine-fertilizer-food-security/

World Economic Forum (WEF). (2024). Agritech for Women Farmers: A Business Case for Inclusive Growth, https://reports.weforum.org/docs/WEF_Agritech_for_Women_Farmers_2024.pdf

World Trade Organisation (WTO). (2023). WTO issues note on trade policy developments following one year of war in Ukraine. https://www.wto.org/english/news_e/news23_e/trdev_02mar23_e.htm

World Trade Organisation (WTO). (2025). Charts – World trade in agricultural products. https://www.wto.org/english/tratop_e/agric_e/ag_imp_exp_charts_e.htm

Wydra, S., Reyhani, M.N., Hüsing, B., & Schwarz, A. (2023). Exploring Innovative Technology Fields for a Circular Bio-Based Economy. https://publica-rest.fraunhofer.de/server/api/core/bitstreams/159d78f0-af08-443c-8a36-39b8c25f59b2/content

Yazdinejad, A., Zolfaghari, B., Azmoodeh, A., Dehghantanha, A., Karimipour, H., Fraser, E., Green, A. G., Russell, C., & Duncan, E. (2021). A Review on Security of Smart Farming and Precision Agriculture: Security aspects, attacks, threats and Countermeasures. Applied Sciences, 11(16), 7518. https://doi.org/10.3390/app11167518

Yee, L., Chui, M., Roberts, R. & Xu, S. (2024). What agents are the next frontier of generative AI. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/why-agents-are-the-next-frontier-of-generative-ai

Zhang, Z., Abdullah, M. J., Xu, G., Matsubae, K., & Zeng, X. (2023). Countries' vulnerability to food supply disruptions caused by the Russia–Ukraine war from a trade dependency perspective. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-43883-4