Addressing uncertainty and normativity in agricultural sustainability assessment: the example of agricultural digitalization

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‘It is of great use to the sailor to know the length of his line, though he cannot with it fathom all the depths of the ocean.’- John Locke: An Essay Concerning Human Understanding

Abstract

Agriculture's role in meeting global food needs has historically relied on increased productivity and land expansion. However, conventional agriculture, despite its productivity, poses daunting environmental challenges, including biodiversity loss, climate change, and water pollution. Socio-economic issues such as price instability and rural decline further complicate agricultural sustainability. Agricultural systems face repercussions from challenges they contribute to, such as climate change impacts and soil degradation, raising concerns about resource depletion and public perception of farming practices. While technological advancements such as digitalization offer promise for efficiency improvements, they also introduce potential risks. The United Nations Sustainable Development Goals and the European Union’s Green Deal's Farm to Fork Strategy underscore the necessity of adopting innovative and sustainable agricultural practices. However, achieving agricultural sustainability requires collaborative efforts beyond policy initiatives, involving stakeholders such as farmers, researchers, and civil society organizations. In this regard, context-specific approaches and comprehensive sustainability assessment are crucial for advancing agricultural sustainability and aligning with policy objectives.

The primary objective of this thesis is to explore how integrative methodologies can enhance the state-of-the-art of agricultural sustainability assessments. To fulfill this objective, in the first study, a review of agricultural sustainability tools and models was conducted, assessing their thematic coverage of integrative sustainability concepts such as ecosystem services and the UN Sustainable Development Goals (SDGs). In the subsequent study, an interdisciplinary approach integrating policy, law, and foresight analysis was utilized to examine agriculturally related policies and laws, discerning their sustainability implications in the realm of digital agriculture under probable future scenarios. In the last study, stakeholder knowledge was integrated through a participatory modeling approach to construct a Bayesian belief network, which assessed the effects of digital agriculture on agricultural sustainability.

The findings of this thesis demonstrate that existing tools and methodologies for assessing agricultural sustainability often lack sufficient integration with the ecosystem service framework and the UN SDGs. Additionally, the thesis emphasizes the advantages of an interdisciplinary approach integrating policy, law, and scenario analysis to evaluate the sustainability impacts of digital agriculture, showing that without clear policy and law to guide and regulate agricultural digitalization, that it will most likely not be leveraged toward achieving sustainability. Finally, the thesis showed that engaging stakeholders in participatory modeling can improve the contextual specificity of agricultural sustainability assessments by capturing both implicit and explicit stakeholder knowledge of local conditions.

The thesis demonstrates different analytical tools for managing uncertainty in sustainability assessment. It further highlights that enhancing the comprehensiveness of indicators within sustainability assessment methods will enable better capture of site-specific characteristics of ecosystem service supply and use, while standardization of indicators will help operationalize outcomes for higher levels of sustainability assessment necessary for achieving sustainability goals.

Keywords: agriculture, sustainability assessment, participatory modelling, policy, law, foresight, digital agriculture, ecosystem services, SDGs, Brandenburg

Zusammenfassung

Die Rolle der Landwirtschaft bei der Deckung des weltweiten Nahrungsmittelbedarfs beruht seit jeher auf Produktivitätssteigerung und Flächenausweitung. Trotz ihrer Produktivität ist die konventionelle Landwirtschaft jedoch mit gewaltigen Umweltproblemen konfrontiert, wie dem Verlust der biologischen Vielfalt, dem Klimawandel und der Wasserverschmutzung. Sozioökonomische Probleme wie Preisinstabilität und ländlicher Niedergang erschweren die Nachhaltigkeit der Landwirtschaft zusätzlich. Die landwirtschaftlichen Systeme sind mit den Auswirkungen der Herausforderungen konfrontiert, zu denen sie beitragen, wie z. B. den Auswirkungen des Klimawandels und der Bodendegradation, was Bedenken hinsichtlich der Erschöpfung der Ressourcen und der öffentlichen Wahrnehmung der landwirtschaftlichen Praktiken aufkommen lässt. Technologische Fortschritte wie die Digitalisierung bieten zwar vielversprechende Möglichkeiten für Effizienz und Ressourcenmanagement, bergen aber auch potenzielle Risiken. Die Ziele der Vereinten Nationen für nachhaltige Entwicklung und die Farm-to-Fork-Strategie des Europäischen Green Deals betonen die Notwendigkeit innovativer und nachhaltiger landwirtschaftlicher Praktiken. Die Verwirklichung der Nachhaltigkeit in der Landwirtschaft erfordert jedoch gemeinsame Anstrengungen, die über politische Initiativen hinausgehen und Akteure wie Landwirte, Forscher und Organisationen der Zivilgesellschaft einbeziehen. In dieser Hinsicht sind kontextspezifische Ansätze und eine umfassende Nachhaltigkeitsbewertung von entscheidender Bedeutung, um die landwirtschaftliche Nachhaltigkeit voranzubringen und mit den politischen Zielen in Einklang zu bringen.

Das Hauptziel dieser Arbeit ist es, zu untersuchen, wie integrative Methoden den Stand der Technik bei der Bewertung der landwirtschaftlichen Nachhaltigkeit verbessern können. Um dieses Ziel zu erreichen, wurde in der ersten Studie ein Überblick über landwirtschaftliche Nachhaltigkeitsinstrumente und -modelle erstellt und deren thematische Abdeckung von integrativen Nachhaltigkeitskonzepten wie Ökosystemleistungen und den UN-Nachhaltigkeitszielen (SDGs) bewertet. In der darauffolgenden Studie wurde ein interdisziplinärer Ansatz verwendet, der Politik, Recht und vorausschauende Analyse integriert, um agrarbezogene Politiken und Gesetze zu untersuchen und ihre Auswirkungen auf die Nachhaltigkeit im Bereich der digitalen Landwirtschaft unter wahrscheinlichen Zukunftsszenarien zu erkennen. In der letzten Studie wurde das Wissen der Stakeholder durch einen partizipativen Modellierungsansatz integriert, um ein Bayes'sches Netzwerk zu konstruieren, das die Auswirkungen der digitalen Landwirtschaft auf die landwirtschaftliche Nachhaltigkeit bewertet.

Die Ergebnisse zeigen, dass bestehende Methoden zur Bewertung landwirtschaftlicher Nachhaltigkeit oft nicht ausreichend mit dem Rahmenwerk für Ökosystemdienstleistungen und den UN-SDGs integriert sind. Die Arbeit betont die Vorteile eines interdisziplinären Ansatzes, der Politik, Recht und Szenarioanalyse integriert, um die Nachhaltigkeitsauswirkungen der digitalen Landwirtschaft zu bewerten. Sie zeigt, dass die Digitalisierung der Landwirtschaft ohne klare politische und rechtliche Vorgaben und Regelungen höchstwahrscheinlich nicht im Sinne der Nachhaltigkeit genutzt werden kann. Schließlich hat die Arbeit gezeigt, dass die Einbeziehung von Stakeholdern in die partizipative Modellierung die Kontextspezifität von landwirtschaftlichen Nachhaltigkeitsbewertungen verbessern kann, indem sowohl implizites als auch explizites Wissen der Stakeholder über lokale Bedingungen erfasst wird. Darüber hinaus wird hervorgehoben, dass die Standardisierung von Indikatoren dazu beitragen wird, Ergebnisse für höhere Ebenen der Nachhaltigkeitsbewertung zu operationalisieren, die für die Erreichung von Nachhaltigkeitszielen erforderlich sind.

Stichworte: Landwirtschaft, Nachhaltigkeitsbewertung, partizipative Modellierung, Politik, Recht, Zukunftsforschung, digitale Landwirtschaft, Ökosystemleistungen, SDGs, Brandenburg

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List of Abbreviations

AI	Artificial Intelligence
BBN	Bayesian Belief Network
CICES	The Common International Classification of Ecosystem Services
DSS	Decision Support System
DPSIR	Driver, Pressure, State, Impact, Response
ES	Ecosystem Service
FAO	Food and Agriculture Organization
GHG	Greenhous gas
GRI	Global Reporting Initiative
IoT	Internet of Things
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
PM	Participatory Modelling
RFID	Radio Frequency Identification
RRI	Responsible Research and Innovation
SA	Sustainability Assessment
SDGs	Sustainable Development Goals
UN	United Nations
VRT	Variable Rate Technology

1 Introduction

The ability of agriculture to consistently supply food and various resources to a growing global population is paramount to the continued existence of human civilization. Historically, agricultural production has been able to keep up with population growth and food demand by increasing cultivated land and enhancing overall productivity. Since the Industrial Revolution, the expansion of agricultural land has experienced exponential growth (Klein Goldewijk et al. 2017), reaching a juncture where half of the Earth's habitable land is now dedicated to agriculture (Ritchie and Roser 2019). Nevertheless, the expansion of agricultural land alone did not align with historical increases in world population and burgeoning food demand. In this context, agricultural intensification (i.e., the increase in yield per unit of land area) emerged as a pivotal factor in sustaining global food needs (Rudel et al. 2009; Pingali 2012). Scientific advances and technological innovations, including the introduction of high-yielding crop varieties, mechanization, and the widespread use of agrochemicals such as mineral fertilizers and pesticides, transformed agriculture and led to significant increases in production in the second half of the twentieth century (Matson et al. 1997; Pingali 2012). However, these advancements have led to environmental challenges that are truly daunting.

Agriculture has impacted the supply of vital ecosystem services (ES) (Foley et al. 2005; IPBES 2018) and contributed to the transgression of several planetary boundaries, including biodiversity loss, climate change, water use, as well as the nitrogen cycle and phosphorus flows, the latter being impacted most by agriculture (Campbell et al. 2017; Rockström et al. 2009). The impact of agriculture on biodiversity is especially pronounced, as the expansion of arable land diminished, simplified, and fragmented natural habitats, resulting in a decline in populations of various species (Tscharntke et al. 2005; IPBES 2018). The intensive use of pesticides has also had a high impact on wild farmland flora and fauna (Geiger et al. 2010; Emmerson et al. 2016), especially insects (Sánchez-Bayo and Wyckhuys 2019; Hallmann et al. 2017) and pollinators (Potts et al. 2010). The pollution of both ground and surface water with nitrogen and phosphate fertilizers (Bijay-Singh and Craswell 2021) has had severe repercussions on aquatic ecosystems through eutrophication (Diaz and Rosenberg 2008; Correll 1998; Erisman et al. 2013). Moreover, the agriculture sector contributes significantly to climate change by being a source of greenhouse gas (GHG) emissions (Vermeulen et al. 2012): land-use change-related CO_2 emissions are estimated to contribute to 14% of annual anthropogenic CO_2 globally, with 10% directly attributed to agriculture through drainage of peatlands and management of organic soils (Mbow et al. 2020). Methane (CH_4) and nitrous oxide (N_2O) emissions, largely resulting from livestock production, are another major source of agricultural-related GHGs (Lynch et al. 2021).

Agricultural systems are also challenged by various socio-economic issues, including the increasing instability of producer prices (Meuwissen et al. 2019), as well as crises and systemic shocks like the global COVID-19 pandemic (Barrett 2020) and the Ukrainian war (FAO 2023), leading to supply chain disruptions. Additionally, demographic shifts and rural decline present a myriad of challenges to the social fabric of farming communities and their long-term viability, particularly concerning the succession of farms and the availability of permanent farm laborers (Burton and Fischer 2015; Maharjan et al. 2020). The changing preferences of consumers and ongoing public discussions about the adverse impacts of agriculture on the environment pose additional challenges for farmers, who must navigate not only economic pressures but also societal resistance to conventional farming practices (Tilman et al. 2011).

At the same time, agricultural systems experience the repercussions of the challenges they play a role in creating. For example, agricultural production is being impacted by climate change. Altered weather patterns, more frequent occurrences of extreme events, and fluctuations in temperature and precipitation lead to unpredictable growing seasons (Webber et al. 2018) and challenges for maintaining yields (Ortiz-Bobea et al. 2021; IPCC 2023). Degradation of soil due to intensive or unsuitable agricultural practices results in the depletion of essential nutrients, soil material and the decline of crucial soil biodiversity, which play a vital role in supporting crop growth (Borrelli et al. 2020). Further, there are concerns that non-renewable resources like phosphorus, which are a key input in agriculture, may be exhausted at current rates of extraction and use (Cakmak et al. 2022).

Current technological advancements are reshaping traditional agriculture and food systems, including the use of big data and artificial intelligence in precision arable farming, controlled environment agriculture for urban food cultivation, novel protein sources, and waste recovery initiatives (Herrero et al. 2020). The rapidly emerging phenomenon of digital agriculture, often termed "Smart Farming," represents a profound shift in agricultural systems (Rose and Chilvers 2018). These digital innovations capitalize on precision and data-driven technologies for real-time, site-specific decisions, while optimizing various aspects of production (Walter et al. 2017), value chains (Poppe et al. 2013; Smith 2020), trade (Jouanjean 2019), and governance (Ehlers et al. 2021). It has been argued by many that digitalization could help address many of the sustainability issues currently afflicting agricultural systems. However, such developments are also being questioned due to their potentially disruptive and deleterious impacts on society (Klerkx and Rose 2020; Lioutas et al. 2021).

Given these challenges, there is a growing recognition and consensus on the importance of adopting innovative and sustainable practices in agriculture (Pretty 2008; Foley et al. 2011). Notably the idea of a sustainable agricultural transformation has been incorporated into the United Nations Sustainable Development Goals (SDGs) (United Nations, 2016). This commitment is further echoed in policies such as the Farm to Fork Strategy of the European Union’s Green Deal (European Commission, 2020), along with various other national strategies and international initiatives aligning with agricultural sustainability objectives (FAO, IFAD, UNICEF, WFP and WHO 2020). Yet, despite the crucial role of policy in setting goals and raising public awareness for agricultural sustainability, it is evident that addressing one of the most pressing challenges of our time, the sustainable transformation of the agricultural sector, requires more than just policy initiatives. Realizing this transformation requires a collaborative effort that engages multiple segments of society, including farmers, researchers, government, civil society organizations, food companies, as well as consumers. There is need, therefore, for context-specific approaches that consider the unique potentials and constraints within individual agricultural settings, especially in terms of ecosystem service (ES) supply and use. Ultimately, these approaches are essential to gain actionable insights into agricultural sustainability and to achieve the objectives outlined in policy (Tappeiner et al. 2021; Binder et al. 2010). To accomplish this, a crucial initial step is a comprehensive assessment and understanding of the impact of agricultural practices, also known as sustainability assessment (SA), which forms the basis for informed decision making and developing suitable solutions. Despite significant efforts invested in agricultural SA, challenges persist due to lack of consensus on the interpretation of sustainable agriculture practices (i.e. normativity), lack of respective data (i.e. uncertainty), lack of standardized assessment methodologies (including indicator selection) and insufficient stakeholder engagement.

Addressing these challenges, the primary objective of this thesis is to provide an examination of several integrative concepts and methodologies to contribute to a deeper and improved understanding of agricultural sustainability and agricultural SA. Specifically, it seeks to build on agricultural SA by investigating and employing the ES concept, sustainability assessment frameworks, and participatory modelling. Due to its increased relevance in recent years and its potential to transform agricultural systems, agricultural digitalization servers as a case study to achieve these aims.

Subsequently, this thesis is guided by the following research questions:

- Research question 1: To what extent are farm-level assessment tools and models capable of covering the ES concept into their methodologies as well as contributing to the SDGs?
- Research question 2: How is digital agriculture currently embedded in preeminent global, EU, and German policies, and what links can be drawn between digital agriculture technologies and to wider sustainability principles outlined in these policies? How could future trends in the agri-food sector influence the adoption and use of digital technologies? How does the current legal setting surrounding digital technologies impact agriculture?
- Research question 3: What are the anticipated impacts of agricultural digitalization according to stakeholders?

In the remainder of the introductory section, the background to agricultural sustainability and its systemic representation is elaborated, drawing on the concepts of multifunctionality, ES, and digital agriculture. Thereafter, characteristics of agricultural SA are explained, relating to methods, including indicator selection, stakeholder participation and addressing uncertainty. Finally, an outline of the thesis and description of the research project in which the thesis was carried out are presented.

1.2 Background concepts and methods

1.2.1 Agriculture and sustainability

While early discussions on the concept of sustainability can be traced back to the environmental movement of the 1960s, it gained mainstream attention with the publication of the Brundtland Report in 1987. In the report, 'sustainable development' was defined as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987). Hence forth referred to as sustainability, this concept has been widely applied, modified, and expanded to encompass various issues, including sustainable agriculture. However, even in the face of broad agreement on the importance of sustainable agriculture, there is considerable variation in the interpretation of the concept. As Rigby and Caceres (1997) highlighted, this phenomenon is attributed to the nature of sustainability as a normative and situated concept. This implies that the understanding of sustainability must consider the specific context and local conditions in which it is embedded, including the various interpretations it may have.

The diverse interpretations on how sustainable agriculture is defined and how it should be pursued have given rise to a multitude of discourses, perspectives, and paradigms, including organic farming (Muller et al. 2017; Niggli 2015), agroecology (Altieri 1989; Gliessman and Tittonell 2015; Wezel et al.

2009), regenerative farming (Francis et al. 1986), conservation agriculture (Hobbs et al. 2008) and sustainable intensification (Garnett et al. 2013; Pretty 2008). While these paradigms have distinct origins, each with its own set of ideologies, as well as unique objectives, theories, postulates and approaches for application, they converge in their shared goal of mitigating the adverse impacts of conventional agricultural practices. This alignment is achieved through a heightened incorporation of considerations for ecological and social aspects with agronomic production. Moreover, these concepts signal an alternative approach to managing agricultural systems, one that moves beyond farm-level production to embrace a holistic, systems-oriented thinking with greater emphasis on understanding the complexity of and interconnectedness between agricultural production and its socio-ecological surroundings.

Adopting a systems thinking approach emphasizes the multi-dimensional and multifunctional nature of agriculture, which highlights the various functions that agriculture can fulfill beyond its primary role of food and fiber production by interacting with social, economic, and environmental systems (Renting et al. 2009; van Huylenbroeck et al. 2007; Helming et al. 2008). For example, agriculture contributes to economies by providing employment opportunities, income generation, and supporting rural livelihoods. Additionality, agriculture plays a role in social systems by shaping cultural identities and traditions, which provides a sense of belonging and shared heritage, contributing to social cohesion of communities (van Huylenbroeck et al. 2007; Nowack et al. 2022). In terms of environmental systems, agriculture has the capacity to influence the environment in both negative and positive ways. Yet, agricultural management frequently entails trade-offs between environmental, economic and social functions, such as balancing the maximization of biomass production with biodiversity conservation, which lead to outcomes that compromise long-term environmental and socio-economic sustainability of such systems.

1.2.2 Agriculture and ecosystem services

More and more, attention is concentrated on exploring multifunctionality in the context of agriculture's impact on ecosystem functions and related ES supply (Huang et al. 2015; Helming et al. 2013). ES can be defined as “the contributions of ecosystem structure and function – in combination with other inputs – to human well-being” (Burkhard et al. 2012). By serving as an integrative framework, the ES concept explicitly demonstrates the direct and indirect economic, social, and ecological contributions that nature provides to society. Over the years, several typologies have been created to classify and categorize the multitude of different types of ES, including the Millennium Ecosystem Assessment (MA) (MEA 2005), The Economics of Ecosystems and Biodiversity (TEEB) (TEEB 2010), and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young 2018). In the CICES framework, ES are broadly categorized according to their provisioning, regulation, and maintenance, as well as cultural functions: however, TEEB and MA classification systems also include a category for supporting ES. Provisioning services provide benefits in the form of materials directly produced by ecosystems such as wild and cultivated food, drinking water, fiber, or timber. Regulation and maintenance services provide benefits by moderating ecosystem processes, including climate regulation, remediation of waste, hydrological cycles, pollination, pest control, carbon storage etc. Cultural services are nonmaterial benefits to human well-being that result from human interaction with the environment, including recreation, education, landscape aesthetics, and spiritual connections.

Within the highly managed environment of agricultural systems, agricultural ES emerge from the coupled interaction between anthropogenic agricultural activities and embedded ecosystem functions (Swinton et al. 2007), which implies a deep and almost inseparable connection between ES and agricultural production (Foley et al. 2005; Bethwell et al. 2021). Agriculture primarily promotes provisioning services like food, fodder, and fuel, while also contributing to regulating services such as climate and water regulation, alongside cultural services like landscape aesthetics and recreational opportunities (Bethwell et al. 2021). Additionally, agricultural production relies on various regulating services, including soil formation, nutrient and water cycling, pollination, and natural pest control. Frequently, however, agricultural production leads to a trade-off between provisioning and regulating services, where an intensification of provisioning services can degrade regulating services (Power 2010). For instance, intensive farming based on monocultures, designed to maximize crop yields, often leads to depletion of nutrients in soil and increased susceptibility to erosion (Bennett et al. 2012). These types of trade-offs are often managed through interventions like irrigation and fertilization. However, such compensatory measures can also give rise to negative externalities such as nitrate leaching and diminished water supplies that have a detrimental impact on environmental and human well-being (Tilman et al. 2002). Hence, reducing trade-offs and limiting the impacts of agriculture production has become a central focus in both agricultural research and policy initiatives (Helming et al. 2013).

Operationalizing the ES perspective has proven challenging in practice (Soulé et al. 2021), as there are difficulties assessing agricultural ES , related to issues such as data availability (Harrison et al. 2014), lack of standardized indicators (Paul et al. 2022), as well as varying methods for quantification and valorization of ES (Voglhuber-Slavinsky et al. 2023). Currently, there is a lack of tools and models specifically designed for evaluating the management of agricultural ES (Soulé et al. 2021). However, this does not preclude the potential for existing agricultural sustainability assessment tools to contribute to the promotion of ES in indirect ways. Based on this premise, Chapter 2 of this thesis examines various generic, farm-level agricultural assessment tools and models to ascertain their protentional capability in assessing the impact of agricultural management on ES by analyzing how they integrate the ES concept into their methodologies.

1.2.3 Agriculture and digitalization

Agricultural digitalization is a rapidly emerging trend, intertwined with varying concepts, such as Precision farming, Smart Farming, Agriculture 4.0 and Digital Agriculture, which are often used interchangeably (Klerkx et al. 2019). Broadly defined, digital agriculture is a form of managing and optimizing agricultural systems (e.g. production, value chains, and food systems) by leveraging a wide variety of data-driven techniques and technologies. In terms of production, *in-situ* sensors provide real-time and site-specific data on soil moisture, temperature, nutrient levels, and crop health, facilitating crop monitoring, pest detection, and yield estimation (Pedersen and Lind 2017; Kivi et al. 2023; Wolfert et al. 2017). Remote sensing technologies such as satellites and drones are used for providing similar crop monitoring data over larger areas (Gao et al. 2020). Artificial intelligence (AI) and algorithms analyze large datasets to detect patterns, trends, and correlations, thereby facilitating tasks like crop monitoring, pest detection, and yield prediction (Wolfert et al. 2017). Variable Rate Technologies (VRT) adjust applied inputs, including seeds, fertilizers, and pesticides, across fields according to variations in soil properties, crop conditions, topography, and other parameters, thereby improving resource efficiency and yields (Finger et al. 2019; Schimmelpfennig 2016; Späti et al. 2021).

GPS technology provides geospatial information for field mapping, navigation, and vehicle guidance. It enables farmers to perform tasks such as planting, spraying, and harvesting with high precision, reducing overlaps, and minimizing input wastage. GPS-guided autonomous steering reduces the necessity for human intervention, leading to reduced labor costs, driver fatigue and heightened productivity (Fielke et al. 2019; Godoy et al. 2012). More recently, although still a fringe development, agricultural digitalization has expanded to include the deployment of robotics and artificial intelligence for enhanced mechanization and automation of production activities (Sparrow and Howard 2021; Marinoudi et al. 2019), such as field crop robots that can work in fleets (Spykman et al. 2021; Lowenberg-DeBoer et al. 2020). Often these devices are connected through the internet, also known as the Internet of Things (IoT), allowing devices to gather and communicate data among themselves. Utilizing data gathered from various sources, computer-based Decision Support Systems integrate data analytics and modelling techniques to manage agricultural enterprises and provide farmers with decision support on complex tasks, such as crop management, irrigation scheduling, fertilizer application, and risk assessment (Fountas et al. 2015; Tummers et al. 2019). The use of mobile phone apps is also considered a part of agricultural digitalization. Farming apps have become ubiquitous throughout the world, providing farmers with information on crop protection, crop selection, weather forecasts, market prices and entry points, e-learning, and communication with other farmers and consumers, as well as promoting citizen science (Daum et al. 2018; Mendes et al. 2020; Dehnen-Schmutz et al. 2016). Within agri-food value chains and food systems, digital technologies facilitate enhanced information exchange among suppliers, producers, consumers, and governments (Wolfert et al. 2017). Technologies like Radio Frequency Identification (RFID) chips and blockchain contribute to increased transparency and traceability throughout food supply chains (Lioutas et al. 2021; Kamilaris et al. 2019).

It has been proposed that adopting these technologies could lead to improved sustainability of agricultural systems. For example, digitalization has the potential to bring about positive effects on the environment through the more efficient use of agrochemical inputs, reducing environmental pollution of fertilizers and pesticides (Finger et al. 2019). It could also enable more diversified agricultural landscapes and promote the provision of ES through enhanced spatial planning (Donat et al. 2022) and decision support (Mouratiadou et al. 2023). Agri-environmental governance stands to benefit from big-data technologies as well, by facilitating the design of site-specific agri-environmental instruments for better resource management and conservation (Ehlers et al. 2021). Digitalization along the agri-food value chain can empower consumers to make informed choices, bolstering food safety measures for governments and securing added value for producers (Poppe et al. 2013). Consequently, there has been backing for agricultural digitalization within policy circles, but the emphasis has leaned heavily towards its utilization for resource efficiency enhancements, rather than recognizing its potential contributions to ES and wider sustainability goals (Lajoie-O'Malley et al. 2020; Garske et al. 2021). This aspect is further explored in Chapter 3 through a review of high-level policy.

Digital agriculture is not without its criticisms, however. Concerns have been raised regarding the potential for scenarios that lead to increases in monocultures and loss of landscape diversity due to highly automated farming practices (Daum 2021). Furthermore, there are concerns about the displacement of laborers (Carolan 2020), reinforcement of power asymmetries (Rotz et al. 2019), reduction of farmer autonomy (Henman 2020), and declining job satisfaction (Prause 2021; Rose et al. 2021). These issues highlight the need for careful consideration and balanced approaches to ensure that the benefits of digitalization are equitably distributed and do not come at the expense of social or environmental well-being (Klerkx and Rose 2020).

With limited empirical research examining its practical implications on society and the environment (Rose et al. 2021; Finger et al. 2019), a great deal of the research up till now on the sustainability of digital agriculture has been largely conceptual. This is primarily because many of the technologies encompassing digital agriculture are relatively new and have not been widely diffused due to several adoption barriers, such as high investment costs (Barnes et al. 2019), lack of operating skills (König et al. 2013), insufficient access to high-speed internet in rural settings (Paustian and Theuvsen 2017), and a general lack of trust and skepticism surrounding data ownership and security (Jakku et al. 2019).

The instrumentalization of digital agriculture, or the objectives for which it is being used to achieve, depends on the underlying paradigm it is associated with (Metta et al. 2022). When viewed through the lens of sustainable intensification, digitalization is often seen as a means to mitigate environmental pollution and land expansion pressures by enhancing efficiency and productivity through improved input management (Lindblom et al. 2017; Dicks et al. 2019). Conversely, from the angle of conventional agriculture, the potential efficiency and productivity gains of digitalization are typically considered from a profit-maximization perspective, with less thought for wider impacts on sustainability (Lajoie-O'Malley et al. 2020). From an alternative perspective, in an integrative approach that goes beyond efficiency and productivity gains, digitalization can be seen through the lens of agroecology as a tool for facilitating better spatial planning and promoting multifunctional and diversified agriculture (Mouratiadou et al. 2023), utilizing ecological processes (Hilbeck et al. 2022). Within this rather new perspective, digital agriculture technologies can be divided into three broad functional categories: monitoring, decision support systems, and communication (Mouratiadou et al. 2023). In this context, monitoring technologies of biodiversity and ES provision can be used for gaining transparency on complex cause-effect relationships within agroecosystems. This monitoring not only facilitates a deeper understanding of these relationships, but also enables the establishment of result-oriented policy measures aimed at promoting sustainable agricultural practices. Decision support software can help farmers and advisors navigate multifunctional and diversified agricultural landscapes, where various targets such as improving yields, ES, and biodiversity conservation need to be consolidated. In communication among stakeholders and land use actors, digital technologies can improve information exchange regarding societal demands on biodiversity and ES. This communication could help to reduce conflicts over the future use of agricultural land by fostering a shared understanding of the importance of ecological resources along the entire value chain, leading to their valorization.

If technologies are adopted and how they are instrumentalized depends heavily on the collective and shared perceptions of stakeholders and how they make sense of the it (Kaplan and Tripsas 2008). In this context, to ensure that technological improvements are successfully incorporated into socio-economic and environmental contexts for sustainable purposes, Reed (2008) emphasized the importance of involving stakeholders in decision-making processes. This is a sentiment echoed by many (Eastwood et al. 2019; Fielke et al. 2022; Klerkx et al. 2019; Metta et al. 2022), who underlined the need for greater societal inclusion in the development and implementation of digital agriculture technologies. This includes involving stakeholders to set goals and develop indicators to measure progress toward sustainability (Basso and Antle 2020), as well as reflect on the potentially disruptive impacts of innovative digital technologies (Rose and Chilvers 2018; Eastwood et al. 2021). Finally, involving stakeholders in research and innovations will be crucial toward gaining their trust for digital technologies in the future, jointly mitigating adverse impacts and promoting acceptance of digital agriculture solutions (Jakku et al. 2019).

However, due to the ambiguity in perspectives of different stakeholders, uncertainty surrounding the effects of digitalization is pervasive, which means a core challenge is developing a conceptualization of digital agriculture – including a vision for its future - that is consensual. This requires taking potential positive and negative impacts of digital agriculture into account through participation by societal actors. In this light, many argue that in order to ensure that digital agriculture contributes to societal well-being and sustainability, a responsible research and innovation approach (RRI) is needed (Eastwood et al. 2019; Klerkx and Rose 2020). Central to the RRI approach are the guiding elements of anticipation, inclusion, reflexivity, and responsiveness (Stilgoe et al. 2013). These elements are intended to inform the design of research and facilitate the anticipation and reflection upon both intended and unintended consequences of innovations and technologies through stakeholder engagement. Moreover, the RRI approach aims to collaboratively design solutions to minimize risks and maximize opportunities of innovations and technologies, thereby fostering socially ethical and sustainable outcomes (Zscheischler et al. 2022). There has been a recent increase in empirical studies assessing digital agriculture through the lens of the RRI framework. For example, Zscheischler et al. (2022) investigated the perceived risks associated with agricultural digitalization in Germany with a group of stakeholders, illuminating risks related data ownership and power dynamics, as well as the effects of automation on farmers' decision-making capacities. Fleming et al. (2021) employed a participatory scenario building method to reflect on probable futures and contrasting sustainability outcomes of digital agriculture in the Australian context. Metta et al. (2022) to assessed the sustainability implications of digital agriculture across 21 Living Labs across Europe, apply the socio-cyber-physical system framework. Employing a multi-stakeholder approach, they identified various effects and trade-offs concerning the enabling, disenabling, boosting, and depleting impacts of digital agriculture. In adopting a similar approach based on anticipation and inclusion, Chapter 4 investigates stakeholder perceptions on digital agriculture through a participatory modelling exercise to derive consensus and assess the potential sustainability impacts of agricultural digitalization in the future.

1.2.4 Agriculture and sustainability assessment

Understanding and dealing with the complex interactions among agricultural management, innovative technologies, and ES is essential to establish an agricultural system that is simultaneously sustainable and resilient to shocks and stresses. This can be facilitated through the process of conducting sustainability assessment (SA). Bond et al. (2012) defined SA as ‘any process that directs decision making toward sustainability’. This intentionally broad definition aims to encompass the diverse ranges of assessment methods and tools that have been developed and widely employed worldwide to assess sustainability. These approaches are often known by various names such as sustainability appraisal, impact assessment, or integrated assessment (Pope 2006). SA can be applied to projects, programs, or policies, however, currently, there is no consensus on its precise definition or standardized methods for its implementation (Bond et al. 2012). Nonetheless, there is a general acknowledgment that SA is mutli-dimensional, incorporating the three pillars of sustainability: environmental, social, and economic (Figure 1) (Pope et al. 2004). Increasingly, a fourth institutional dimension is considered, recognizing that good governance is a cornerstone of sustainable management (Purvis et al. 2019).

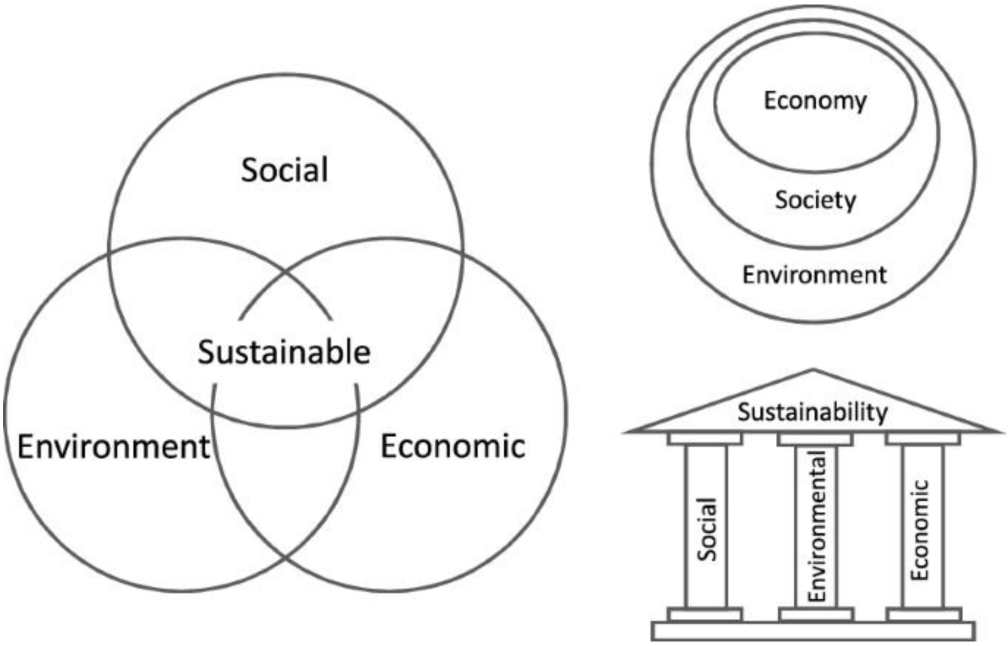


Figure 1 Common representation of sustainability as conjoined or concentric circles, or 'pillars'. Taken from Purvis et al. 2019.

Numerous works have explored classifying and detailing the methodological traits of current SA (Bond et al. 2012; Ness et al. 2007; Singh R.K. et al. 2012). Hacking and Guthrie (2008) proposed a three dimensional scheme to categorize assessment practices based on defining features such as strategicness, integratedness and comprehensiveness (Figure 2). In their scheme, SA distinguishes itself from other assessments, such as environmental impact assessment (EIA), for example, by being more strategic through a broad and future-oriented focus, more integrative through the incorporation of various techniques and themes, and more comprehensive as it encompasses social, economic, and environmental aspects of sustainable development. Another similar view on SA is provided by Sala et al. (2015), who emphasized that SA should include a holistic approach to comprehend the interactions between nature and society; exhibit transdisciplinarity by integrating diverse methodologies and epistemologies to facilitate co-production of knowledge among stakeholders; establish strong connections to specific social and local contexts; and include values in identifying solutions. Hereby, SA should possess a normative function, seeking to provide orientation by addressing value-laden aims and objectives in envisioning sustainable human-environment systems. Lastly, although often overlooked, Sala et al (2015) asserts that it should address uncertainties of impacts through a probabilistic approach to promote robust decision making.

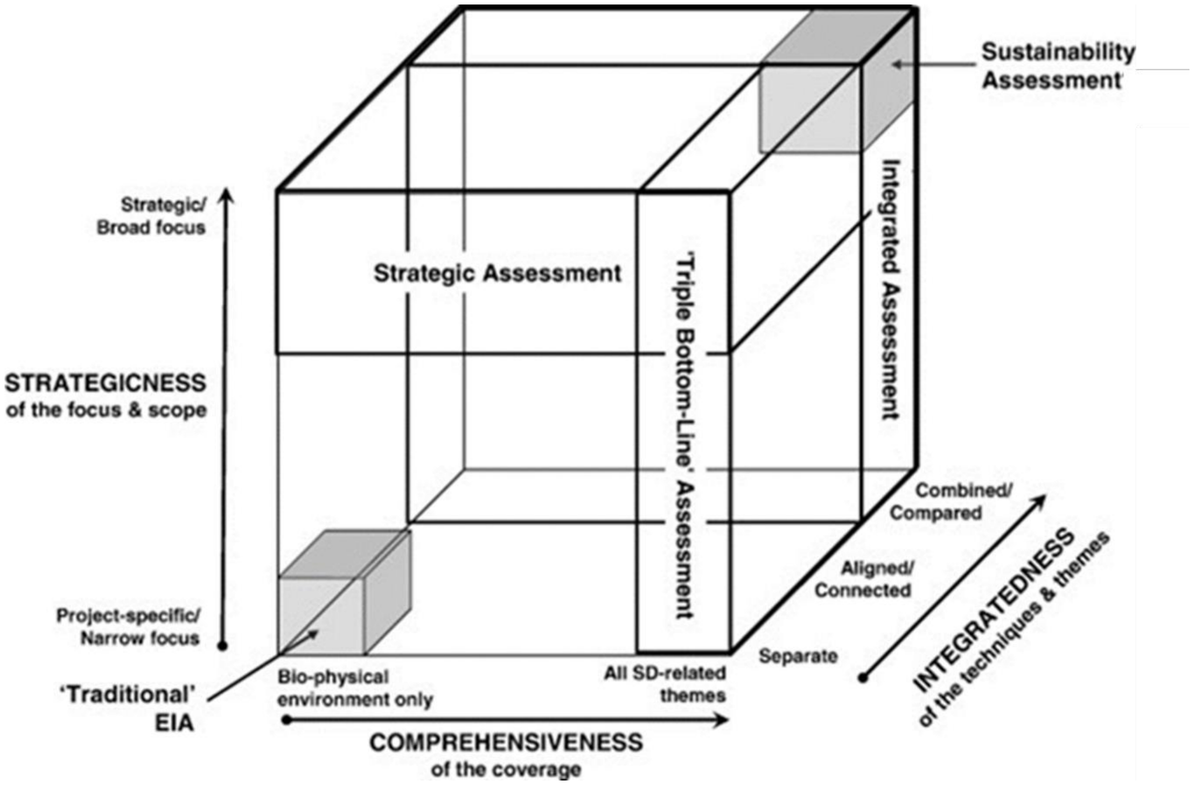


Figure 2. A three-dimensional space where diverse forms of assessment can be positioned, as derived from Hacking and Guthrie 2008

There are a variety of analytical tools that can be used to evaluate sustainability within SA, which have been thoroughly outlined in the literature (Ness et al. 2007; Gasparatos and Scolobig 2012; RIDDER et al. 2007). The most popular SA tools include indicators and indexes, monetary, biophysical models, and Multi-Criteria Analysis (Gasparatos 2010). Systems-based approaches, including indicator-based frameworks, are preferred over singular metrics (e.g., monetary- or biophysical-based indexes) (Gasparatos 2010), as they allow for the understanding of multi-dimensional aspects of sustainability, along with the complex interactions and trade-offs among indicators and sustainability dimensions (Chopin et al. 2021). Careful consideration on the context of the sustainability problem, including underlying value assumptions embedded within each methodology, should guide tool selection on a case-by-case basis (Gasparatos and Scolobig 2012).

Concurrently, a multitude of methods and tools have been developed to obtain understanding on the sustainability performance of agricultural systems (Wustenberghs et al. 2015; Lampridi et al. 2019; Coteur et al. 2019). Generally, the focus of these methods is to assist farmers in agricultural management and provide insights to policymakers, informing them about the anticipated effects of policy or project implementation (*ex-ante)* or assessing the consequences after-implementation (*ex-post)* (Chopin et al. 2021). Indicator frameworks - which are featured prominently in the research presented in this thesis - are perhaps the most popular methodology in agricultural SA. Several studies have been conducted to describe the variability of existing approaches within this domain (Schader et al. 2014; Marchand et al. 2014; Arulnathan et al. 2020; Olde et al. 2017a). Indicator frameworks typically consist of a hierarchical structure made up of dimensions, themes, and indicators. At the top of the hierarchy are sustainability dimensions, e.g., economic, social, environmental. Each dimension is usually subdivided into themes and sub-themes. These themes and sub-themes delineate specific objectives for sustainability performance, such as diminishing greenhouse gas emissions, fostering community investment, and guaranteeing worker safety. At the lowest stratum of the hierarchy lie indicators, representing the smallest unit of analysis in the framework. Weight and sum aggregation techniques are usually used to compile indicators into scores for themes and sub-themes.

Binder et al. (2010) categorized indicator-based assessment methods in agriculture according to their normative, systemic, and procedural dimensions as suggested by Wiek and Binder (2005). They identified three types: (i) top-down farm-level assessment methods; (ii) top-down regional assessment methods with some stakeholder participation; and (iii) bottom-up, integrated participatory assessment methods with continuous stakeholder involvement. Top-down farm assessments focuses on evaluating individual farms, typically with the farmer as the user group, with a top-down approach for selecting indicators, usually with limited stakeholder participation. Top-down regional assessment with some stakeholder participation involves stakeholders in indicator development and extends the assessment to the regional level. Bottom-up, integrated participatory assessment targets multiple stakeholders at the regional scale, where stakeholders are involved throughout the entire process, including goal setting and indicator development. Binder et al. (2010) also examined the trade-offs among these various method types, acknowledging that while top-down approaches prove beneficial for benchmarking and monitoring, they may lack the contextual specificity that is captured by bottom-up methods. Consequently, they contend that bottom-up approaches offer the greatest adaptability and are, thus, best suited to tackle the inherent challenges of multidimensional and multifunctional agriculture.

Despite the call for stakeholder involvement in agricultural SA, there remains an absence of such engagement (Arulnathan et al. 2020; Bond et al. 2012). The reasons behind this stem from the significant amount of time and resources required to involve stakeholders, alongside difficulties in accessing them and maintaining their commitment, among other factors (Zscheischler et al. 2018). On the part of those conducting SA, successful stakeholder engagement requires expertise in transdisciplinary science, which can be challenging as it entails familiarity with diverse knowledge systems and the ability to communicate effectively across them. Facets of top-down method types are examined in more detail in Chapter 2 within the context of ES and the SDGs, while Chapter 4 employs a bottom-up, integrated participatory assessment method to evaluate agricultural sustainability within the context of agricultural digitalization.

1.2.5 Indicators for agricultural sustainability assessment

Sustainability indicators generally form the backbone of agricultural SA. Indicators can be defined as metrics that provide information on the ‘status, trend, or performance of underlying complex systems’ (McCool and Stankey 2004). Over the years, a multitude of indicators have emerged to gauge sustainability, particularly with regards to environmental factors (Latruffe et al. 2016), resulting in what has been termed an 'indicator zoo' by some scholars (Soulé et al. 2021). This shift has redirected attention within the SA community away from the process of indicator development toward the process of selecting them (Bockstaller et al. 2009). Selecting the right indicators is critical since it affects what is measured, how it is measured, and what conclusions can be drawn from the findings. Since they are often the most disaggregated variable used in an SA (Chopin et al. 2021), the indicators used in each SA define the ‘hard’ boundaries of the assessment by clearly delimiting the thematic, temporal, and spatial scope. Therefore, it is important to develop transparent and well-defined procedures and criteria for selecting indicators for SA (Dale and Beyeler 2001; Olde et al. 2017b).

Common criteria for selecting individual indicators relate to relevance (does the indicator fit the context and quality of study?), practicability (is it easy to measure and implement?), and end user value (is it clear and does it fulfil the expectations of ends users?). End user value is recognized as especially relevant to derive assessments that are transformative and enduring (Olde et al. 2018), necessitating stakeholder involvement. Nevertheless, there exists significant disagreement among experts regarding which criteria for indicator selection should be prioritized (Olde et al. 2017b). Of course, considerations regarding data reliability and availability should also be made when choosing indicators (Olde et al. 2017b). However, a comprehensive SA must first consider what *should* be measured and not exclusively what *can* be measured, otherwise the results of the assessment may unintentionally obscure sustainability deficits (Paul and Helming 2019). Selecting indicators should therefore ideally follow a systematic procedure, however currently there are no established guidelines or standards for selecting indicators for agricultural SA. In the realm of sustainability reporting, materiality analysis is proposed by the Global Reporting Initiative (GRI) as a structured means for choosing indicators. Ideally, such an approach should be conducted with the help of stakeholders. However, until now, materiality analysis has predominantly found application in business contexts, with minimal utilization within agricultural SA (Whitehead 2017; Beske et al. 2020).

Further, indicators for SA should be selected as distinct sets, based on their capacity to address a particular question or problem (Latruffe et al. 2016). Selecting indicator sets using a causal network is recommended by Niemeijer and Groot (2008), as it shows how indicators interact, elucidating their relationships and contributing to a more comprehensive and realistic systemic representation. For this, they suggest employing the commonly utilized DPSIR (Driver, Pressure, State, Impact, Response) framework to categorize indicators and structure the selection process. A comparable approach to selecting indicators was employed in Chapter 4 to derive a set of indicators for an SA focused on agricultural digitalization Finally, in selecting indicator sets, Lebacq et al. (2013) identified three criteria: (a) parsimony, requiring a minimal number of non-redundant indicators; (b) consistency, ensuring that all necessary indicators are included; and (c) sufficiency, indicating that the set is comprehensive, covering all sustainability objectives.

In agricultural SA, various generic methods and tools have emerged, some of which are reviewed in Chapter 2, each with its own set of indicators (Chopin et al. 2021). While these assessments facilitate comparisons and benchmarking among different farming systems, their top-down selection of indicator sets, often intended for broad geographic applicability, may overlook local contextual factors, thus constraining their usefulness for generating sustainability improvements at the local level (Schader et al. 2014). When comparison and benchmarking is not the objective of the SA, context-specific assessments (as utilized in Chapter 4) can be used to engage local stakeholders in the selection of indicators. Such approaches enhance the comprehensiveness of local assessments for local conditions (Dale et al. 2019), foster stakeholder learning and buy-in, and ultimately increase the likelihood of actionable enhancements to sustainability (Reed 2008). However, comprehensiveness of an assessment can compromise its usability (Olde et al. 2018), where, if assessments attempt to include too many indicators, conducting assessments may become overly complex as well as challenging to communicate findings to farmers and policymakers (Bockstaller et al. 2008).

1.2.6 Stakeholder participation and agricultural sustainability assessment

Bottom-up approaches involving stakeholder engagement are increasingly recognized as essential for driving systemic change (Norström et al., 2020). Reed (2008) outlines two primary arguments supporting stakeholder involvement. The first, grounded in normative considerations, emphasizes democratic ideals, citizenship, and equity. This viewpoint posits that involving stakeholders helps mitigate the risk of marginalization within decision-making contexts or society, fostering active citizenship and collaboration, ultimately yielding broader societal benefits. The second argument, rooted in pragmatism, highlights that involving stakeholder in environmental decisions enhances the adaptability of interventions to local conditions. This is because participatory processes enable better decision-making by incorporating a broader range of information and enhancing foundational understanding (Blackstock et al. 2007), thus aiding in anticipating unforeseen outcomes before they manifest (König et al. 2013; Paas et al. 2021). This aspect is particularly salient when evaluating agricultural sustainability at landscape and larger scales, necessitating the inclusion of stakeholders beyond farmers who may influence or be impacted by changes in agricultural management (Wu 2013; Eichler Inwood et al. 2018).

Through participatory approachs it becomes feasible to integrate local contexts, provide decision-makers and projects with actionable information, and develop indicators that better reflect the perspectives of local stakeholders (Paas et al. 2021; Moreau et al. 2023). This is especially relevant when considering the impacts of agricultural management on ES supply and use given their profound reliance on site-specific bio-climatic conditions, alongside their strong link to cultural heritage and structural dynamics shaping local communities and economies. Further, participatory approaches can be employed to enhance the adoption or utilization of new knowledge and technologies (Jackson-Smith and Veisi 2023; Reed 2008), as well as help mitigate conflict and increase acceptance of scientific work (Jakku et al. 2019; Blackstock et al. 2007).

The extent of stakeholder involvement can vary in each assessment, depending on the study's particular objectives and the resources at hand (Neef and Neubert, 2011). Various operational objectives, such as 'diagnostic and informing', 'co-learning', or 'co-management' (Tippett et al. 2007), demand differing levels of stakeholder participation at various stages of the assessment process. A diverse array of methods and tools are available to facilitate stakeholder engagement in any one of these endeavors (Voinov and Bousquet 2010). Participatory modelling (PM), or modelling with stakeholders, is an increasingly popular method in participatory assessments (Gray et al. 2017). PM is a problem-solving approach that improves system-understanding and decision-making by synthesizing stakeholder knowledge and values in a coherent manner through collaborative learning. PM integrates stakeholder insights with model-based methods: stakeholders contribute their qualitative knowledge to frame the issue, identify relevant themes and indicators, and guide the development of assessment models. Models in this context then aid in translating stakeholder qualitative input into quantitative and semi-quantitative outcomes. PM approaches therefore allowa for the incorporation of both qualitative and quantitative analyses, which provides a balance of comprehensiveness and accuracy. There are many analytical tools available for modelling with stakeholders, including system dynamics, fuzzy-cognitive mapping, agent-based modelling, and Bayesian belief networks (Voinov and Bousquet 2010), among others. The literature has delineated both the strengths and weaknesses of PM tools (Gray et al. 2017), along with providing guidance for selecting the appropriate one (Voinov et al. 2018). Chapter 4 of this thesis employs a Bayesian belief network (BBN) approach for PM, aiming to achieve a consensus regarding the potential impacts of digital agriculture among a diverse group of stakeholders. The choice of a BBN approach in this case stems from the high uncertainty surrounding the future impacts of digital agriculture. In this context, compared to other PM methods, BBNs stand out in explicitly incorporating uncertainty of knowledge, making them well-suited for problems characterized by high uncertainty (Düspohl et al. 2012).

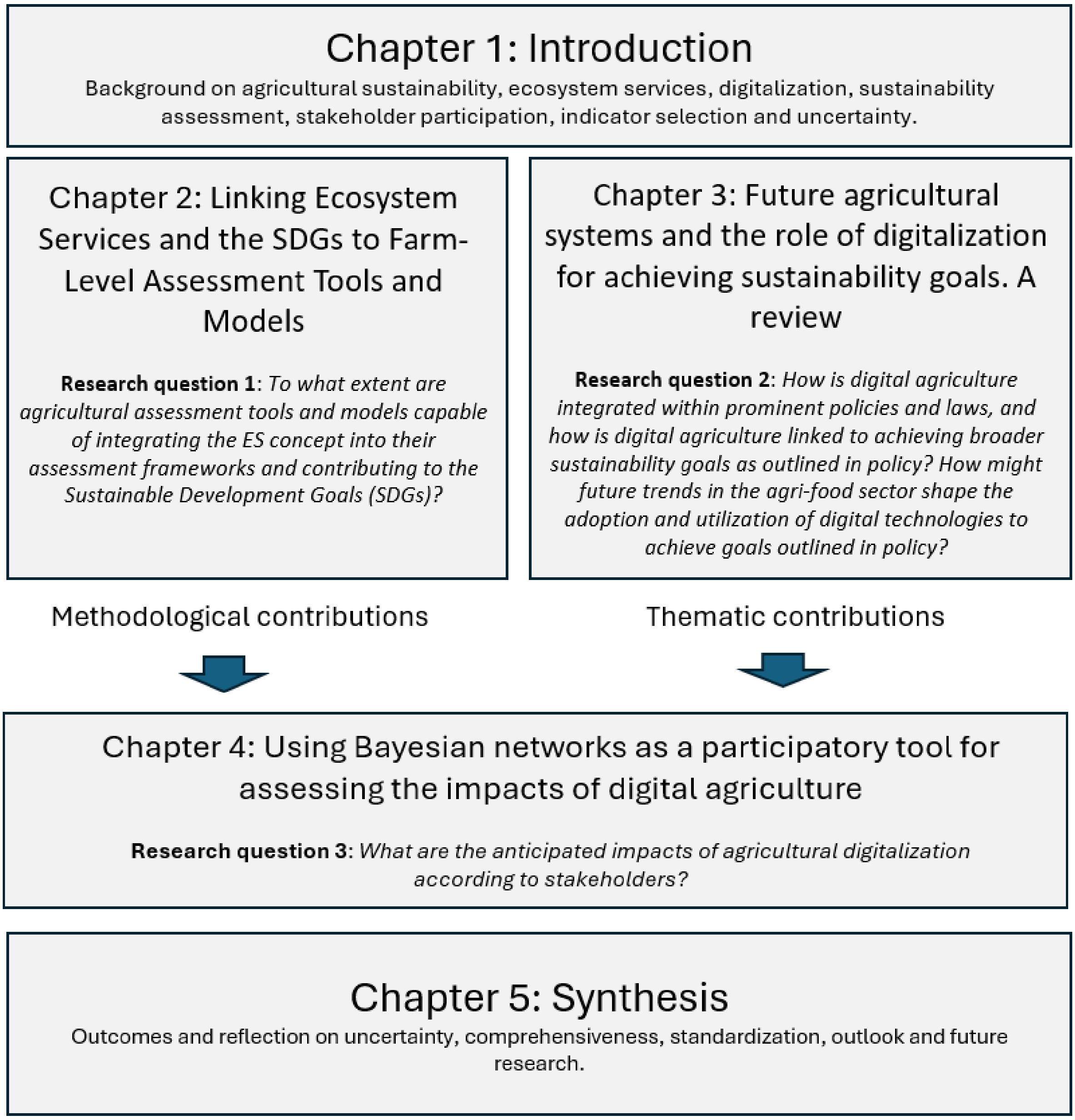
1.2.7 Uncertainty and agricultural sustainability assessment

It could be argued that agricultural SA is characterized by deep uncertainty, as uncertainty manifests in various forms, including epistemic uncertainty, ontological uncertainty, and ambiguity (Salliou et al. 2017). Epistemic uncertainty arises due to limitations in knowledge and understanding, such as incomplete data or flawed modelling assumptions, posing challenges when assessing sustainability across diverse domains and projecting future outcomes (Walker et al. 2003). This is often the case for complex systems like ecosystems or social systems where observational data is scarce. Ontological uncertainty stems from the inherent variability and unpredictability of natural and social systems (e.g. human behavior, policy shifts, technological progress, global economic fluctuations, and unforeseen natural events), making it difficult to predict and manage sustainability impacts accurately (ibid.). Uncertainty also arises due to differing perspectives of individuals (e.g. goals, beliefs, expectations) on what constitutes sustainability, also known as normative uncertainty or ambiguity, complicating assessment processes (Salliou et al. 2017). This form of uncertainty is typical of 'wicked’ problems as described by Rittel and Webber (1973). Problems that are wicked are uncertain in nature, as they are often highly complex and lack a straightforward solution due to competing interests and perspectives. This characteristic is shared by numerous contemporary societal issues, including agricultural sustainability and agricultural digitalization, as explored in Chapters 3 and 4 of this thesis. Due to its relative novelty, there is significant debate regarding the desirability of digital agriculture, as its widespread impacts are still largely unknown. Here, a notable challenge lies in the lack of consensus (i.e. normative uncertainty) among stakeholders regarding the impacts of digital agriculture as well as the causal relationships (i.e. epistemic and ontological uncertainty) leading to them.

Considering the various sources of uncertainties linked to evaluating the sustainability of agricultural systems, it may be unrealistic to expect SA to consistently provide definitive answers as to what is sustainable (Ciuffo et al. 2012). Nonetheless, addressing uncertainty within an assessment can improve the reliability and robustness of SA and establish a deeper understanding of the sustainability issues under investigation (Schaubroeck et al. 2020). However the perception exists that incorporating uncertainty somehow diminishes the credibility of assessment results (Glasson and Therivel 2013), the idea being that if results are seen as uncertain, that might lead to skepticism or mistrust from stakeholders, undermining the perceived reliability of the assessment process itself. On the other hand, acknowledging and reflecting on uncertainty in SA can also be viewed as a positive practice as it can bolster the transparency and credibility of scientific findings by providing a nuanced understanding of complex, real-world issues. Various analytical techniques exist for managing uncertainty in agricultural SA (Ciuffo et al. 2012). When sufficient data is available, quantitative and statistical analyses can be employed to quantify uncertainty of data sets or models predictions using measures such as standard deviation, variance, or confidence intervals. Uncertainty of models can also be assessed via sensitivity analysis. However, in complex agricultural socio-economic systems where data and robust models are often limited, alternative approaches are necessary. Stakeholder involvement and expert judgment, as demonstrated in Chapter 4, along with scenario analysis, as examined in Chapter 3, provide effective methods for tackling uncertainties arising from data constraints within these contexts.

1.3 Overview of thesis structure

In this cumulative dissertation, the research questions outlined at the beginning of thesis are addressed in three successive chapters, Chapters 2 and 3 corresponding to articles published in international scientific journals and Chapter 4 to a manuscript currently under revision (refer to the List of Publications) (See Figure 3 for an overview of thesis structure).



Chapter 1: Introduction

Background on agricultural sustainability, ecosystem services, digitalization, sustainability assessment, stakeholder participation, indicator selection and uncertainty.

Chapter 2: Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Models

Research question 1: *To what extent are agricultural assessment tools and models capable of integrating the ES concept into their assessment frameworks and contributing to the Sustainable Development Goals (SDGs)?*

Chapter 3: Future agricultural systems and the role of digitalization for achieving sustainability goals. A review

Research question 2: *How is digital agriculture integrated within prominent policies and laws, and how is digital agriculture linked to achieving broader sustainability goals as outlined in policy? How might future trends in the agri-food sector shape the adoption and utilization of digital technologies to achieve goals outlined in policy?*

Chapter 4: Using Bayesian networks as a participatory tool for assessing the impacts of digital agriculture

Research question 3: *What are the anticipated impacts of agricultural digitalization according to stakeholders?*

Chapter 5: Synthesis

Outcomes and reflection on uncertainty, comprehensiveness, standardization, outlook and future research.

Figure 3 Overview of thesis structure.

To answer the first research question, Chapter 2 (*Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Models*) reviews a selection of well-known, farm-level sustainability assessment tools and models, followed by a thematic analysis of their indicators to evaluate their strengths and weaknesses in incorporating the concepts of ES and SDGs. Chapter 3 (*Future agricultural systems and the role of digitalization for achieving sustainability goals. A review*) answers the second research question by analyzing the implications of digital agriculture on high-level policies and legislation within the global, European Union, and German context. The study includes a foresight analysis aimed at understanding how future frame conditions of digitalization in the year 2035 could potentially impact the achievement of policy goals and the implementation of laws at the EU and German levels. In Chapter 4 (*Using Bayesian networks as a participatory tool for assessing the impacts of digital agriculture*), to answer the third research question, participatory modeling is used to assess and quantify the potential impacts of digital agriculture in 10 years according to stakeholder perspectives, focusing on the regional scale using the German federal state of Brandenburg as a case study. This involved co-constructing a BBN to facilitate the identification of the main impacts of digital agriculture and modelling uncertainties associated with these impacts through scenario analyses. The findings from Chapter 2 and 3 contribute methodological and thematic insights to Chapter 4, respectively. Last, in Chapter 5, outcomes of the cumulative work are synthesized, exploring aspects of uncertainty and normativity, comprehensiveness and standardization of sustainability assessment, accompanied by an outlook and recommendations on future research.

The work of this thesis was conducted within the research project DAKIS (Digital Agricultural Knowledge and Information Systems), which is – among other things - developing a computer-based DSS to allow farmers and advisors to incorporate ES and biodiversity in farm-level and landscape agro-economic planning (Mouratiadou et al. 2023). The technical component of the DAKIS DSS runs models and simulations using high-resolution, real-time, location-specific data obtained from both in-situ measurements and remote sensing. Building on these models, the project is also anticipating the incorporation of field robots into its DSS framework. The DAKIS research project represents compelling exploration into how digital agriculture technologies can enhance the provision of ES and promote agricultural sustainability, providing motivations for the question addressed within this thesis. Most of the project’s activities are located within the German federal state of Brandenburg, therefore Germany served as focal point in the policy and legal review in Chapter 3, while Brandenburg served as the case study for Chapter 4.

2.
Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Models

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Article

Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Models

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Abstract: A number of tools and models have been developed to assess farm-level sustainability. However, it is unclear how well they potentially incorporate ecosystem services (ES), or how they may contribute to attaining the United Nations Sustainable Development Goals (SDGs). Understanding how farm-level assessment tools and models converge on these new paradigms of sustainability is important for drawing comparison on sustainability performances of farming systems, conducting meta-analyses and upscaling local responses to global driving forces. In this study, a coverage analysis was performed for several farm-level sustainability assessment (SA) tools (SAFA, RISE, KSNL, DLG) and models (MODAM, MONICA, APSIM), in regard to their potential for incorporating ES and contribution to attaining the SDGs. Lists of agricultural-relevant CICES classes and SDG targets were compiled and matched against the indicators of the tools and models. The results showed that SAFA possessed the most comprehensive coverage of ES and SDGs, followed by RISE and KSNL. In comparison to models, SA tools were observed to have a higher degree of potential for covering ES and SDGs, which was attributed to larger and broader indicators sets. However, this study also suggested that, overall, current tools and models do not sufficiently articulate the concept of ecosystem services.

Keywords: agriculture; SA; ecosystem services; SDGs CICES; tools; models; coverage analysis

1. Introduction

Agriculture provides a diverse range of benefits to human well-being. Besides primarily producing food, fodder, fiber, and fuel, agriculture plays a crucial role, for example, in carbon storage, nutrient cycling, hydrological flow regulation, biodiversity conservation, as well as sustaining rural economies and cultural heritage. In this sense, agricultural systems can be considered multifunctional, as they fulfill several purposes simultaneously [1,2]. However, agricultural management often generates trade-offs between functions, e.g., maximization of biomass production versus conserving biodiversity, resulting in outcomes that are detrimental to long-term environment and socio-economic sustainability [3,4]. To promote informed decisions and sustainable agricultural management, integrated and systems-based approaches are needed in science, policy and practice [5].

In agricultural research and policy, the ecosystem service (ES) concept is increasingly used as an integrative framework [6,7] to demonstrate the benefit of nature to human well-being [8]. Derived from biophysical processes and functions, ES produce benefits and values that are used by humans [9]. Within the highly managed environment of agricultural systems, agricultural ES are the product of the coupled interaction between agricultural activity and the ecosystems functions in which they are embedded [10]. Agricultural ES include, among others: the provision of biomass, regulation of hydrological cycles, sequestration of carbon, maintenance of pollinators, and cultural services related to tourism and landscape attractiveness.

At the level of international policy and debate, the United Nations Sustainable Development Goals (SDGs) [11] acknowledge the importance of sustainably managing ecosystems (e.g., SDG 6: Clean Water, SDG 13: Climate Action, SDG 14: Life Below Water, SDG 15: Life on Land). Although the SDGs do not specifically mention agricultural ES, sustainable agriculture is seen as a prerequisite to sustainable global development and eliminating hunger (SDG 2: Zero hunger) [12]. Taken together, sustainably managing agricultural ES is an integral part of achieving the SDGs [13,14]. Similar sentiments are reflected in the Farm to Fork Strategy of the European New Green Deal [15] and many other national strategies and policies. However, the challenge still remains as to how to translate global objectives to local action, while simultaneously considering the site-specific characteristics of local agricultural sustainability [16]. Consequently, improving agriculture sustainability begins first with understanding how decisions on the farm-level can directly and indirectly impact ecological and socio-economic systems.

A large number of approaches have been developed for assessing agricultural sustainability, which has resulted in a variety of farm-level sustainability assessment (SA) tools and models [16,17]. Farm level SA tools and models are designed with the intent of guiding agricultural management toward sustainability. Farm-level tools are typically used by practitioners and consultants for comprehensive, ex-post assessment and strategic planning, whereas models are mainly used within research for making anticipatory simulations, usually with a narrower range of sustainability objectives. Differences in purpose and approach between SA tools and models substantially influences how they individually articulate sustainability performance of farm management [18,19]. Specifically, differences in thematic scope, e.g., the range of environmental, social and economic topics covered by a given SA tool or model, determines how well they can potentially incorporate ES in their assessment. Although many farm-level tools and models are not intended to explicitly account for ES and SDGS, the notion that their thematic coverage can implicitly cover ES and SDGs should not be excluded from consideration. It is interesting, therefore, to evaluate the potential of farm-level SA tools and models, to incorporate ES and contribute to attaining the SDGs by carefully reviewing their methodologies.

The focus of this study is twofold: the first, to assess a group of well-established, farm-level SA tools (SAFA, RISE, KSNL, DLG) and models (MODAM, MONICA, APSIM), according to their potential for covering agriculture-related ES; the second, to evaluate how these SA tools and models support the realization of the SDGs. Accordingly, two objectives are defined: (1) review and catalog information on the methodologies of each SA tool and model; (2) review and compare thematic content of each tool (indicators) and model (outputs), concerning the coverage of ecosystem services and SDGs. By elucidating similarities and differences on the thematic scope of each SA tool and model, the overarching goal of this study is to gain insights into how SA methods can be improved to better reflect new paradigms of sustainability within agriculture.

2. Methodology

The field of agricultural sustainability assessment is marked by a diversity of agricultural SA tools, varying in purpose (e.g., self-assessment/monitoring, advisory, certification, research, policy making) level of assessment (e.g., field, farm, supply chain, product), degree of integration (e.g., environmental, social, economic dimensions), level of precision (e.g., qualitative, quantitative), scope (e.g., geographical, sectoral, thematic), target group (e.g., policy makers, advisors, farmers), indicator selection (e.g., pre-defined, customizable), and methods for indicator weighting and aggregation (e.g., multi-criteria analysis, life-cycle analysis, indexes) [20–22].

Many studies have engaged in reviewing and comparing agriculture SA tools. Gasparatos et al. [22] categorized SA into monetary, bio-physical and indicator-based approaches. Ness et al. [23] developed a framework that classified SA according to temporal scope (e.g., ex-ante or ex-post assessment) and whether they were product related, integrated, or indicator based. Binder et al. developed a comparison framework to analyze agricultural tools, in regard to normative, systemic and procedural characteristics, categorizing tools according to top-down or bottom-up approaches [24]. Reviewing SA tools according to time, data and budgetary requirements, Merchand et al. [25] identified two types of farm-level assessment: rapid assessment appraisals (RSA) and full assessment appraisals (FSA). De Olde et al. [19] conducted a coverage analysis, to explore similarities and differences of thematic scope between SA tools, and developed a continuum that describes farm-level tools, according to difficulty of implementation versus degree of comprehensiveness [26].

Farm models are similar to SA tools, in that they can be used to help guide farming decisions toward more sustainable management. However, agricultural models themselves are primarily designed for conducting scientific research and, secondarily, for farm-level decision support [27]. Farm models typically combine multiple process-based models to simulate the impacts of management decisions in a prospective (ex-ante) capacity on bio-physical and economic processes at the field, farm and regional scale [28]. Farm models can be divided into static or dynamic approaches, where time is a driving factor of dynamic models, allowing the integration of 'real-time' changes of bio-physical and economic processes in simulations. In contrast, static models use linear programming, which means that they cannot readily capture changes from feedback loops inherent in bio-physical processes [27].

Although existing farm-level SA tools and models tend to place significantly more emphasis on assessing the environmental dimension of sustainability rather than social or economic dimensions [19,29], they have not been designed with the expressed purpose of capturing the value of agricultural ES. However, this does not exclude the possibility that current SA tools and models can implicitly cover ES through their methods and thematic scope (indicators). The same can be said in terms of the potential of SA tools and models to contribute to attaining the SDGs, as their thematic scope may implicitly incorporate many of the same normative values. Therefore, SA results derived from models and tools are extremely valuable, not only for the specific cases of their application, but also in meta-analyses to derive generalized information about farming systems performances. This would allow an upscaling of local responses to global driving forces, such as climate change, global demand dynamics or policies. However, such meta-analysis is only possible, if standardized terminology (ontology) and indicators are used that allow for comparisons across tool and model applications. In this sense, it is necessary to review and compare farm-level SA tools and models, to assess their potential for explicitly and implicitly covering ES, and their contribution to the attainment of the SDGs.

To choose SA tools and models for this study, basic selection criteria had to be fulfilled, such that tools and models should (*i*) be usable for making management decisions on the farm level, (*ii*) utilize indicator-based scoring, (*iii*) use multi-criteria analysis, (*iv*) been applied within Germany as a test case example, and (*v*) have sufficient primary literature available in English or German. We chose Germany as a test case, because it is characterized by comparably large scale, low yield gap agriculture, with high education levels of farmers, who are accustomed to the use of tools and models for strategic decision making. Based on these criteria, four farm-level SA tools (SAFA, RISE, KSNL, DLG) and three farm-level models (MODAM, MONICA, APSIM) were selected for this study.

The next sub-sections provide brief overviews of each tool and model involved in the study, outlining general information (see Table 1), and classified according to Schader et al. [20] on key characteristics, including primary purpose, level of assessment, geographical scope, sector, and themes, as well as structure (see Table 2).

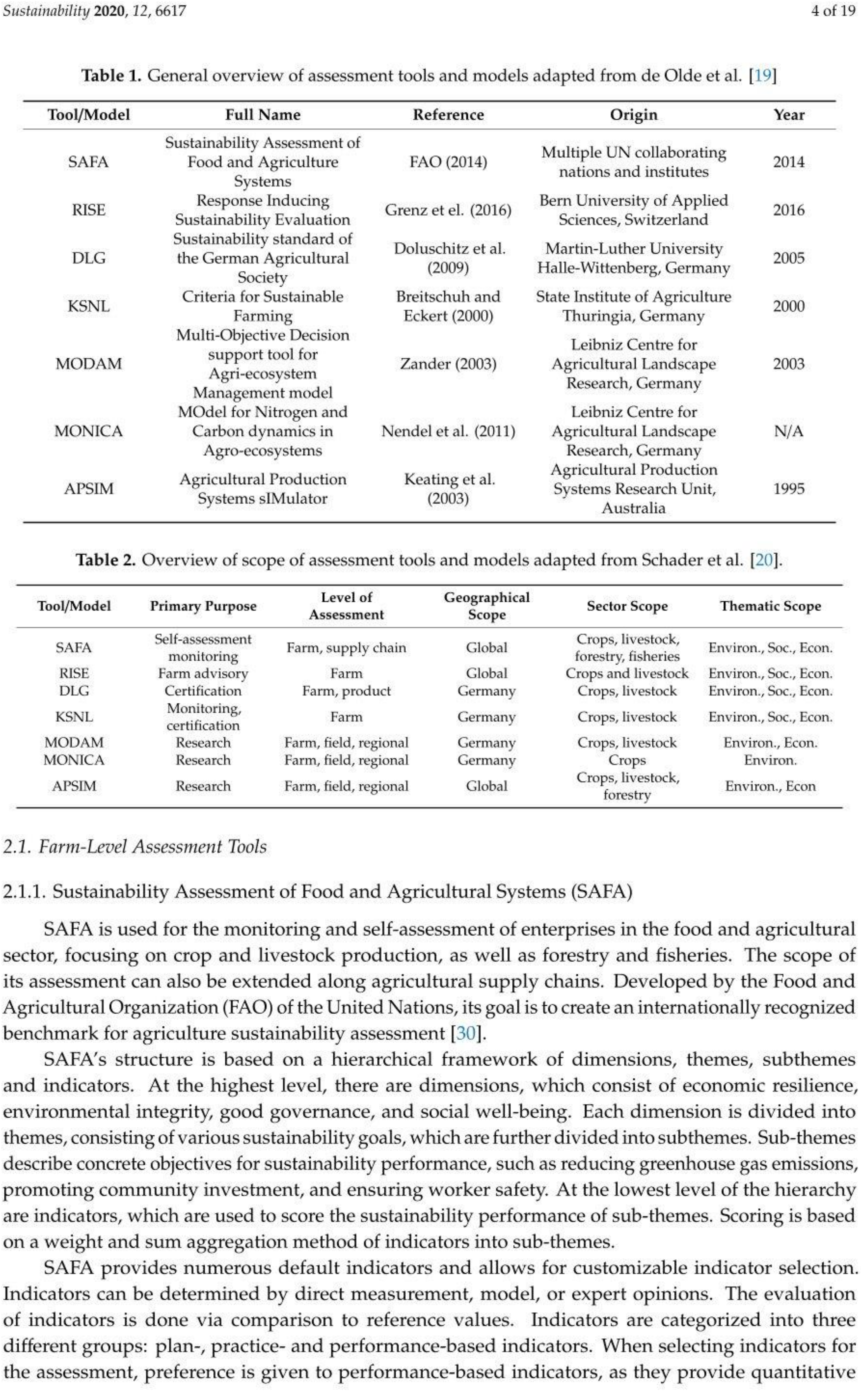

Table 1. General overview of assessment tools and models adapted from de Olde et al. [19]

Tool/Model	Full Name	Reference	Origin	Year
SAFA	Sustainability Assessment of Food and Agriculture Systems	FAO (2014)	Multiple UN collaborating nations and institutes	2014
RISE	Response Inducing Sustainability Evaluation	Grenz et el. (2016)	Bern University of Applied Sciences, Switzerland	2016
DLG	Sustainability standard of the German Agricultural Society	Doluschitz et al. (2009)	Martin-Luther University Halle-Wittenberg, Germany	2005
KSNL	Criteria for Sustainable Farming	Breitschuh and Eckert (2000)	State Institute of Agriculture Thuringia, Germany	2000
MODAM	Multi-Objective Decision support tool for Agri-ecosystem Management model	Zander (2003)	Leibniz Centre for Agricultural Landscape Research, Germany	2003
MONICA	MOdel for Nitrogen and Carbon dynamics in Agro-ecosystems	Nendel et al. (2011)	Leibniz Centre for Agricultural Landscape Research, Germany	N/A
APSIM	Agricultural Production Systems sIMulator	Keating et al. (2003)	Agricultural Production Systems Research Unit, Australia	1995

Table 2. Overview of scope of assessment tools and models adapted from Schader et al. [20].

Tool/Model	Primary Purpose	Level of Assessment	Geographical Scope	Sector Scope	Thematic Scope
SAFA	Self-assessment monitoring	Farm, supply chain	Global	Crops, livestock, forestry, fisheries	Environ., Soc., Econ.
RISE	Farm advisory	Farm	Global	Crops and livestock	Environ., Soc., Econ.
DLG	Certification	Farm, product	Germany	Crops, livestock	Environ., Soc., Econ.
KSNL	Monitoring, certification	Farm	Germany	Crops, livestock	Environ., Soc., Econ.
MODAM	Research	Farm, field, regional	Germany	Crops, livestock	Environ., Econ.
MONICA	Research	Farm, field, regional	Germany	Crops	Environ.
APSIM	Research	Farm, field, regional	Global	Crops, livestock, forestry	Environ., Econ

2.1. Farm-Level Assessment Tools

2.1.1. Sustainability Assessment of Food and Agricultural Systems (SAFA)

SAFA is used for the monitoring and self-assessment of enterprises in the food and agricultural sector, focusing on crop and livestock production, as well as forestry and fisheries. The scope of its assessment can also be extended along agricultural supply chains. Developed by the Food and Agricultural Organization (FAO) of the United Nations, its goal is to create an internationally recognized benchmark for agriculture sustainability assessment [30].

SAFA's structure is based on a hierarchical framework of dimensions, themes, subthemes and indicators. At the highest level, there are dimensions, which consist of economic resilience, environmental integrity, good governance, and social well-being. Each dimension is divided into themes, consisting of various sustainability goals, which are further divided into subthemes. Sub-themes describe concrete objectives for sustainability performance, such as reducing greenhouse gas emissions, promoting community investment, and ensuring worker safety. At the lowest level of the hierarchy are indicators, which are used to score the sustainability performance of sub-themes. Scoring is based on a weight and sum aggregation method of indicators into sub-themes.

SAFA provides numerous default indicators and allows for customizable indicator selection. Indicators can be determined by direct measurement, model, or expert opinions. The evaluation of indicators is done via comparison to reference values. Indicators are categorized into three different groups: plan-, practice- and performance-based indicators. When selecting indicators for the assessment, preference is given to performance-based indicators, as they provide quantitative metrics for measuring sustainability performance. When performance-based indicators are not readily available to the assessor, plan- and practice-based indicators are used instead. Default indicators are provided in the SAFA manual and specified in an indicator supplementary document [31]. SAFA does not provide farms with certification, however, if a farm can demonstrate that the assessment was conducted transparently, reference can be made to 'Consistency with the SAFA principles and procedures' [30].

2.1.2. Response-Inducing Sustainability Evaluation (RISE)

RISE is a holistic, indicator-based sustainability tool that focuses on production at the farm level [32]. Developed by the Swiss College of Agricultural, Forest and Food Sciences in 2000, the purpose of RISE is to support farmers in recognizing specific on-farm deficiencies in sustainability performance. Its secondary purpose is to communicate ideas of regional and global sustainability for use at the policy level. Since 2016, RISE has adopted many of the indicators of SAFA to describe in an effort to promote standardization and comparability.

RISE consists of 10 themes and 46 indicator. Themes cover a range of environmental issues, e.g., biodiversity, water usage, and soil quality, as well as social and economic issues, e.g., working conditions and economic viability. Indicators are used to evaluate sustainability at the theme level. RISE allows for selecting indicators based on goal setting, or based on what type of farming enterprise is under review. Data on indicators are collected from regional databases, as well as questionnaire-based interviews with the farmer. Algorithms and thresholds are used to aggregate indicators and generate theme scores. RISE does not provide certification, however the assessment generates a report outlining recommendations to improve sustainability.

2.1.3. Sustainability Standard of the German Agricultural Society (DLG Sustainability Standard)

The DLG sustainability standard provides analysis and certification for farms and agricultural products within Germany. The assessment covers food, energy crops and livestock production at the farm and plot level. It was conceived in 2005 by the German Agricultural Society, an agricultural section representation, in cooperation with the Technical University of Munich, Martin-Luther University Halle-Wittenberg and the Institute for Sustainable Agriculture Halle [33], with the goal to ensure that agriculture actively promotes a sustainable economy through documentation and communication.

The DLG standard is based on the REPRO environmental and economic management model [34], which consist of a variety of highly complex and interwoven sub-models. The assessment is structured along environmental, economic and social dimensions, which are further divided into a total of 11 sectors of analysis and 25 indicators. Sectors of analysis in the environmental dimension include climate protection, resource input, biodiversity, and soil and water protection. Data on indicators are obtained from three years of field records and financial statements, as well as a questionnaire filled out by the farmer. Indicators are described through a variety of thresholds and regional benchmarks, which are aggregated into a sub-index at the level of each dimension. All three dimensions are then aggregated into an overall sustainability index. A DLG assessment is conducted by a certified auditing agency, which provides a report on farm sustainability and detailed information on each indicator. Certification of the DLG sustainability standard is issued to a farm, providing that specific standards of sustainability are fulfilled.

2.1.4. Criteria for Sustainable Farming (KSNL)

The KSNL assessment provides sustainability analysis and certification for crop, livestock and bioenergy production at the farm level. Its aim is to provide farmers with advice, by identifying deficiencies regarding different SA criteria. Beginning with the criteria for ecologically compatible farming (KUL) module that was developed by the State Institute of Agriculture Thuringa in 1994, KSNL was formally established in 2000, with the addition of the criteria for economically compatible farming (KWL) module and criteria for socially compatible farming (KSL) module [35]. The KUL, KWL, and KSL modules are divided into a total of 12 categories and 37 criterion. Categories within KUL include fertilizer balances, soil protection, pesticide use, biodiversity, and energy balance. Criterion are evaluated and scored according to predetermined tolerance thresholds. The KSNL assessment allows farmers to compare their sustainability performance according to criteria against those of their peers within Germany. If sustainability thresholds are attained, then KSNL provides farm certification.

2.2. Farm-Level Assessment Models

2.2.1. Multi-Objective Decision Support Model for Agri-Ecosystem Management Model (MODAM)

MODAM is a static, process-based model that employs multi-objective linear programing to assess farm-level economic and environmental sustainability of crop and livestock production [36,37]. Hosted by the Leibniz Centre for Agricultural Landscape Research (ZALF), MODAM is primarily used for research, to investigate production practices according to associated economic and environmental targets. As such, the model consists of two separate economic and environmental sub-models that are interlinked, so that specific production processes can be evaluated according to trade-offs of impacts on environmental and economic outcomes. The model accounts for metrics on economic performance (e.g., costs, revenues, and gross margins), and ecological indicators (e.g., nitrate leaching, erosion and greenhouse gasses). Using a fuzzy-logic tool, the effects of production practice on selected ecological indicators is assessed and indexed, in relation to site-specific impacts. The model allows for the selection of environmental indicators, or environmental quality targets (EQTs), and the site-specific analysis of impacts on EQTs from different production practices. MODAM is capable of performing scenario analysis, by integrating changes in exogenous variables, such as prices, and therefore is suitable for conducting impact assessments of agri-environmental policies. MODAM has been mainly applied in Europe, in particular Germany [38].

2.2.2. Model for Nitrogen and Carbon Dynamics in Agro-Ecosystems (MONICA)

Primarily used for research, MONICA is a dynamic, process-based model that is mainly used to simulate crop growth under different climate conditions [39]. The model functions to analyze the relationship between crop growth and soil characteristics under different climatic conditions and cropping practices. By building on the nitrogen cycle simulation of the HERMES model [40], MONICA introduces a carbon cycle component to simulate the long-term impacts of soil organic content (SOC) and crop growth under changes in atmospheric CO_2 [41]. Simulations are conducted on the plot level with a resolution of 1 m^2, and can be extended to farm, as well as regional level impacts assessments. Most applications have been conducted within a European context, such as simulating impacts on SOC of different residue management scenarios [42] and predicting the success of various crop rotations under different climate scenarios [43].

2.2.3. Agricultural Production Systems sIMulator (APSIM)

Developed in the early 1990s by the Agricultural Production Systems Research Unit (APSRU) of the Queensland State Government in Australia, the original purpose of the APSIM modelling framework was to model plant growth under various bio-physical and economic conditions [44]. In recent years, the growing popularity of APSIM has led to an expansion of its modular framework, and to numerous additions to its modelling capabilities, allowing for the modelling of soil, tree, and livestock bio-physical processes under various management practices [45]. APSIM uses dynamic, process-based modelling to incorporate bio-physical feedbacks in its simulations. It has been used in research, to assess farm-level management practices, climate change and climate risk adaptation strategies, agro-forestry strategies, livestock and pasture strategies, and nutrient leaching at field and regional scales [46,47].

2.3. Agriculture-Related Ecosystem Services

The concept of ecosystem services (ES) is used to demonstrate the benefit of nature to human well-being [8]. Principally, agricultural ecosystems supply benefits to farmers and society through the provisioning of materials (e.g., food, feed, fiber, and energy). However, agricultural activity is also linked to a wide range of less tangible ES, including pest regulation, maintaining nutrient and hydrological cycles, pollination, erosion, bio-remediation and diversity of genetic resources, as well as scenic beauty and recreation. Within the highly managed environmental context of agricultural management, ES are the product of the coupled interaction between agricultural management and the ecosystems in which they are embedded [10].

In order to assess agricultural ES, it is necessary to categorize and classify them, using a standardized typology. The primary motivation behind standardizing ES is to facilitate the comparison of studies across regional and thematic boundaries, allow for upscaling and deriving synthesis information, as well as to make ES studies policy relevant [6]. Over the years, several typologies have been created, including the Millennium Ecosystem Assessment [8], The Economics of Ecosystems and Biodiversity [48] and the Common International Classification of Ecosystem Services (CICES) [49]. This study utilizes the CICES (V5.1) framework, as it provides the most comprehensive ES classification system to date, represents the state-of-the-art in its field, and is used for ES accounting by the European Environmental Agency [50]. CICES provides a hierarchical and nested structure of sections, divisions, groups, classes and class types. Sections are divided into biotic and abiotic provisioning, regulation and maintenance, and cultural services. This study utilizes these sectional distinctions to organize the structure of the analysis, and identifies ES based on the class level. CICES identifies 83 ES classes in total.

However, because not all CICES classes are germane to agricultural management, a short list of the most relevant ES classes was compiled to facilitate the analysis of this study. Only services that were deemed relevant to arable farming in a European context were considered for the analysis, e.g., services related to marine ecosystems were excluded. The resulting list included 31 ES classes (see Appendix A). As many CICES classes have long and cumbersome names, it was prudent to use abbreviated CICES class names, adopted from Paul et al. [51], to facilitate the analysis.

The short list of 31 agriculture-related CICES classes was then used to conduct a coverage analysis for each SA tool and model. Using descriptions of indicators obtained from the literature, the indicators from each tool and model were compared and matched to ES classes in the short list. Determining whether an indicator could be matched to an ES class was qualitative, and required a degree of interpretation, i.e., direct and explicit linkages between ES and indicators were sometimes difficult to make. Instead, by referencing the content included in the primary literature of the tools and models, as well as scientific publications documenting their usage, it was possible to interpret how some tool and model indicators could be potentially used as proxy values for determining ES coverage. For example, in some cases, matching was straightforward, e.g., the CICES class 'Soil quality by decomposition and fixing processes' (2.2.4.2) could be matched to indicators associated with soil organic matter. In other cases, matching had to be made more indirectly, e.g., CICES classes associated with the provision of biomass, such as 'Cultivated terrestrial plants for nutrition' (1.1.1.1) or 'Reared animals for nutrition' (1.1.3.1), could be matched only to a proxy indicator, like farm income. Various examples of specific matches between ES classes and tool indicators are shown in Table 3.

2.4. Agriculture-Related Sustainable Development Goals

In 2015, the General Assembly of the United Nations adopted the Sustainable Development Goals [11]. As the cornerstone of the 2030 Agenda of Sustainable Development, the 17 SDGs lay out a broad path toward achieving environmental, social and economic sustainability on a global scale. To achieve the SDGs, 169 time-bound targets have been specified. UN members are required to report annually on progress toward attaining these targets [52].

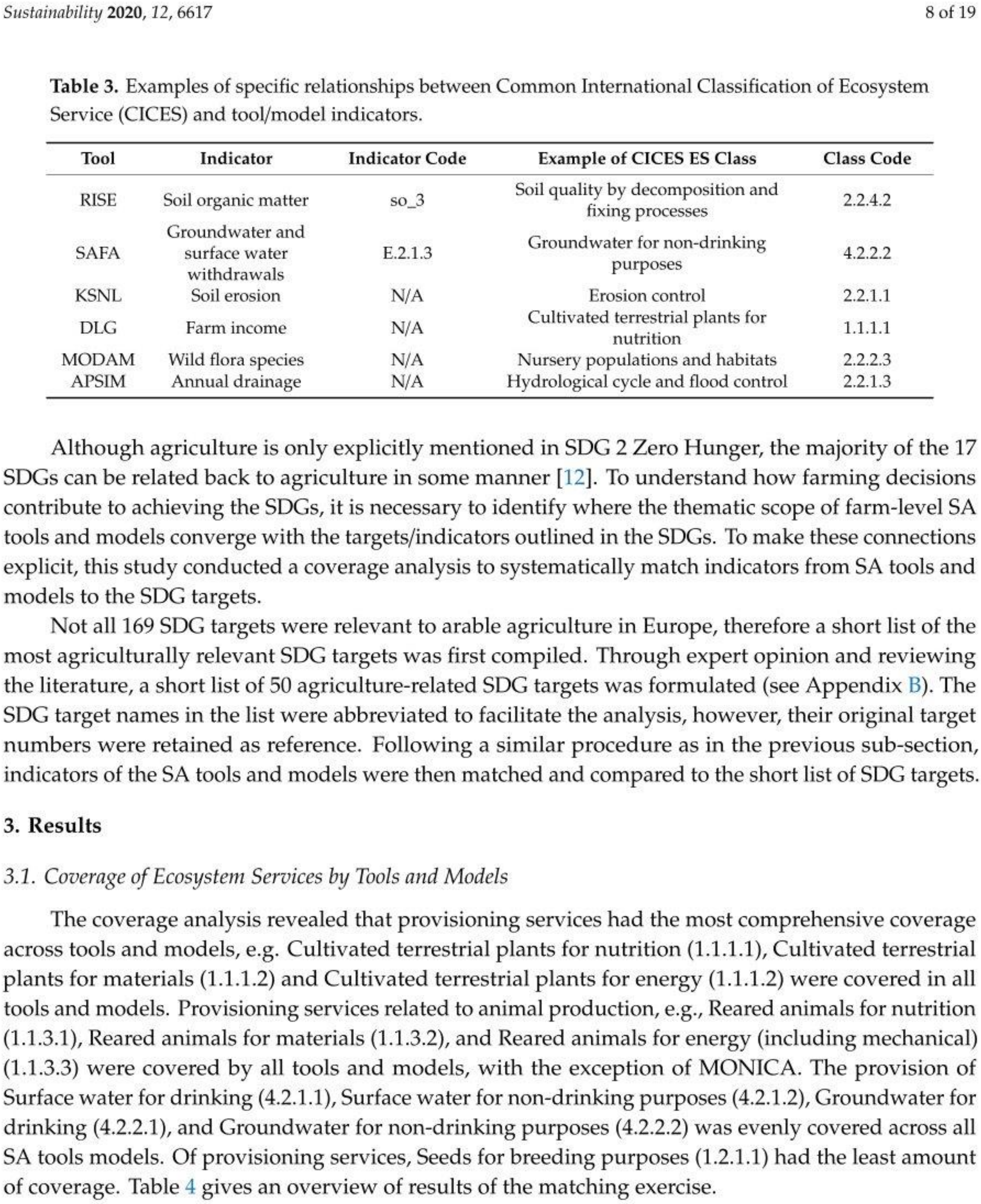

Table 3. Examples of specific relationships between Common International Classification of Ecosystem Service (CICES) and tool/model indicators.

Tool	Indicator	Indicator Code	Example of CICES ES Class	Class Code
RISE	Soil organic matter	so_3	Soil quality by decomposition and fixing processes	2.2.4.2
SAFA	Groundwater and surface water withdrawals	E.2.1.3	Groundwater for non-drinking purposes	4.2.2.2
KSNL	Soil erosion	N/A	Erosion control	2.2.1.1
DLG	Farm income	N/A	Cultivated terrestrial plants for nutrition	1.1.1.1
MODAM	Wild flora species	N/A	Nursery populations and habitats	2.2.2.3
APSIM	Annual drainage	N/A	Hydrological cycle and flood control	2.2.1.3

Although agriculture is only explicitly mentioned in SDG 2 Zero Hunger, the majority of the 17 SDGs can be related back to agriculture in some manner [12]. To understand how farming decisions contribute to achieving the SDGs, it is necessary to identify where the thematic scope of farm-level SA tools and models converge with the targets/indicators outlined in the SDGs. To make these connections explicit, this study conducted a coverage analysis to systematically match indicators from SA tools and models to the SDG targets.

Not all 169 SDG targets were relevant to arable agriculture in Europe, therefore a short list of the most agriculturally relevant SDG targets was first compiled. Through expert opinion and reviewing the literature, a short list of 50 agriculture-related SDG targets was formulated (see Appendix B). The SDG target names in the list were abbreviated to facilitate the analysis, however, their original target numbers were retained as reference. Following a similar procedure as in the previous sub-section, indicators of the SA tools and models were then matched and compared to the short list of SDG targets.

3. Results

3.1. Coverage of Ecosystem Services by Tools and Models

The coverage analysis revealed that provisioning services had the most comprehensive coverage across tools and models, e.g. Cultivated terrestrial plants for nutrition (1.1.1.1), Cultivated terrestrial plants for materials (1.1.1.2) and Cultivated terrestrial plants for energy (1.1.1.2) were covered in all tools and models. Provisioning services related to animal production, e.g., Reared animals for nutrition (1.1.3.1), Reared animals for materials (1.1.3.2), and Reared animals for energy (including mechanical) (1.1.3.3) were covered by all tools and models, with the exception of MONICA. The provision of Surface water for drinking (4.2.1.1), Surface water for non-drinking purposes (4.2.1.2), Groundwater for drinking (4.2.2.1), and Groundwater for non-drinking purposes (4.2.2.2) was evenly covered across all SA tools models. Of provisioning services, Seeds for breeding purposes (1.2.1.1) had the least amount of coverage. Table 4 gives an overview of results of the matching exercise.

Table 4. Coverage of CICES ecosystem service classes by SA tool and model.

Ecosystem Service	Code	ES Category	SAFA	RISE	DLG	KSNL	MODAM	MONICA	APSIM
Cultivated terrestrial plants for nutrition	1.1.1.1	Provisioning	x	x	x	x	x	x	x
Cultivated terrestrial plants for materials	1.1.1.2	Provisioning	x	x	x	x	x	x	x
Cultivated terrestrial plants for energy	1.1.1.3	Provisioning	x	x	x	x	x	x	x
Reared animals for nutrition	1.1.3.1	Provisioning	x	x	x	x	x		x
Reared animals for materials	1.1.3.2	Provisioning	x	x	x	x	x		x
Reared animals for energy (including mechanical)	1.1.3.3	Provisioning	x	x	x	x	x		x
Seeds for breeding purposes	1.2.1.1	Provisioning	x	x					
Biotic remediation of waste	2.1.1.1	Regulation/maintenance	x	x					
Biotic filtration, sequestration and storage of waste	2.1.1.2	Regulation/maintenance	x	x	x	x		x	x
Visual screening	2.1.2.3	Regulation/maintenance							
Erosion control	2.2.1.1	Regulation/maintenance	x	x	x	x	x		x
Hydrological cycle and flood control	2.2.1.3	Regulation/maintenance	x	x					x
Pollination	2.2.2.1	Regulation/maintenance	x	x	x	x	x		
Seed dispersal	2.2.2.2	Regulation/maintenance	x				x		
Nursery populations and habitats	2.2.2.3	Regulation/maintenance	x	x	x	x	x		
Pest control (including invasive species)	2.2.3.1	Regulation/maintenance	x	x	x	x	x		
Disease control	2.2.3.2	Regulation/maintenance	x	x	x				
Soil quality by decomposition and fixing processes	2.2.4.2	Regulation/maintenance	x	x	x	x	x	x	x
Chemical condition of freshwaters	2.2.5.1	Regulation/maintenance	x	x		x		x	x
Chemical composition of atmosphere and oceans	2.2.6.1	Regulation/maintenance	x	x	x	x		x	x
Local regulation of air temperature and humidity	2.2.6.2	Regulation/maintenance	x	x				x	x
Recreation through activities in nature	3.1.1.1	Cultural			x	x			
Recreation through observation of nature	3.1.1.2	Cultural			x	x			
Education and training interactions with nature	3.1.2.2	Cultural				x			
Culture or heritage from interaction with nature	3.1.2.3	Cultural	x						
Surface water for drinking	4.2.1.1	Provisioning	x	x	x	x	x		
Surface water for non-drinking purposes	4.2.1.2	Provisioning	x	x	x	x	x		
Groundwater for drinking	4.2.2.1	Provisioning	x	x	x	x	x		
Groundwater for non-drinking purposes	4.2.2.2	Provisioning	x	x	x	x	x		
Abiotic filtration, sequestration and storage of waste	5.1.1.3	Regulation/maintenance	x	x				x	
Control of liquid flows	5.2.1.2	Regulation/maintenance	x	x					

In regard to regulation and maintenance services, SA tools were more comprehensive in their coverage than models. SAFA and RISE had the most complete coverage of regulation and maintenance services of all tools and models. Biotic filtration, sequestration and storage of waste (2.1.1.2), Erosion control (2.2.1.1), Pollination (2.2.2.1), Nursery populations and habitats (2.2.2.3), and Pest control (including invasive species) (2.2.3.1) classes were covered by all SA tools. Visual screening (2.1.2.3) was not covered by any SA tools or models.

Cultural services had the least amount of coverage. Recreation through activities in nature (3.1.1.1) and Recreation through observation of nature (3.1.1.2) were covered in KSNL and DLG, but were absent in all other tools and models. SAFA was the only tool to cover Culture or heritage from interaction with nature (3.1.2.3). Cultural services were not covered by any of the models.

3.2. *Overview of SDG Coverage*

SDG2: Zero hunger, SDG8: Decent work and economic growth, and SDG15: Life on land, had the highest amount of coverage across SA tools and models, which was followed by SDG6: Clean water and sanitation, SDG13: Climate action, SDG12: Responsible consumption and production, and SDG1: End poverty. Some degree of coverage was found for SDG3: Good health and well-being, SDG7: Affordable and clean energy SDG14: Life below water, and SDG16: Peace and justice and strong institution, while none of the tools or models covered SDG9: Industry, innovation and infrastructure. Table 5 provides an overview of the resulting coverage analysis.

In regard to individual SDG targets, targets 2.04 Promote practices that improve land and 8.04 Resource use efficiency, were covered by all SA tools and models. Additionally, targets 1.02 Reduce poverty by half and 2.03 Increase agricultural productivity, were covered by all tools and models with the exception of MONICA. Targets 6.06 Protect water ecosystems, 13.01 Adaptive capacity to climate-related hazards, 14.01 Prevent/reduce marine pollution (nutrient pollution) and 15.02 Protect terrestrial ecosystems, shared a similar degree of coverage across SA tools and models.

Overall, SA tools showed a greater amount of coverage of SDG targets than models. Out of the SA tools, SAFA had the highest coverage of SDGs, followed by RISE, KSNL, and DLG. Of the models, APSIM covered the most targets, followed by MODAM and MONICA.

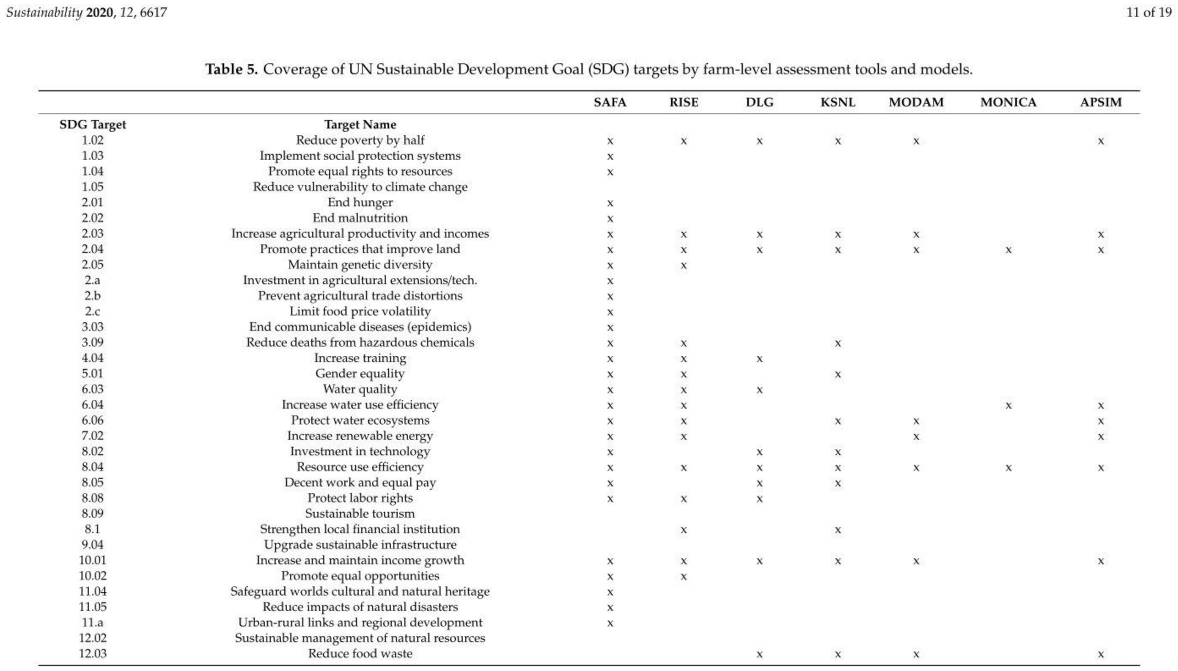

Table 5. Coverage of UN Sustainable Development Goal (SDG) targets by farm-level assessment tools and models.

		SAFA	RISE	DLG	KSNL	MODAM	MONICA	APSIM
SDG Target	**Target Name**							
1.02	Reduce poverty by half	x	x	x	x	x		x
1.03	Implement social protection systems	x						
1.04	Promote equal rights to resources	x						
1.05	Reduce vulnerability to climate change							
2.01	End hunger	x						
2.02	End malnutrition	x						
2.03	Increase agricultural productivity and incomes	x	x	x	x	x		x
2.04	Promote practices that improve land	x	x	x	x	x	x	x
2.05	Maintain genetic diversity	x	x					
2.a	Investment in agricultural extensions/tech.	x						
2.b	Prevent agricultural trade distortions	x						
2.c	Limit food price volatility	x						
3.03	End communicable diseases (epidemics)	x						
3.09	Reduce deaths from hazardous chemicals	x	x		x			
4.04	Increase training	x	x	x				
5.01	Gender equality	x	x		x			
6.03	Water quality	x	x	x				
6.04	Increase water use efficiency	x	x				x	x
6.06	Protect water ecosystems	x	x		x	x		x
7.02	Increase renewable energy	x	x			x		x
8.02	Investment in technology	x		x	x			
8.04	Resource use efficiency	x	x	x	x	x	x	x
8.05	Decent work and equal pay	x		x	x			
8.08	Protect labor rights	x	x	x				
8.09	Sustainable tourism							
8.1	Strengthen local financial institution		x		x			
9.04	Upgrade sustainable infrastructure							
10.01	Increase and maintain income growth	x	x	x	x	x		x
10.02	Promote equal opportunities	x	x					
11.04	Safeguard worlds cultural and natural heritage	x						
11.05	Reduce impacts of natural disasters	x						
11.a	Urban-rural links and regional development	x						
12.02	Sustainable management of natural resources							
12.03	Reduce food waste			x	x	x		x

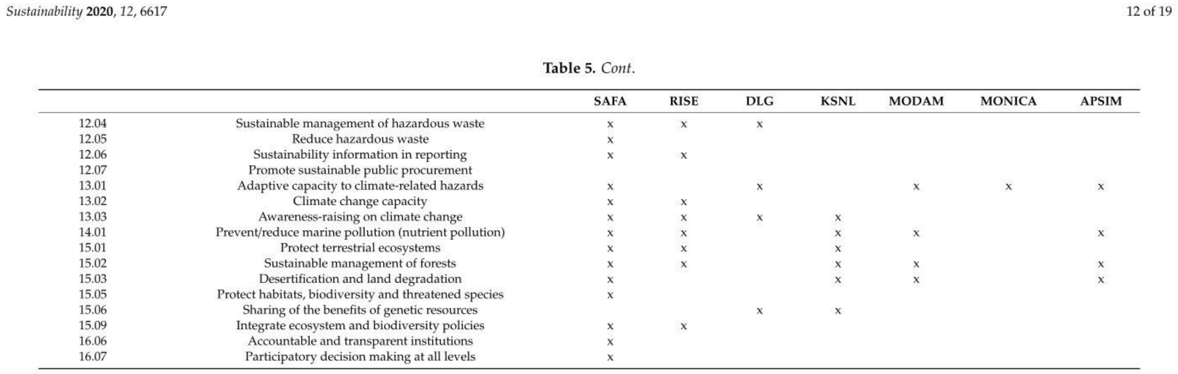

Table 5. *Cont.*

		SAFA	RISE	DLG	KSNL	MODAM	MONICA	APSIM
12.04	Sustainable management of hazardous waste	x	x	x				
12.05	Reduce hazardous waste	x						
12.06	Sustainability information in reporting	x	x					
12.07	Promote sustainable public procurement							
13.01	Adaptive capacity to climate-related hazards	x		x		x	x	x
13.02	Climate change capacity	x	x					
13.03	Awareness-raising on climate change	x	x	x	x			
14.01	Prevent/reduce marine pollution (nutrient pollution)	x	x		x	x		x
15.01	Protect terrestrial ecosystems	x	x		x			
15.02	Sustainable management of forests	x	x		x	x		x
15.03	Desertification and land degradation	x			x	x		x
15.05	Protect habitats, biodiversity and threatened species	x						
15.06	Sharing of the benefits of genetic resources			x	x			
15.09	Integrate ecosystem and biodiversity policies	x	x					
16.06	Accountable and transparent institutions	x						
16.07	Participatory decision making at all levels	x						

4. Discussion

By conducting a coverage analysis that focused on indicators of SA tools and models, it was possible to evaluate their thematic coverage, which revealed substantial differences in their relative potential to cover ES and its contribution toward attaining the SDGs. SA tools (SAFA, RISE, DLG, KSNL) had broader potential coverage of agriculture-related CICES classes in comparison to the farm-level models (MODAM, MONICA, APSIM). Out of all tools and models involved in the study, only SAFA and RISE could be considered comprehensive in terms of both potentially covering ES and attaining the targets outlined in the SDGs.

Overall, SAFA had the broadest potential coverage of ES and SDGs. Although SAFA only mentions ES explicitly in Ecosystem enhancing practice (E 4.1.2) and Structural diversity of ecosystem services (E 4.1.3), the general importance of ecosystems within the context of agriculture management is repeatedly mentioned throughout its manual and Supplementary Material. SAFA's relatively broad coverage of SDG targets can be attributed to the affiliation of the FAO with the UN; and, as SAFA predates the SDGs, it can only be assumed that some of the sustainability criterion outlined in SAFA were used in shaping the SDG targets. RISE showed a similar degree of coverage in terms of ES and SDGs, which can be attributed to recent efforts on behalf of RISE, to harmonize its indicators with those of SAFA [32]. Based on these findings, we conclude that SAFA should continue to be regarded as the standard for farm-level sustainability assessment.

The results suggest that a broad range of indicators, as well as customizable indicator selection, is conducive toward covering a broader range of ES and SDG targets. This was specifically observed in SA tools such as SAFA and RISE. By design, SAFA and RISE are intended to be globally applicable in scope, which means: they must be adaptable to a diverse variety of geographic and normative contexts, hence the necessity to provide a broad set of customizable indicators [53]. This flexibility of indicators allowed SAFA and RISE to cover a wide range of ES and SDGs. On the other hand, it should not be overlooked that customizable indicator selection could unintentionally, or even intentionally, obscure deficiencies in regard to sustainability performance if not based on a proper materiality analysis [54].

A divergence was observed between tools and models, in regard to their potential coverage of ES and SDGs; models generally possessed far fewer indicators and, thus, exhibited a narrower coverage of ES and SDGs. On the basis of the definition of tools and models, as well as the distinction between them used in this paper, models are more limited than tools with regards to the thematic scope, because they are typically developed and applied for answering questions within research and policy that are often highly context-specific. Additionally, due to the level of scientific rigor associated with conducting research, model assessments are limited to indicators whose values have been validated through scientific studies. However, even though models covered fewer ES classes, Merchand et al. [25] argued that tools or models which rely more on quantitative indicators and complex algorithms to capture indicator interaction have a higher amount of credibility, which lends itself toward more accurate portrayals of some ES. On the other hand, sustainability assessment is about identifying trade-offs between competing sustainability targets [55]. A wide range of indicators is therefore a pre-requisite for any model or tool employed for SA.

De Olde et al. [26] pointed out that the comprehensiveness of a tool or model is at odds with its usability. This suggests that if tools and models try to capture too many ES (via the inclusion of more indicators) that conducting the assessment and communicating results to farmers and policy-makers may be too difficult. This should be taken into consideration when developing future farm level SA tools and models.

Even though the ES concept has an environmental bias [56] (which some have claimed is already a problem in current SA [25]), there is still room for better articulating and integrating the ES concept in farm-level tools and models. However, until there is consensus on terminology, i.e., indicators for measuring agricultural ES, it will be difficult to explicitly account for them in farm-level assessments [57]. Additionally, as consensus grows on how to measure agricultural ES, it will become easier to assess how the sustainable management of agricultural ES contributes to broader sustainability objectives, such as the SDGs.

The contribution of local, farm-level decision making to sustainability targets at the global level is a question of high relevance in global assessment studies. However, generalization and the upscaling of local level assessments to global level requires the ability to compare and aggregate across a wide range of local case study results. This, again, is only possible with standardized metrics and indicators [57,58], in particular when novel methods of automated data mining and text analysis are employed [59]. The utilization of the CICES indicator terminology in SA tools and models would be an important step forward in the generalization and upscaling of local assessment outcomes.

5. Conclusions

This study evaluated current farm-level assessment tools and models, in light of new concepts and principles of sustainability. A coverage analysis was conducted to investigate how adequately ES and the UN SDGs are potentially incorporated by the thematic content (indicators) of a select group of common farm-level tools (SAFA, RISE, DLG, KSNL) and scientific models (MODAM, MONICA APSIM). The results of the study revealed that SAFA outperformed its counterparts in terms of its potential to cover ecosystem services and the SDGs, which suggests that it should continue to be viewed as the standard within the field of farm-level sustainability assessment. This review also found deficiencies in current tools and models, as they do not sufficiently articulate the concept of ecosystem services within their methods. Moving forward, tools and models should be developed that explicitly consider ES and the SDGs. To achieve this, a harmonization of terminology regarding agricultural ES is a pre-requisite. Additionally, SA could benefit from the further standardization of metrics and indicators, as per SAFA and RISE. In doing so, future assessment tools and models will be better equipped to reflect new paradigms of sustainable agriculture.

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Appendix A

Table A1. List of agriculture-related ecosystem services according to CICES classification scheme.

Provisioning		Regulation and Maintenance		Cultural	
Biotic	**CICES Code**	**Biotic**	**CICES Code**	**Biotic**	**CICES Code**
Cultivated terrestrial plants for nutrition	1.1.1.1	Biotic remediation of waste	2.1.1.1	Recreation through activities in nature	3.1.1.1
Cultivated terrestrial plants for materials	1.1.1.2	Biotic filtration, sequestration and storage of waste	2.1.1.2	Recreation through observation of nature	3.1.1.2
Cultivated terrestrial plants for energy	1.1.1.3	Erosion control	2.2.1.1	Education and training interactions with nature	3.1.2.2
Reared animals for nutrition	1.1.3.1	Hydrological cycle and flood control	2.2.1.3	Aesthetics from interactions with nature	3.1.2.4
Reared animals for materials	1.1.3.2	Pollination	2.2.2.1		
Reared animals for energy (including mechanical)	1.1.3.3	Seed dispersal	2.2.2.2		
Genetic material from plants for designing organism	1.2.1.3	Nursery populations and habitats	2.2.2.3		
Abiotic		Pest control (including invasive species)	2.2.3.1		
Surface water for drinking	4.2.1.1	Disease control	2.2.3.2		
Surface water for non-drinking purposes	4.2.1.2	Soil quality by decomposition and fixing processes	2.2.4.2		
Groundwater for drinking	4.2.2.1	Chemical condition of freshwaters	2.2.5.1		
Groundwater for non-drinking purposes	4.2.2.2	Chemical composition of atmosphere and oceans	2.2.6.1		
		Local regulation of air temperature and humidity	2.2.6.2		
		Abiotic			
		Abiotic filtration, sequestration and storage of waste	5.1.1.3		
		Control of liquid flows	5.2.1.2		

Appendix B

Table A2. List of agriculture-related SDG targets.

Target Name (Abbreviated)	SDG Target	Target Name (Abbreviated)	SDG Target
Reduce poverty by half	1.02	Strengthen local financial institutions	8.1
Implement social protection systems	1.03	Upgrade infrastructure	9.04
Promote equal rights to resources	1.04	Increase and maintain income growth	10.01
Reduce vulnerability to climate change	1.05	Promote equal opportunities	10.2
End hunger	2.01	Safeguard worlds cultural and natural heritage	11.04
End malnutrition	2.02	Reduce impacts of natural disasters	11.05
Increase agricultural productivity and incomes	2.03	Urban-rural links and regional development	11.a
Promote agricultural practices that improve land	2.04	Sustainable management of natural resources	12.02
Maintain genetic diversity	2.05	Reduce food waste	12.03
Investment in agricultural extensions/tech.	2.a	Sustainable management of hazardous waste	12.04
Prevent agricultural trade distortions	2.b	Reduce hazardous waste	12.05
Limit food price volatility	2.c	Sustainability information in reporting	12.06
End communicable diseases (epidemics)	3.03	Promote sustainable public procurement	12.07
Reduce deaths from hazardous chemicals	3.09	Adaptive capacity to climate-related hazards	13.01
Increase training	4.04	Climate change capacity	13.02
Gender equality	5.01	Awareness-raising on climate change	13.03
Water quality	6.03	Prevent/reduce marine pollution (nutrient pollution)	14.01
Increase water use efficiency	6.04	Protect terrestrial ecosystems	15.01
Protect water ecosystems	6.06	Sustainable management of forests	15.02
Increase renewable energy	7.02	Desertification and land degradation	15.03
Investment in technology	8.02	Protect habitats, biodiversity and threatened species	15.05
Resource use efficiency	8.04	Sharing of the benefits of genetic resources	15.06
Decent work and equal pay	8.05	Integrate ecosystem and biodiversity policies	15.09
Protect labor rights	8.08	Accountable and transparent institutions	16.06
Sustainable tourism	8.09	Participatory decision making at all levels	16.07

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Future agricultural systems and the role of digitalization for achieving sustainability goals. A review

MacPherson, J., Voglhuber-Slavinsky, A., Olbrisch, M., Schöbel, P., Dönitz, E., Mouratiadou, I., Helming, K.

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REVIEW ARTICLE

Future agricultural systems and the role of digitalization for achieving sustainability goals. A review

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Abstract

By leveraging a wide range of novel, data-driven technologies for agricultural production and agri-food value chains, digital agriculture presents potential enhancements to sustainability across food systems. Accordingly, digital agriculture has received considerable attention in policy in recent years, with emphasis mostly placed on the potential of digital agriculture to improve efficiency, productivity and food security, and less attention given to how digitalization may impact other principles of sustainable development, such as biodiversity conservation, soil protection, and human health, for example. Here, we review high-level policy and law in the German and European context to highlight a number of important institutional, societal, and legal preconditions for leveraging digital agriculture to achieve diverse sustainability targets. Additionally, we combine foresight analysis with our review to reflect on how future frame conditions influencing agricultural digitalization and sustainability could conceivably arise. The major points are the following: (1) some polices consider the benefits of digital agriculture, although only to a limited extent and mostly in terms of resource use efficiency; (2) law as it applies to digital agriculture is emerging but is highly fragmented; and (3) the adoption of digital agriculture and if it is used to enhance sustainability will be dependent on future data ownership regimes.

Keywords Digital agriculture · Sustainability · Policy · Foresight · Agri-digital law

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1 Introduction

Digitalization is a rapidly growing trend within agriculture. Digital agriculture, or "Smart Farming," is characterized by the use of precision and data-driven technologies to assist farmers with real-time and site-specific decision making (Wolfert et al. 2017; Rose and Chilvers 2018; Weersink et al. 2018). It leverages technologies including the Internet of Things (IoT), sensors, drones, robotics, cloud computing, artificial intelligence (AI), decision support software (DSS), and blockchain, for example, to optimize agricultural production processes (Walter et al. 2017; Kamilaris et al. 2017), value chains (Poppe et al. 2013, Smith 2020), international trade (Jouanjean 2019), agricultural systems (Basso and Antle 2020), and governance systems (Ehlers et al. 2021).

By and large, digital agriculture is viewed as a promising means for sustainably boosting food production to feed a growing world population (Foley et al. 2011; Shepherd et al. 2020). Along with improving agricultural productivity, digitalization could provide a diverse range of benefits to the environment and society. For instance, digital agriculture could help alleviate pressures on scarce resources (Wolfert et al. 2017), improve food safety through increased traceability (Walter et al. 2017), as well as combat climate change (Balafoutis et al. 2017). Other potential benefits of agricultural digitalization include the creation of new types of high-skilled job opportunities (Rotz et al. 2019b), fostering global agricultural markets (Jouanjean 2019), as well as improvements to animal welfare (Dawkins 2017).

Due to the relative novelty of digital agriculture, there is still a considerable amount of uncertainty surrounding its impact on sustainability (Klerkx and Rose 2020). Skeptics have warned that digitalization could perpetuate *status-quo* economic modes of production (Bronson and Knezevic 2016), while raising concerns about the ownership, privacy and sovereignty of data, and how this could reinforce concentrations of power among large ag-tech service providers (Rotz et al. 2019a; Clapp and Ruder 2020). Additionally, automation could lead to displacement of certain types of low-skilled jobs in the agri-food sector (Carolan 2020), or could lead to "algorithm governance" where farmers lose their autonomy to manage their own farms (Henman 2020). Lastly, the electricity demand required to power the infrastructure underpinning digital technologies (e.g., servers) and potential greenhouse gas emissions therein could produce spillovers and deserves further exploration (Leroux 2020).

Nevertheless, the potential benefits of digital agriculture have garnered attention in policy circles and are increasingly included, albeit as a side topic, in high-level policy strategies. To date, no study has tried to summarize this development, with the exception of Lajoie-O'Malley et al. (2020). Their findings pointed out that visions of digitalization as articulated by international institutions such as the World Bank, Organization for Economic Co-operation and Development (OCED), and Food and Agricultural Organization (FAO) focus primarily on reducing food shortages through agricultural intensification, while largely ignoring environmental concerns, such as the provision of ecosystem services.

Principles and agreements outlined in high-level policy strategies (soft law) play a crucial role in determining the frame conditions for technological innovation and adoption through shaping public discourse, directing public funding for research and development, as well as setting subsidies and regulations (hard law). In this respect, policy can have a strong influence on the future of digital agriculture. Therefore, it is necessary to take stock of how current policy strategies consider agricultural digitalization and, going further, investigate how digitalization can implicitly support broader sustainability goals. Additionally, given the undetermined future of digital agriculture, studies are needed that plot potential trajectories of societal trends to assess how it may affect sustainability (Klerkx and Rose 2020). Finally, equal consideration needs to be given to the evolving legal landscape surrounding digital agriculture, as this will play an important guiding role in the digital transformation of agriculture, as well (Härtel 2019, 2020a).

It is worth noting that institutional, regulatory, and socio-technical conditions vary across countries, cultures, and scales, meaning the frame conditions for digital agriculture and the way it is instrumentalized may also vary. For example, in terms of policy, the USDA Agricultural Innovation Agenda (United States Department of Agriculture (USDA) 2020) and the European Commission Farm to Fork (F2F) Strategy (European Commission 2020a) both acknowledge the importance of sustainability and reducing the environmental footprint of the agricultural sector. While both policies incorporate digital agriculture within their strategies, the former embraces a productivist paradigm with no restrictions on the input of pesticides or fertilizers, while the latter focuses on resource use efficiency improvements by setting targets to starkly reduce agrochemicals inputs. These two fundamentally different approaches could lead to very different manifestations of digital agriculture in the future. In this regard, studies are needed that account for these context-specific factors when assessing possible developments of agricultural digitalization.

To these ends, this research is motivated by the following questions: (i) how is digital agriculture currently embedded in preeminent global, EU, and German policy, and what links can be drawn between digital agriculture technologies and to wider sustainability principles outlined in these policies; (ii) how could future trends in the agri-food sector influence the adoption and use of digital technologies; and (iii) how does the current legal setting surrounding digital technologies impact agriculture? The results of this study are meant to highlight a number of important institutional, societal, and legal preconditions for leveraging the potential of digitalization to align agricultural production with sustainable development targets. Further, our research offers a novel example of transdisciplinary research by combining policy, foresight and legal analyses.

The paper is organized as follows. Section 2 provides an overview of the methodologies employed in the policy, foresight and legal analyses. Section 3 reviews agriculture-related goals of several preeminent policy strategies at the global, European, and German national level, paying particular attention to how digitalization is articulated within each strategy, as well as drawing links between agriculture-related goals and key enabling technologies from the literature. Section 4 concerns the foresight analysis, describing future frame conditions of four different scenarios, and analyzing how they affect hotspots of agricultural digitalization and the achievement of sustainability principles. Section 4 reviews current agri-digital law across multiple governance levels. Section 5 synthesizes and discusses the results of the proceeding sections which is followed by a conclusion in Section 6 (Fig. 1).

2 Methodology

In Section 3, we reviewed the documents of seven preeminent sustainability policies spanning German, European, and global policy levels. These policies were selected based on the judgment of the authors that they are highly relevant in regard to their influence on agricultural sustainability and, in general, guiding the development of lower-level policies and regulations. Germany was chosen as a focal point for this study due to its relatively advanced agri-food sector and for its standing as a notable leader in sustainability and bioeconomy policy. In the first step of the policy review process, policy documents were scanned for agriculture-related goals as well as links to digital agriculture (Section 3.1). Then, agriculture-related goals were inductively sorted into clusters based on cross-cutting sustainability principles that emerged from the policies (Section 3.2). Finally, connections were drawn between the agriculture-related goals and key digital technologies (Section 3.3). Examples of key technologies and their potential applications were taken from the literature (Wolfert et al. 2017; Lieder and Schröter-Schlaack 2021; Weersink et al. 2018).

In Section 4, we present four different scenarios, providing insights into how the framework conditions for agriculture in 2035 in Germany might look like, including what the effects on natural resources could be as well as what role digital decision support systems can play for farmers in this context (Dönitz et al. 2020). The framework conditions for German agriculture are subject to constant change. Yet despite these uncertainties, we can still make assumptions about probable future developments. Indeed, political, economic, societal, ecological, and technological developments must be included to create robust solutions and scenarios assist to deal with the high complexity of these interacting factors. Based on a complex network of relevant factors, the scenarios present a description of possible situations in the future. The scenario method is an established and proven instrument within the foresight methods for addressing uncertainties (Gabriel et al. 2016; Dönitz and Schirrmeister 2013; Godet 2001; van Notten et al. 2003).

Across the scenarios, we identified the most influential factors for the topic of digitalization in agriculture. Key factors such as "Information flow along the value chain and acceptance of service platforms" and "Diffusion of new technologies in primary production" have a strong influence on all other and are highly relevant for digitalization in agriculture. We presented the respective future assumptions of these two factors per scenario and further combined the information with the key technological areas, while also highlighting respective legal implication (Section 4.2). We then explore how these scenarios converge with sustainability principles identified in the policy analysis (Section 4.3).

In Section 5, we review the current state of law surrounding digital agriculture, which is situated in a legal multi-level system, at the European and German national level. We outlined requirements for a consistent legal framework as an enabler for the digital transformation of agriculture by analyzing legal implications for the policies and the foresight scenarios.

To structure our research and provide linkages between the policy, foresight, and legal analyses, we focus on the contribution of agricultural digital technologies to enhance the sustainability of agricultural systems via improved *monitoring, decision support, and communication* as suggested by Mouratiadou et al. (2021) (see Table 1). For an overview of the methodology, see Fig. 2.

Fig. 1 Autonomous weeding machine (AVO) from ecoRobotix. Photo available for download from https://ecorobotix.com/en/contact

3 Connections to digital agriculture and sustainability principles in policy

A review of high-level policy strategies revealed a multitude of agricultural-related sustainability goals and several links to digital agriculture (see Table 2 for overview of policies included in the review). In relation to the former, we were able to cluster goals according to five sustainability principles, which emerged as cross-cutting themes in the policies. In the following sub-sections, explicit links to digitalization as found within the reviewed policy documents are presented (Section 3.1). Agriculture-related goals as found within the policy documents are outlined according to the following cross-cutting sustainability principles: biomass production (Section 3.2.1), climate change mitigation and adaption (Section 3.2.2), biodiversity conservation (Section 3.2.3), soil health (Section 3.2.4), and health and nutrition (Section 3.2.5). Finally, we draw links between agriculture-related goals and key enabling digital technologies (Section 3.3).

3.1 *Digital agriculture in policy*

To date, there is no comprehensive strategy dedicated specifically to digital agriculture at the global, European, or German policy level. However, digitalization is often considered by policy as a driver, or means, toward achieving certain sustainability goals. Three of the reviewed policies refer explicitly to digital agriculture (the F2F Strategy, the German 2035 Arable Farming Strategy, and the German National Bioeconomy Strategy), which is summarized in Table 3. The remaining policies of this review (e.g., the Paris Agreement, the SDGs, the National Climate Action Plan 2050, and the German Sustainability Strategy) do not explicitly consider agricultural digitalization within their documents.

The F2F Strategy acknowledges the importance of digitalization for making more efficient use of agricultural inputs, as well as making better use of climate and environmental data for improving the resilience of food systems to the impacts of climate change (European Commission 2020a). The Strategy

Table 1 Functions of digital technologies for sustainable agriculture (adopted from Mouratiadou et al. 2021)

Function	Description
Monitoring	Effective and transparent monitoring of biodiversity and ecosystem service provision, facilitating the understanding of cause-effect relationships in agroecosystems and the establishment of result-oriented policy measures
Decision support	Improved agricultural decision support, for multifunctional diversified agricultural landscapes to consolidate diverse targets on yields, ecosystem services, biodiversity, and deliver resource use efficiency improvements
Communication	Enhanced communication between stakeholders and land use actors, enabling information exchange on societal demands on biodiversity and ecosystem services along the value chain and reducing conflicts on the future use of agricultural land

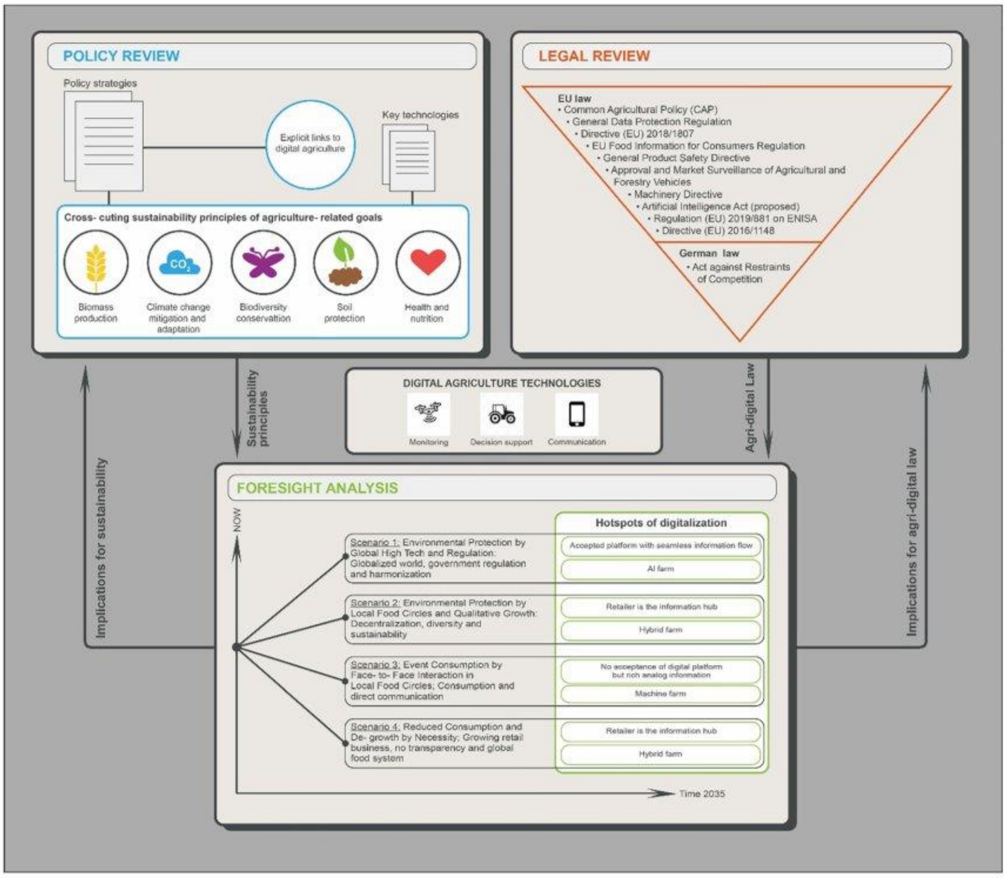

Fig. 2 An overview of the methods and linkages of the different sections. Implications of digital agriculture as found in the policy and legal reviews are explored through scenarios in the foresight analysis to reflect on future sustainability

also aims to exploit the potential of digitalization in value chains using product tracking to provide consumers with more information regarding how their food is produced, thereby promoting healthier and "greener" food choices. The increase of the availability of high-speed broadband internet to rural areas throughout the EU is also in focus so that farmers can better capitalize on digital technologies, including AI and precision techniques that lead to better soil management. Additionally, the F2F Strategy intends to expand the Farm Accountancy Data Network (FADN) for monitoring as well as creating a common European agricultural data space for fostering interoperability of data.

At the German national level, digitalization is one of the twelve "action areas" included in the 2035 Arable Farming Strategy (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2019). The Strategy identifies mobile phone and GPS coverage as preconditions to facilitate the use of existing technologies and the development of new resource efficient approaches. The Strategy outlines seven digitalization-related measures: (1) establish an independent "quality control body" for assessing digital applications; (2) improve soil health through developing innovative digital technologies for soil tillage, fertilization, and plant protection; (3) promote digital technology for small and medium-sized farms, as well as for multi-farm use; (4) create statutory framework conditions for the use of digitalization; (5) implement nationwide coverage of real-time kinematic GPS and ensure access to public data for farmers; (6) establish test sites throughout Germany; and (7) review preconditions to establishing "data sovereignty" of farmers.

Germany's National Bioeconomy Strategy underscores the potential of combining digitalization and simulations to improve understanding of systemic modeling (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2020). Systemic modeling, as the Strategy advocates, should be used in "impact assessment, prediction and the targeted design of efficient and tailor-made bio-based processes" (p.30, ibid.). In conjunction, measures that involve monitoring and control of bio-technological processes, smart sensor technology, AI, automation, miniaturization, parallelization of process steps, and high-throughput analyses are prioritized under the Strategy. The Strategy also identifies the necessity of data harmonization, data management systems, advancement of interfaces, and development and implementation of standards as preconditions to the successful integration of digitalization in the future bioeconomy. Lastly, increased digitalization and "big-data" analysis will enable the quantification of the impacts of bioeconomy measures and their contribution to the overall economy.

3.2 *Cross-cutting sustainability principles*

3.2.1 *Biomass production*

The primary task of agriculture is to produce biomass for food, energy, and materials. In the SDGs, food production is addressed by SDG 2 (Zero Hunger) with the objective to increase agricultural productivity and incomes (Target 2.03) (United Nations 2016). In Europe and Germany, food production is relatively high, so biomass production, as it relates to food security, is not perceived as a crucial sustainability issue. However, in the F2F Strategy, food production within Europe is addressed in terms of promoting resilience of food systems against shocks and crises, such as the recent COVID-19 pandemic (European Commission 2020a). At the national level, Germany acknowledges its contribution to producing food for the global food system i.e. 'world food basket' (Deutsche Bundesregierung 2017, 2018).

Biomass production also plays a central role in the bioeconomy by providing a resource base for the production of bio-fuels and bio-materials. As part of the SDGs, Target 7.2 "increase substantially the share of renewable energy in the global energy mix," can be indirectly linked to the production of biomass for bio-fuels (United Nations 2016). At the European level, the F2F Strategy proposes advancements in the circular, bio-based economy as part of a holistic strategy of the European Green Deal to create a carbon-neutral EU by the second half of the century (European Commission 2020a). Specifically, the Strategy encourages the creation of bio-refineries to produce bio-fertilizers, protein feed, bioenergy, and bio-chemicals. In addition, farms are to reduce methane emission by investing in anaerobic digesters for biogas production from agricultural wastes and residues.

Germany is noteworthy for its history as a leader in advancing bioeconomy policy. In 2010, Germany established the National Research Strategy "BioEconomy 2030" (Bundesministerium für Bildung und Forschung (BMBF) 2010), which focused on building the knowledge base for the bioeconomy by providing funding for public and private research for the development of bioeconomy innovations. In 2013, Germany adopted the National Policy Strategy for the Bioeconomy (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2014), which set out wide sweeping

Table 2 Overview of policies included in the review

Policy strategy	Publisher	Governance level	Reference
Paris Agreement	United Nations Framework Convention on Climate Change (UNFCCC)	Global	UNFCCC Secretariat 2019
Sustainable Development Goals (SDGs)	United Nations (UN)	Global	United Nations 2016
Farm to Fork (F2F) Strategy of the European Green Deal	European Commission	Europe	European Commission 2020a
Climate Action Plan 2050	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU)	National (Germany)	Deutsche Bundesregierung 2016
National Sustainable Development	German Federal Government	National (Germany)	Deutsche Bundesregierung 2017 & 2018
2035 Arable Farming Strategy	Federal Ministry of Food and Agriculture (BMEL)	National (Germany)	Bundesministerium für Ernährung und Landwirtschaft 2018
National Bioeconomy Strategy	Federal Ministry of Food and Agriculture (BMEL)	National (Germany)	Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2020

Table 3 Policy strategies and explicit links to digital agriculture

Policy strategy	Links to digital agriculture
F2F Strategy	• Use climate data to improve adaptation to climate change
	• Increase resource use efficiency via precision technologies
	• Provide more information to consumers using digital solutions
	• Secure Common Agricultural Policy funds toward fostering digital innovation
	• Increase access to high-speed broadband internet to rural areas to mainstream adoption of use of precision agriculture and artificial intelligence (satellites)
	• Broaden agricultural databases i.e. Farm accountancy data network (FADN)
	• Create common European agricultural data space
2035 Arable Farming Strategy	• Increase mobile network coverage
	• Establish quality control body for digital applications
	• Develop innovative digital technologies for soil tillage, fertilization and plant protection to promote healthy soils
	• Make technology available for small and medium-sized farms, as well as for multi-farm use
	• Create statutory framework conditions for the use of digital technologies
	• Implement nationwide coverage of real-time kinematic -GPS and ensure access to public data for farmers
	• Establish test sites for new technologies throughout Germany
	• Review preconditions for establishing 'data sovereignty'
National Bioeconomy Strategy	• Improve understanding of systemic modeling
	• Foster data harmonization
	• Improve data management systems
	• Advance user interfaces
	• Implement standards
	• Use big data for quantification of the impacts of bioeconomy measures to overall economy

goals for a creating a sustainable bioeconomy. As of 2020, Germany published the new National Bioeconomy Strategy, building on previous policy strategies and laying out guidelines, strategic goals, and implementation objectives for the funding of research and creation of a policy framework (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2020). Of the six strategic goals laid out in the Strategy, two share a strong connection to agriculture production, namely "enhance and apply biological knowledge" and "establish a sustainable raw material base for industry." These goals correspond to measures that will fund research in areas that model biological systems, develop novel production organisms, and sustainably generate biogenic resources. In relation to the latter, the implementation of concrete measures for smart farming, organic farming, and vertical farming are to be prioritized.

3.2.2 *Climate change mitigation and adaptation*

From a global perspective, the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Sustainable Development Goals (SDGs) represent the preeminent strategies addressing climate change mitigation and adaptation. Under the Paris Agreement, global average temperature is to be kept under a 2 °C rise above pre-industrial levels and nations are required to outline their own intended nationally determined contributions (INDC) toward limiting emissions. As of 2016, 74% of the countries who have signed the Agreement have included measures to limit emission from the agriculture sector as part of their INDCs (UNFCCC Secretariat 2019). Similarly, SDGs aims to reduce the impacts of climate change through mitigation and adaptation (SDG 13: Climate Change), where countries are to strengthen resilience and adaptive capacity of climate change (Target 13.1), as well as implement climate change mitigation measures (Target 13.2) by developing INDCs and national adaption strategies (United Nations 2016).

At the European level, the F2F Strategy aims to limit agricultural GHG emissions by focusing mainly on the livestock sector (European Commission 2020a). Measures to limit these emissions include advancing innovative feed additives and reducing carbon "leakages" from feed imports by promoting EU-grown plant proteins. The Strategy also identifies the potential of agriculture soils to sequester carbon and advocates that farmers should be provided economic incentives for carbon sequestering practices (i.e., carbon farming) through the Common Agricultural Policy and carbon markets.

Within Germany, the National Climate Action Plan 2050 (Deutsche Bundesregierung 2016) sets out to achieve GHG neutrality by the second half of the century. Under the Plan, agriculture should emit no more than 58–61 million tons of CO_2-equivelants per year by 2030, equating to a 31–34% reduction from 1990 by 2030. Emission reductions in agriculture are to be met primarily by limiting nitrous oxide (N20) emissions from fertilizers and expanding the share of land under organic farming. In relation to the former, nitrogen surpluses are not to exceed 70 kg N/ha by 2028–2032, which is to be achieved through a stricter enforcement of the German Fertilization Ordinance (Düngeverordnung vom 26. Mai 2017 (BGBl. I S. 1305)) and by promoting need-based fertilization using variable-rate technologies. Additionally, the Arable Farming Strategy 2035 acknowledges the importance of reducing nitrous oxide emissions from fertilizers to mitigate GHG emissions (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2019).

3.2.3 *Biodiversity conservation*

Conserving biodiversity and ecosystem integrity is an integral part of attaining the SDGs (United Nations 2016). SDG 2 (Zero Hunger), for example, recognizes the significance of maintaining terrestrial and freshwater ecosystems (target 2.4) and genetic diversity (target 2.5) as the basis for sustainably producing enough food. In concordance with Biodiversity Strategy for 2035 (European Commission 2020c) of the European Green Deal, the F2F Strategy acknowledges the impacts of agriculture intensification on biodiversity. The Strategy identifies the use of chemical pesticides, excess nutrients from fertilizer, and lack of livestock diversity as the primary factors driving agriculture-related biodiversity decline. Under the Strategy, the use of pesticides is to be reduced 50% by 2030 by promoting integrated pest management strategies. In line with the EU Nitrates Directive 91/676/EEC, excess nutrients from fertilizers are to be reduced by 20% by 2030 through precision application methods and low-input farming, thus reducing environmental impacts to biodiversity in water bodies (European Commission 2020a).

Germany's National Sustainable Development Strategy strives to protect biodiversity and strengthen implementation of the National Strategy for Biological Diversity through achieving 65 targets/indicators, related to increasing diversity and landscape quality, promoting organic farming and reducing agricultural inputs, such as nitrogen- and phosphorous-based fertilizers (Deutsche Bundesregierung 2017, 2018). In the 2035 Arable Farming Strategy, protecting biodiversity is an overarching topic, bridging multiple goals within the strategy regarding soil fertility, crop diversity and rotation, nitrogen surpluses, and plant protection (Bundesministerium für Ernährung und Landwirtschaft 2018). As one of the eight production-areas of action, "Biodiversity" encompasses the halt of species decline, promoting habitat connectivity at the landscape level, establishing regional goals and associated monitoring mechanisms, as well as evaluating economic ramifications of changes in land use to promote biodiversity.

3.2.4 *Soil health*

In relation to the SDGs, the importance of soil is formulated in Target 15.3: "restore degraded land and soil, as well as strive for a world that is land degradation neutral by 2030" and Target 2.4 in regard to utilizing agricultural production methods that improve land and soil quality (United Nations 2016). The protection of soil is interwoven with several other primary goals in the F2F Strategy. For example, goals to drastically reduce the use of chemical pesticides and excess nutrients will mitigate the pollution of soil (i.e., fertilizers use should be reduced by at least 20% by 2030 without compromising soil fertility) (European Commission 2020a).

In Germany, the National Bioeconomy Strategy recognizes the importance of developing a bioeconomy that is environmentally sustainable in terms of soil fertility and preserving soil functions, emphasizing the need for a systemic and location-specific approach for the production of biogenic material (Bundesministerium für Ernährung und Landwirtschaft (BMEL) 2020). Among soil-related goals in Germany's 2035 Arable Farming Strategy, soil fertility and soil biodiversity should be improved, erosion and compaction reduced, humus content should be kept stable through admixture, and land take by non-agricultural usage is to be reduced to under 30 ha per day and net zero by 2050 (Bundesministerium für Ernährung und Landwirtschaft 2018).

3.2.5 *Health and nutrition*

On the global level, food security and adequate nutrition are concerns for a large part of the world's population (FAO, IFAD, UNICEF, WFP and WHO 2020). This is addressed by the UN SDGs by SDG 2 (Zero Hunger) and applies mainly to developing countries with histories of chronic hunger and malnutrition. In the European context, however, issues related to over-nutrition (e.g., obesity and chronic disease) are more prominent and is linked to achieving SDG 3 (Good Health and Well-being). Although not explicitly addressed within the SDGs, reducing the use of chemical pesticides in agricultural production works toward attaining SDG 3, specifically Target 3.9 (reducing deaths from hazardous chemicals) as well as SDG 8 (Promoting safe working conditions) (United Nations 2016).

Likewise, the F2F Strategy underlines the connection between developing a sustainable food system and encouraging healthier diets among the EU population. In the Strategy, emphasis is placed on creating a "food environment" that ensures consumers have access to healthy food, as well as information to help them make informed decisions about their food choices. Goals to improve food labeling in terms of nutritional content and production details are intended to facilitate this process (European Commission 2020a). Similarly, Germany's Sustainable Development Strategy plans to addresses health through delivering better information to consumers via improved labeling and awareness-raising activities that promote healthier diets (Deutsche Bundesregierung 2018).

3.3 *Key digital technologies for achieving sustainability principles*

Our study identified a range of technologies and potential applications for achieving sustainability principles (see Supplementary Table 1). Monitoring enhancing technologies are particularly useful for assessing cross-compliance and designing evidence-based policy (Ehlers et al. 2021). Remote sensing technologies, such as satellite imaging, unmanned aerial vehicles (UAVs), combined with AI can be used to assess changes in land use over large geographic areas (Ferreira et al. 2020), which is useful for monitoring compliance and assessing efficacy of policy (Weersink et al. 2018). Changes in land use can be used as proxies to determine biodiversity conservation, biomass production, and climate change mitigation and adaptation (Weersink et al. 2018). In the future, by combining remote sensing with data obtained from on-farm sensors, digital agriculture could offer real-time and highly granular detail on how production practices are impacting sustainability, such as ecosystem service provisioning, which could open up new avenues for implementing and designing agri-environmental regulations and standards (Ehlers et al. 2021).

Technologies that enhance decision support through increased precision of agrochemical inputs (e.g., variable-rate technologies (VRT), yield monitoring, DSS, GPS tractor navigation, cloud computing) could address a broad range of sustainability principles as outlined in policy by reducing: nitrous oxide emission from fertilizers (climate change mitigation), residual toxicity from pesticides (biodiversity conservation and human health), as well as compaction and nutrient imbalances in soils (soil protection) (Lieder and Schröter-Schlaack 2021).

Communication enhancing technologies can significantly optimize logistics and trade (Poppe et al. 2013, Jouanjean 2019) as well as make food-value chains more transparent to consumers and governments (Walter et al. 2017). Radio-frequency identification (RFID), distributed ledger technologies (i.e., Blockchain), and QR codes enhance traceability of products and transparency on production conditions. In this context, depending on societal demand and legal regulations on food labeling, communication technologies could play a critical part in contributing to the achievement of certain sustainability principles. The growing use of these technologies in the food value-chain implies more importance on behalf of distributors, processors, and retailers on influencing sustainability in future food regimes (Prause et al. 2021).

4 Foresight and its implications for sustainability principles and agri-digital law

In this section, the main characteristics of four scenarios as developed by Dönitz et al. (2020) are described in regard to their implications for digital agriculture, agri-digital law, and the achievement of sustainability principles outlined in the previous section. The qualitative scenarios present alternative future framework conditions, influencing functions and requirements of a decision support system for farmers. Although the framework conditions for German agriculture are subject to constant change, these scenarios allow us to make insights about probable future developments, as well as describe political, economic, societal, ecological, and technological developments in order to create robust solutions. These scenarios assist in dealing with the high complexity and interactions of unknown future developments. Using a network of relevant factors, they present a description of possible situations in the future.

4.1 *Description of future scenarios*

To identify the social and technological changes, which are relevant for the agri-business in the upcoming years and over a longer timeframe, it was necessary to look beyond the borders of the sector. Key factors that determine the contexts for the scenarios have been structured using the STEEPL (social, technological, environmental, economic, policy, and legal) approach. According to their relevance for the agri-business, the factors were prioritized and aggregated to 15 key factors with high-relevance (Dönitz et al. 2020). In the current study, to uncover critical factors that are dynamic and strongly linked, the interconnections between the key factors were analyzed (see Section 4.2). The factors "Information flow along the value chain and acceptance of service platforms" and "Diffusion of new technologies in primary production" were identified. Due to their strong influence on and through the other factors, they play an important role in the systems and consequently in the scenarios. They play a special role in the context of the digitalization of agriculture. Therefore, the short descriptions of the scenarios below focus on these two factors.

4.1.1 *Scenario 1: Environmental protection by global high tech and regulation; globalized world, government regulation and harmonization*

In Scenario 1, a centralized state control system ensures food supply. An essential point is reduced consumption and the fulfillment of the basic needs. In addition, worldwide coordination of legal standards and global networking works flawlessly. Value chains are transparent and food labels are coordinated. In general, food supply is sustainable and non-profit-oriented. International cooperation provides sufficient momentum to proactively address climate change and to make it a driver for innovation and change. Consumers and industry are open to new technologies. The flow of information along the entire value chain enables consumers to track their products, which puts pressure on producers to maintain high production standards. Most products are purchased through centralized e-commerce managed by the state. Production surpluses flow into a well-functioning global food supply system, ensuring global food security and less food waste. Energy-efficient vertical farming technologies are important for fresh products, like vegetables. Digital platforms assist farmers in their daily work; they provide solutions to various problems.

4.1.2 *Scenario 2: Environmental protection by local food circles and qualitative growth; decentralization, diversity and sustainability*

Society recognizes the importance of new technologies in the food industry to assist environmental protection. The direct connection of society to agriculture is enabled not only by the large number and diversity of farms, but also by decentralized retailing acting as information hubs. They control the value chains, make them efficient and transparent, so that labels are no longer necessary. Agricultural production is highly differentiated; the value chains are short and transparent. Consumers accept the seasonal variances of food supply. The communication flow between farmers and consumers is very high. The so-called hybrid farms, a mixture of manually operated large machines and small autonomous robots, work hand in hand. Technologies in the first place have to be beneficial for the environment. Otherwise, they are not accepted. The technological change is promoted by the legal framework. It provides security for business investment in the development of new agricultural technologies and is the source of farmers' and consumers' trust.

4.1.3 *Scenario 3: Event consumption by face-to-face interaction in local food circles; consumption and direct communication*

People buy in shops or at local food markets. Food shopping is considered important and people look forward to it. They enjoy talking to the producer or simply to their neighbor. As a result, e-commerce only occupies a certain market segment. There is no enthusiasm for new technologies in society, which is reflected by the resistance to advanced digitalization in many areas. Society does not trust or accept new technologies and digital platforms due to security problems in the past and the growing power of global companies. Farmers do not want to rely on new technologies either. They primarily use large, manually driven machines and technological development focuses on assistance systems. Only parts of the agricultural processes have been digitalized, and the connection to further steps in the value chain is missing. Some parts in the production chain have a certain level of intelligence, but there is no connection between them.

4.1.4 *Scenario 4: Reduced consumption and de-growth by necessity; growing retail business, no transparence and global food system*

In this scenario, the retail business is the big winner in the global food systems. The area for agricultural production and the area for promoting biodiversity are strictly separated. Both areas are controlled via Agriculture 4.0 with sensors, drones, and other monitoring systems. All this leads to a highly intensive agricultural specialization. New technologies based on AI support farmers in achieving the highest possible efficiency. The data exchange required to optimize AI technologies is not subject to any regulatory restrictions. Retailers are also using AI technologies to design centralized e-commerce that maximizes profit. They exercise high control over agricultural production. The global value chain is not transparent to the consumer. The profit margin for farmers is low and only very specialized farms can economically survive. It is not a high quality but a low price that matters to consumers. Extreme weather conditions challenge agricultural production. Farmers' cooperation is assisted by digital platforms, especially the sharing of large machinery is promoted by that.

4.2 *Combination of scenarios and key technological areas*

The analysis of the interrelationships between key factors assists to reveal main drivers of change. This analysis helped to achieve a common understanding of (i) how the key factors in context scenarios influence each other and—as a consequence—(ii) to shape different context scenarios by identifying the most crucial interrelations of factors. To evaluate the extent of influence between each pair of key factors (in both directions), the following scales have been used: "0": no direct influence; "1": medium influence; "2": strong influence. On this basis different characteristics of each factor, as an element in the system consisted of 15 factors, can be specified: active and passive factors (with high influence or affectability) as well as critical or dormant factors (with high or low involvement in the system) (Vester 2019). Some key factors have a strong influence on all other factors in this system and at the same time were identified to play an important role for digitalization of agriculture. The influence analysis conducted to build the scenarios in the project DAKIS (Dönitz et al. 2020) shows that the factors "Information flow along the value chain and acceptance of service platforms" and "Diffusion of new technologies in primary production" have a strong influence on all other factors considered in scenarios. Therefore, in the following, these two factors are described with regard to their role within the key technological areas in terms of monitoring, decision support, and communication enhancing technologies (see Table 4 and Supplementary Table 2).

In Table 4, it is explained what the respective assumptions of the two factors, "Information flow along the value chain and acceptance of service platforms" and "Diffusion of new technologies in primary production" per Scenario 1 and per Scenario 4 imply for the requirements of digitalization in terms of monitoring, decision support, and communication enhancing technologies. Furthermore, where applicable, legal consequences of these digitalization requirements are presented. Please see Supplementary Table 2 for complete analysis of all scenarios.

4.3 *Convergence of sustainability principles and scenarios*

In this sub-section, we analyze implications of the four scenarios from the foresight analysis on digital agriculture and the achievement of sustainability principles identified in the policy analysis. The scenarios provide illustrative and contrasting examples of how digital agriculture technologies could impact sustainability.

Scenario 1 (Environmental Protection by Global High Tech and Regulation; Globalized world, government regulation and harmonization) has a high potential for achieving a broad spectrum of sustainability goals through state control and leveraging digital technologies. In this scenario, sustainability goals, as dictated by governments, are consistently achieved with aid of technologies that enhance monitoring, decision support, and communication. For example, communication enhancing technologies (e.g., blockchain, RFID, QR codes) ensure high transparency to consumers on production conditions in terms of their impacts on the sustainability principles of human health, biodiversity conservation, and climate change. Additionally, these technologies as well as on-farm data obtained from management enhancing technologies are used by governments for monitoring compliance with regulations and standards. In terms of primary production, in Scenario 1, technologies that enhance decision support (e.g., sensors, DSS, UAV, VRT, AI, robotics) are wide-spread, significantly reducing the use of pesticides and fertilizers that are harmful to humans and the environment, thereby contributing to the principles of biodiversity conservation, soil protection, climate change mitigation, and human health. Additionally, monitoring technologies (e.g., satellite imaging, agricultural census data) combined with the free flow of harmonized data allow governments to assess whether sustainability goals are being met and to design policy accordingly.

Scenario 2 (Environmental Protection by Local Food Circles and Qualitative Growth; Decentralization, diversity and sustainability) also describe a future food system with a high-degree of digitalization in terms of utilizing monitoring, decision support, and communication enhancing technologies. However, a key distinction of this scenario is that the information flow of food system data is not controlled centrally by state governments, as in Scenario 1, but instead is controlled through decentralized networks of retailers. Here, communication enhancing technologies that promote transparency of productions conditions combined with consumer demand for "greener" products are the main drivers behind achieving sustainability principles. Given this, along with the decentralized and local food system as described by Scenario 2, digital agriculture is most likely leveraged for achieving region-specific goals, meaning that goals formulated at higher policy levels may be less in focus. This could have positive impacts for sustainability principles such as biodiversity conservation, climate change *adaptation*, and soil protection, which generally require site-specific solutions, but negative impacts for principles of climate change *mitigation* and biomass production (e.g., food security), which are primarily addressed by national and international policy and where the momentum of a joint international approach is needed to be effective.

Scenario 3 (Event Consumption by Face-to-Face Interaction in Local Food Circles; Consumption and direct communication) describes a future that is least optimistic in terms of leveraging digital agriculture to achieve sustainability goals. In this scenario, acceptance of digital technologies by farmers and consumers is low due to elevated concerns for data privacy and distrust of large agricultural-tech companies, preferring instead conventional technologies, such as manually driven tractors, and face-to-face communication, such as farmers markets. A lack of consumer preference for healthier and environmentally friendly products means that digital technologies that enhance transparency to consumers are not valued or utilized to their fullest extent. Continuation of conventional management methods means that biomass production is not significantly increased, climate change mitigation is not addressed, soil and biodiversity conditions continue to deteriorate, and lack of systemic monitoring impedes the assessment of policy goal attainment.

Table 4 Scenario 1 and 4. The Role of the scenario factors "Information flow along the value chain and acceptance of service platforms" and "Diffusion of new technologies in primary production" within the key technological areas. For complete analysis of all scenarios see Supplementary Table 2

Hotspots of digitalization within the scenarios		Key technological areas		
		Monitoring	Decision support	Communication
Scenario 1	**Accepted platform with seamless information flow** New technologies and the expansion of network coverage allow more people to retrace agricultural production methods. Information is exchanged between producer and costumer.	• high transparency of the value chain encourages monitoring and the further use of the generated data	• consumers are able to retrace their products, which puts pressure on producers to uphold high production standards• efficiency improvements in the whole process from smart production until delivery of goods by connected and verified (blockchain) information, learning effects from big data and just-in-time optimizations	• new technologies and the expansion of network coverage allow more people to have access to knowledge about agricultural production methods• knowledge expansion in all directions: Digital platforms with detailed information about complete production chain • USP for farmers to give detailed information about their production environment (also as a business model)• seamless flow of information between every step of production chain; bidirectional flow of information (from producer to costumer, from costumer to producer)
	AI farm Sensors are integrated in every part of the production chain and collect various kind of data. These information enable the use of artificial intelligence at every stage of the value chain.	• sensors are integrated in every part of production and allow a resource efficient management of input flows • sensors on the farm enables the diversified and side specific management of land which directly promotes biodiversity and ecosystems	• there are different application of AI on the farm; widely deployed are small scaled autonomous robotics with advantages for efficiency and safety • the farmer has more diverse business management responsibilities, e.g. AI supports making economic decisions by providing sales figures in order to adjust production	• the AI Farm is very efficient and successful, as information flow along the whole value chain is possible • e-agriculture strategies address ICT opportunities, with the agricultural production as a focal point, but as well integrating the well-connected agricultural production chain
	Legal consequences of digitalization requirements			

Scenario 4 (Reduced Consumption and De-growth by Necessity; Growing retail business, no transparence and global food system) describes a highly digitalized agri-food system controlled by retailers that is similar to Scenario 2. In Scenario 4, however, information flow is completely controlled by international retailers and is not transparent to consumers or governments. Further, a high level competitiveness between service providers means that there is no interportability of farm-generated data. This has important implications for achieving sustainability principles. For example, since production conditions are not transparent, consumer demand for environmentally friendly products cannot be fully realized and government monitoring of farm-level compliance with environmental regulation is impeded. In effect, whether or not sustainability goals are achieved in this scenario is highly subject to the economic interests of retailers and digital technology providers.

5 Agri-digital law

The function of law consists of realizing the worked out sustainability goals and by setting clear rules. This provides clear rules for transactions between stakeholders of digitally driven farming systems that balance the legitimate interests of farmers on the protection of their personal/entrepreneurial data and the interest of service providers to run new business models (Härtel 2019). Additionally, an Agri-Digital Law, as developed by Ines Härtel, is able to give incentives for investments in the development and use of innovative technologies, as outlined in the developed foresight scenarios. At the current stage, a holistic legal framework does not exist and there are still many legal questions to clarify that depend on the technical design of ICT-based applications and devices in general. However, some groundwork has been established which gives orientation for the further design of a future legal framework

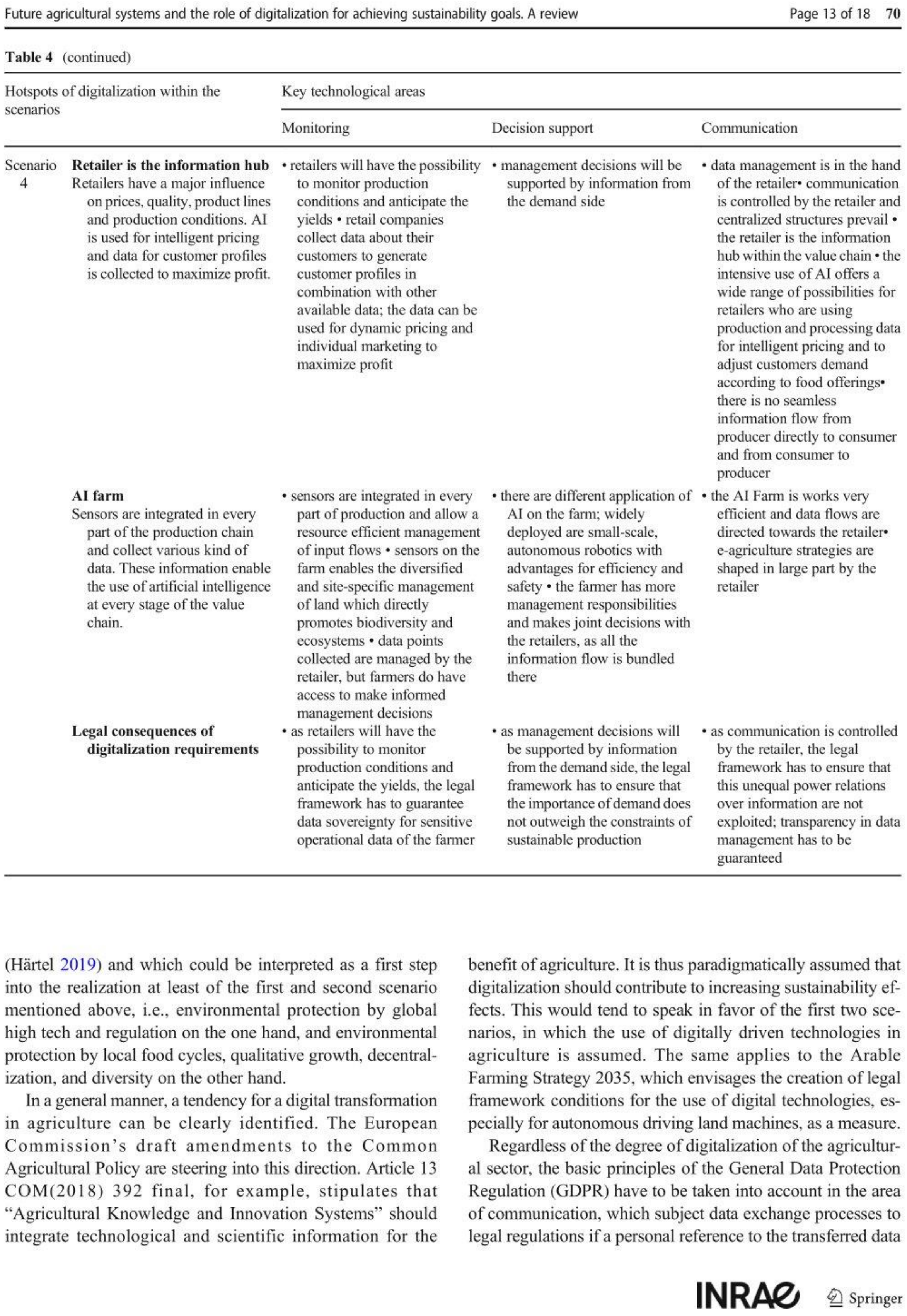

Table 4 (continued)

Hotspots of digitalization within the scenarios		Key technological areas		
		Monitoring	Decision support	Communication
Scenario 4	**Retailer is the information hub** Retailers have a major influence on prices, quality, product lines and production conditions. AI is used for intelligent pricing and data for customer profiles is collected to maximize profit.	• retailers will have the possibility to monitor production conditions and anticipate the yields • retail companies collect data about their customers to generate customer profiles in combination with other available data; the data can be used for dynamic pricing and individual marketing to maximize profit	• management decisions will be supported by information from the demand side	• data management is in the hand of the retailer• communication is controlled by the retailer and centralized structures prevail • the retailer is the information hub within the value chain • the intensive use of AI offers a wide range of possibilities for retailers who are using production and processing data for intelligent pricing and to adjust customers demand according to food offerings• there is no seamless information flow from producer directly to consumer and from consumer to producer
	AI farm Sensors are integrated in every part of the production chain and collect various kind of data. These information enable the use of artificial intelligence at every stage of the value chain.	• sensors are integrated in every part of production and allow a resource efficient management of input flows • sensors on the farm enables the diversified and site-specific management of land which directly promotes biodiversity and ecosystems • data points collected are managed by the retailer, but farmers do have access to make informed management decisions	• there are different application of AI on the farm; widely deployed are small-scale, autonomous robotics with advantages for efficiency and safety • the farmer has more management responsibilities and makes joint decisions with the retailers, as all the information flow is bundled there	• the AI Farm is works very efficient and data flows are directed towards the retailer• e-agriculture strategies are shaped in large part by the retailer
	Legal consequences of digitalization requirements	• as retailers will have the possibility to monitor production conditions and anticipate the yields, the legal framework has to guarantee data sovereignty for sensitive operational data of the farmer	• as management decisions will be supported by information from the demand side, the legal framework has to ensure that the importance of demand does not outweigh the constraints of sustainable production	• as communication is controlled by the retailer, the legal framework has to ensure that this unequal power relations over information are not exploited; transparency in data management has to be guaranteed

(Härtel 2019) and which could be interpreted as a first step into the realization at least of the first and second scenario mentioned above, i.e., environmental protection by global high tech and regulation on the one hand, and environmental protection by local food cycles, qualitative growth, decentralization, and diversity on the other hand.

In a general manner, a tendency for a digital transformation in agriculture can be clearly identified. The European Commission's draft amendments to the Common Agricultural Policy are steering into this direction. Article 13 COM(2018) 392 final, for example, stipulates that "Agricultural Knowledge and Innovation Systems" should integrate technological and scientific information for the benefit of agriculture. It is thus paradigmatically assumed that digitalization should contribute to increasing sustainability effects. This would tend to speak in favor of the first two scenarios, in which the use of digitally driven technologies in agriculture is assumed. The same applies to the Arable Farming Strategy 2035, which envisages the creation of legal framework conditions for the use of digital technologies, especially for autonomous driving land machines, as a measure.

Regardless of the degree of digitalization of the agricultural sector, the basic principles of the General Data Protection Regulation (GDPR) have to be taken into account in the area of communication, which subject data exchange processes to legal regulations if a personal reference to the transferred data can be established. In this respect, technological implications also arise for monitoring. In this context, the politically articulated data sovereignty of farmers within the framework of the Arable Farming Strategy 2035 must be taken into account, as it is currently realized in particular through the basic provisions of the GDPR. According to the case law of the European Court of Justice in the Schecke case, the GDPR applies to the majority of agricultural businesses, as the company name allows conclusions to be drawn about the natural persons behind it, particularly in the case of smaller agricultural businesses (Kipker and Bruns 2020). This lays an important foundation for farmers' data sovereignty, which is also relevant from a technological point of view with regard to monitoring. Furthermore, a "Code of conduct on agricultural data sharing by contractual agreement" has been in place at European level since 2018 and has been signed by a total of nine stakeholder organizations (Härtel 2020b). At the German national level, there is also a scientific recommendation on "farmer data sovereignty" in the context of an agricultural data space with "agricultural data" as a new category of data (Härtel 2020b).

Portability of non-personal data files is subject to self-regulation under Regulation (EU) 2018/1807 on a framework for the free movement of non-personal data in the European Union. According to this, the service providers are to develop their own rules of action within a framework predetermined by EU law (Härtel 2020b). In this respect, for example, certification systems are to be established to enable users to benchmark data processing products. Environmental management could also be able to be taken into account here. With regard to the portability of data, the Act against Restraints of Competition was recently amended, according to which Section 19a (2) No. 5 the Federal Cartel Office is authorized to intervene by way of platform supervision against interoperability restrictions that hinder competition. The question of the compatibility of this regulation with European Union law is viewed critically in the literature (Grünwald 2020).

With regard to on-farm management, the first legal foundations for the use of distributed ledger technologies are developing (i.e., Blockchain), which in turn can increase the validity of the data input for farm management systems. From a legal perspective, the use of distributed ledger technologies in the context of management systems must take into account that the interest in valid and high-quality data must be appropriately balanced with the right to be forgotten from Article 17 of the GDPR (Schöbel 2021).

If future IT-supported management decisions takes the demand side into account and the retailer thus functions as an information hub, it is possible to fall back on an already quite differentiated regulatory regime which, in addition to special legal regulations, such as those for organic products, regional products, or marketing standards of the Common Agricultural Policy, is based in particular on the EU Food Information Regulation and specific legal provisions at the European and nationals levels.

In case that future data platforms, such as those on which a preliminary study in 2020 was based (Bartels et al. 2020) and digital decision support systems pave the way toward an AI or hybrid farm (as outlined in Scenarios 1 and 2), the legal implications of the use of AI systems in the backend would have to be taken into account (Härtel 2020a). To date, the use of artificial intelligence in agriculture is not subject to special legal safety requirements. However, the general liability regime is already applicable, consisting of the General Product Safety Directive, the Machinery Directive implemented in Germany by the 9th Regulations to the Product Safety Act, and the Regulation on the Approval and Market Surveillance of Agricultural and Forestry Vehicles (Härtel 2020a). In April 2021, the European Commission released a proposal for an Artificial Intelligence Act. This regulation proposal implies a differentiated statutory regime which contains increased legal requirements for the use of AI in critical infrastructures. Since agriculture ensures food security for the population, it has to be regarded as a part of the critical infrastructure. In this respect, instrumental provisions are made for risk management systems, quality requirements for training, validation and test data sets, technical documentation regarding risk classification, monitoring obligations throughout the life cycle, transparency of information to users, supervision by natural persons, accuracy, robustness, as well as cybersecurity of the AI system.

In the run-up to any technological implementation of platform and decision support systems, the limits of agricultural digital law must also be taken into account, which arise, for example, for the use of drone-based sensor technologies or the use of robots (Härtel 2019). A high degree of legal innovation is apparent in the Commission's draft of the planned Digital Services Act, which is to contain a comprehensive regulatory concept for digital services in the future.

The possible future use of digitally driven technologies requires stakeholder trust, which in turn depends heavily on cybersecurity. With regard to cybersecurity, ENISA (European Union Agency for Cybersecurity) is to act as a networking body between member state authorities, thereby contributing to ensuring a high level of security of network and information systems, which is the regulatory subject of Regulation (EU) 2019/881 on ENISA and on information and communications technology cybersecurity certification as well as of Directive (EU) 2016/1148 concerning measures for a high common level of security of network and information systems across the Union (Specht 2018).

All the aforementioned groundwork has to be further developed, but from legal perspective a clear tendency toward the digital transformation of agriculture can be observed. This expressively implies systems for the exchange of agricultural knowledge and information. If technical evolution and legal design go hand in hand, then the conditions for the formulation of a suitable, coherent, and consistent legal framework are necessary. With regard to the future, legal experts should work together in an interdisciplinary fashion in order to be able to advise legal policy concerning the future development of a legal framework that leads to a balance of interests, gives incentives for innovation and is adaptive for disruptive technologies that might arise within the context of digital transformation of agriculture.

6 Discussion

Digital agriculture could potentially deliver improvements to sustainability across food systems. This stance can be found in several of the policies we reviewed, although only to a limited extent. Of the reviewed policies, the F2F Strategy, 2035 Arable Farming Strategy, and the National Bioeconomy Strategy stood out in terms of their incorporation of digital agriculture in their documents. Our study showed that policies consider digital agriculture mostly in terms of resource use efficiency, while its benefits for achieving other sustainability principles such as biodiversity conservation, soil protection, and climate change adaptation and mitigation are not thoroughly reflected. Similar findings of policy from high-level institutions were found by Lajoie-O'Malley et al. (2020). Nevertheless, the reviewed policies converged on certain points concerning frame conditions for implementing digital agriculture, such as developing a statutory framework, working toward data harmonization, as well as increasing high speed internet availability to rural areas.

Our study showed technologies that improve decision support, such as VRT, cloud computing, IoT, yield mapping, digital soil mapping, sensors, and UAVs are particularly relevant toward achieving the majority of agriculture-related goals and, by extension, diverse sustainability principles. Further, technologies that enhance monitoring such as satellite imaging, AI, and agricultural census data are particularly relevant for promoting biomass production, climate change mitigation and adaption, as well as biodiversity conservation. Lastly, communication technologies such as RFIDs, QR codes, and distributed ledger technology (e.g., Blockchain) promote transparency along the value chain, thereby contributing to goals related to health and nutrition as well as biodiversity conservation. Given the rapid growth and innovation in digital agriculture, policy should do more to highlight these potential applications and refer to the burgeoning literature on the topic.

A shortcoming of the reviewed policies should be noted. Although they acknowledge the growing role of consumer demand in shaping agricultural production systems, they do not sufficiently consider how digitalization is increasingly embedded in this process. Our foresight analysis suggests that communication enhancing technologies will bring consumers and producers closer together, which is also echoed in the literature (Birner et al. 2021). Digital technologies can provide more detail and transparency to consumers on the production conditions and nutritional content of their food, as well as provide farmers with better information on consumer preferences and trends. This new dynamic between consumer and producers could be a decisive factor in achieving sustainability goals in the future. In this context, our study also shows a growing importance of retailers in the agri-food sector as brokers of information between farmers and consumers, potentially connecting them in short value chains, which means retailers could have significant influence over agriculture in future food regimes (Prause et al. 2021). Failure of policy to recognize how digitalization is transforming food value chains could be a shortcoming in connecting the farm to fork and considering the agri-food sector as a whole.

There are many adoption barriers of digital agriculture technologies. High investment costs (Rose and Chilvers 2018) and lack of training and advisory services for farmers are some of the main barriers to adoption, especially for small- and medium-scale farmers (Paustian and Theuvsen 2017). Policy can help surmount these barriers through offering financial assistance to farmers and innovators in the form of tax-breaks and/or subsidies that help compensate short-term opportunity costs and long-term financial risks associated with technological innovation and investment (Ehlers et al. 2021). As suggested in the literature and taken up in the 2035 Arable Farming Strategy and the F2F Strategy, providing agriculture training (i.e., digital skill sets) and advisory services for farmers could foster a more inclusive digital agriculture for small-scale, agri-food businesses (Piñeiro et al. 2020; Long et al. 2016). Coupling advisory services and training with financial assistance for digital technologies will increase chances that digital agriculture will be leveraged to its fullest potential. Ultimately, these type of measures may help to avoid a digital divide between large-scale and small-scale farmers in the future (Rotz et al. 2019b; Revenko and Revenko 2019).

There are many things to account for in regard to how ownership of data will shape the future of digital agriculture. As data becomes more central in the future agri-food sector, whoever controls this data will have immense influence on dictating to which ends it is being used, including how and if it used for achieving sustainability principles. Currently, there is a trend toward consolidation of the control of data among large agriculture technology companies (i.e., "data grab"), which raises doubts as to whether digital agriculture when left in the hands of big business will be used for sustainable ends or reinforce neoliberal and productivist paradigms (Birner et al. 2021; Prause et al. 2021; Clapp and Ruder 2020). With the exception of the 2035 Arable Farming Strategy, which mentions the need to create a statutory framework and explore preconditions of data sovereignty, there is a striking absence of language addressing this issue in the reviewed policies.

Although fragmented, the current framework of laws surrounding digital agriculture is evolving, albeit at a pace behind technological development. Precedence shows that laws are typically reactive. This puts policy in a position of responsibility that should anticipate the digital transformation of agriculture and be an active guide toward steering it in the direction of sustainability. It is the view of these authors that this can best be achieved by empowering farmers' enterprises by protecting their legal rights in regard to the control of their data (i.e., data sovereignty). The literature provides many examples of ways for leveling the playing field between large ag-tech companies and farmers. Overall, it may be necessary to reconceptualize data generated from agriculture as its own class of data with its own set of regulations (Härtel 2020b). This would be a key step in making certain types of non-personal data available to farmers, companies, as well as government and research institutions who could use it to achieve wider sustainability objectives.

We would like to mention a few limitations of this study. Our review of policies is not exhaustive, meaning that some policies that consider digital agriculture may be missing from our analysis such as the Common Agriculture Policy of the EU, for example, which would be too wide for the scope for this paper and would deserve a study in its own right. However, our review does not intend to be exhaustive, but rather to demonstrate how current and widely recognized sustainability policies potentially intersect with digital agriculture. In future studies, it would certainly be interesting to look at which policy measures can be used not only at the farming level, as described above, but also, for example, at the level of consumers or retailers. Additionally, by focusing on Germany, we were able to provide an in-depth analysis. However, depending on the country of interest, policy development and the digital transformation of agriculture may look very different. This means future research should focus on how policy and digital agriculture is taking shape in other countries to assess and compare impacts of digitalization under different frame conditions (see Fleming et al. 2021).

In regard to the scenarios, although they provide rich details on probable futures, they are theoretical propositions about what *could* happen in the future. The inherent uncertainty of the future makes it impossible to anticipate all factors that might have an influence on digital agriculture, especially considering the rapid changes brought about by digital technologies in other parts of society. Indeed, an unforeseeable event could alter the validity of our scenarios. Nevertheless, it is prudent to make assumptions about probable futures in order to anticipate potential change and avoid sub-optimal outcomes. Finally, in regard to our legal analysis, there are surely many developments of statues in private law that will shape digital agriculture, but these would be impractical to cover within the scope of this research. However, we find that the precedent established by public law more relevant to the level of analysis of this study.

7 Conclusion

Whether or not digital agriculture can provide solutions to sustainability problems depends on how it is currently embedded in policy, as well as how future frame conditions and legal settings shape its implementation. Otherwise, digitalization may just become another instrument for reinforcing the paradigm of economic efficiency. Research is therefore required that takes stock of missions and goals of current societal sustainability imperatives that potentially intersect with digital agriculture, while identifying optimal future and legal frame conditions for exploiting the potential of digitalization in order to achieve societal targets. In so doing, such research will facilitate the development of mission-oriented policies that contemplate and anticipate the institutional and technological preconditions and potential unintended consequences of evolving technological transition pathways (Klerkx and Rose 2020).

In this regard, our study offers a unique perspective on how digital agriculture may be leveraged to achieve policy targets under different future scenarios and an evolving legal framework. The results show that digital agriculture is taken up in some high-level policies, but only to a limited extent. However, we identified how digital technologies could be applied more broadly in agri-food systems to achieve sustainability principles outlined in policy strategies. Additionally, our results corroborated those found in the literature that the adoption of digital technologies and the ends to which they are being used are largely dependent on future data ownership regimes. Our foresight analysis highlighted how control of information and ownership of data may unfold under different probable futures and what this means for the achievement of sustainability principles. The legal analysis provided additional insights to a preliminary, fragmented legal framework that is currently evolving in favor of free flow of non-personal, farm-generated data for public and private use.

Overall, the integration of monitoring, decision support, and communication enhancing technologies along the entire agri-food chain is needed to cultivate a real "game changing" Agricultural 4.0. It is therefore prudent of high-level policy to be future-oriented by anticipating a greater role of digitalization not only in agricultural production, but also in governance, retail, and consumption. This will probably require a change in thinking about agriculture, since digitization may shift or blur traditional lines in agri-food systems, bringing us in new ways closer to the food we eat.

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Code availability Not applicable.

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

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4.

Using Bayesian networks as a participatory tool for assessing the impacts of digital agriculture

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Agricultural Systems (in revision)

Using Bayesian networks as a participatory tool for assessing the impacts of digital agriculture

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Abstract

CONTEXT

The transition to digital agriculture is likely to lead to systemic changes that will affect production, consumption, governance, and the wider environment of agricultural systems. Nevertheless, the absence of sufficient evidence and ambiguities in perspectives create an ongoing lack of clarity regarding the potential impacts of digital agriculture. Therefore, to discern potential impacts while addressing system complexities, uncertainties, as well as normative aspects associated with this transition, future-oriented and transdisciplinary approaches are needed that actively involve diverse knowledge and values of affected stakeholders.

OBJECTIVE

This research aimed to explore the impacts and processes of agricultural digitalization according to stakeholders. The main objective were to identify key impact areas of agriculture, examine the intersection of digital agriculture with these areas, and uncover uncertainties associated with these impacts and underlying processes.

METHODS

Through participatory modelling procedure, diverse stakeholders from the German region of Brandenburg constructed a Bayesian Belief Network (BBN). The BBN facilitated the identification of the main impacts of digital agriculture and allowed for the modeling of uncertainties associated with these impacts through scenario analyses.

RESULTS AND CONCLUSIONS

Stakeholders perceived several socioeconomic advantages of digitalization, particularly in terms of bolstering economic stability through improved risk management and enhanced resource use efficiency, validating existing claims in the literature. The perception seems to be influenced by highly variable yields and market uncertainties, as well as shortages in labor in the region. On the other hand, there was significant uncertainty among stakeholders concerning landscape diversification and its impact on biodiversity. This uncertainty arises from the potential profitability of cultivating marginal land under heightened digitalization-induced efficiency, posing a risk of diminishing natural habitat and landscape heterogeneity. Local historical trends towards landscape simplification as result of technology-driven efficiency improvements may be a cause for this perception.

SIGNIFICANCE

This study contributes to the limited body of future-oriented research assessing the impacts of digital agriculture through learning from stakeholder knowledge and values. While there is theoretical potential for digitalization to enhance biodiversity, realizing such positive impacts is improbable without improved communication and policy incentives, given the historical trend of efficiency-driven pathways. Further, to guide informed decision-making and foster societal acceptance of digital solutions, the study underscores the need for a nuanced evaluation of digital agriculture's potential impacts that considers local conditions.

Key words

Digitalization; Participatory modelling; Co-learning; Mental model; Uncertainty; Sustainability

1. Introduction

Digitalization is expected to massively transform agriculture in the coming years and a great deal of optimism surrounds it, as it could significantly increase agricultural efficiency and productivity, while at the same time reducing negative externalities in the form of environmental impacts and costs (Shepherd et al. 2020; Basso and Antle 2020). At the moment, this is the dominant narrative embedded in agricultural policy (MacPherson et al. 2022; Lajoie-O'Malley et al. 2020) and a key selling point for related industries (Clapp and Ruder 2020). However, agriculture is enmeshed in a myriad of other pressing sustainability issues, including biodiversity loss, landscape homogenization, climate change, deterioration of soil health, water eutrophication, animal welfare concerns, supply chain disruptions, market volatility, land grabbing as well as structural change of rural communities. Currently, there is a flourishing research field investigating ways which digital agriculture could be leveraged to address some of these issues.

Digitalization has the potential to improve the efficiency of agrochemical inputs, generating positive knock-on effects for the environment (Wolfert et al. 2017; Finger et al. 2019). It could also enable optimized spatial planning and decision support, which may lead to more sustainable agricultural landscapes (Donat et al. 2022; Mouratiadou et al. 2023; Zhai et al. 2020). Agri-environmental governance also stands to benefit from developments in big-data technologies for tailoring site-specific agri-environmental instruments (Ehlers et al. 2021). Nonetheless, the paradigm of digital agriculture is being questioned. For example, Daum (2021) points to a highly robotized scenario that could result in more monocultures and less diverse landscapes. Concerns have also been made about displacing laborers (Carolan 2020), reinforcement of power asymmetries (Birner et al. 2021; Clapp and Ruder 2020; Carbonell 2016) the reduction of farmer autonomy (Henman 2020) and a decline in job satisfaction (Rose et al. 2021; Prause 2021).

Adoption of digital and precision technologies has remained rather low in Europe (Lowenberg-DeBoer and Erickson 2019) and varies by region (Barnes et al. 2019). Low uptake of these technologies has been attributed to high initial investment costs (Barnes et al. 2019), lack of operating skills (Klerkx and Rose 2020), insufficient access to broadband internet in rural areas (Paustian and Theuvsen 2017), and lack of trust among farmers due to issues of data sovereignty and privacy (Jakku et al. 2019). These barriers do not appear to be insurmountable in the long term, as costs for digital agricultural technologies are declining (Birner et al. 2021), training networks are emerging (in the EU: SFATE - Smart Farm Training for Employment and Digital Innovation Hubs), high-speed internet access is becoming a global reality (e.g. via Starlink), and agri-digital legal frameworks are beginning to take shape (Härtel 2021). Despite this, in the absence of governance, digitalization may primarily enhance economic efficiency without fully realizing its potential to improve environmental and social integrity (MacPherson et al. 2022).

Digitalization will not necessarily happen overnight, but will probably occur as a gradual, background transition over the next decades (Klerkx and Rose 2020). While it appears that we are at the beginning of this transition, society is at a crucial turning point in terms of directing digital agriculture toward sustainability. However, because of the ambiguity in perspectives of different stakeholders, uncertainty surrounding the effects of digitalization is pervasive, which means a core challenge is developing a conceptualization of digital agriculture – including a vision for its future - that is consensual. This requires bringing the potential positive and negative impacts of digital agriculture to the foreground through participation by societal actors. In other words, agricultural digitalization is happening, but it needs to be made visible through deliberation and analysis by society as to not miss out on potential opportunities and reduce exposure to potential risks.

To secure technological improvements into current and future socio-economic and environmental contexts, Reed (2008) emphasized the importance of involving stakeholders in decision-making processes. This sentiment has been echoed by Klerkx et al. (2019) who underlined the need for greater societal inclusion in the development and implementation of digital agriculture technologies. This includes involving stakeholders to set goals and develop indicators to measure progress toward sustainability (Basso and Antle 2020), as well as reflect on the potentially disruptive impacts of innovative digital technologies (Rose and Chilvers 2018; Eastwood et al. 2021). Finally, involving stakeholders in research will be crucial toward gaining their trust for digital technologies in the future, jointly mitigating adverse impacts and promoting acceptance of digital agriculture solutions (Jakku et al. 2019).

Many argue that in order to ensure that digital agriculture contributes to societal well-being and sustainability, a responsible research and innovation approach (RRI) is needed (Eastwood et al., 2019; Rijswijk et al., 2021; Klerkx and Rose, 2020). Central to the RRI approach are the guiding elements of anticipation, inclusion, reflexivity, and responsiveness (Stilgoe et al 2013). These elements are intended to inform the design of research and facilitate the anticipation and reflection upon both intended and unintended consequences of innovations and technologies through stakeholder engagement. Moreover, the RRI approach aims to collaboratively design solutions to minimize risks and maximize opportunities of innovations and technologies, thereby fostering socially ethical and sustainable outcomes (Zscheischler et al 2022). There has been a recent increase in empirical studies assessing digital agriculture through the lens of the RRI framework. For example, Zscheischler et al. (2022) investigated the perceived risks associated with agricultural digitalization in Germany with a group of stakeholders, illuminating risks related data ownership and power dynamics, as well as the effects of automation on farmers' decision-

making capacities. Fleming et al. (2021) employed a participatory scenario building method to reflect on probable futures and contrasting sustainability outcomes of digital agriculture in the Australian context. Metta et al. (2022) applied the socio-cyber-physical system framework to assess the sustainability implications of digital agriculture across 21 Living Labs across Europe. Employing a multi-stakeholder approach, they identified various effects and trade-offs concerning the enabling, disenabling, boosting, and depleting impacts of digital agriculture.
While these ap

In adopting a similar approach based on anticipation and inclusion to assess the potential impacts of agricultural digitalization, our study asks the following research question:

- What are the anticipated impacts of agricultural digitalization according to stakeholders?

Addressing this question, the current study aims to achieve three main objectives:

- to identify the key areas of impact that digital agriculture is likely to influence within the next 10 years.
- to identify the causal pathways linking digital agriculture to key impact areas; and,
- to examine the uncertainties of stakeholder perceptions associated with these impacts and causal pathways.

To achieve these objectives, our study conducts a participatory modelling process to construct a Bayesian Belief Network (BBN). Because BBNs are widely acknowledged for their ability to transparently integrate knowledge from diverse domains and effectively handle the inherent uncertainty associated with interactions of complex systems (Voinov and Bousquet 2010), we find BBNs suitable for assessing the complexity and unknowns of agricultural digitalization with stakeholders.

The participatory modeling process of large-scale agriculture in the German region of Brandenburg sheds light on stakeholders' views of digitalization, which fostered a co-learning experience. The process provided a platform for constructive discussion between diverse stakeholders, while to the greatest possible extent mitigating overly emotional and less objective debates. In a broader sense, the findings reveal patterns of thought of various stakeholder groups regarding digitalization, drawing attention to societal concerns for researchers and policymakers.

2. Methods and materials

2.1 Participatory modelling with Bayesian belief networks

Modelling with stakeholders, or participatory modelling, is a problem-solving approach that improves system understanding and decision-making by synthesizing stakeholder knowledge and values in a coherent manner. More specifically, participatory modelling has been defined as 'a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality '(Voinov et al. 2018). These shared representations of reality provide descriptions of the problem at hand by defining the impacts and potential solutions (Voinov and Bousquet 2010). There are many tools and methods available for modelling with stakeholders (Voinov et al. 2018), however this study employs a Bayesian Belief Network (BBN) approach to engage stakeholders in a participatory modelling process.

BBNs are graphical representations of real-world systems that rely on probabilities to model relationships and dependencies (Kjaerulff and Madsen 2013). They are visually represented as Directed Acyclic Graphs (DAGs), which consist of three main elements: (1) nodes representing variables of the system under investigation; (2) directed arrows indicating causal or probabilistic dependencies between nodes; and (3) probability distributions expressed in Conditional Probability Tables (CPTs). These CPTs describe the probability distribution of a node given the states of its parent nodes, quantifying the statistical dependence between variables. While BBNs are often used to model causal relationships, they can also represent associations or dependencies without implying causation. The use of a DAG ensures that there are no cycles in the graph, preventing feedback loops. BBNs enable the propagation of information throughout the network through techniques like Bayesian inference. This allows for the calculation of updated probabilities for variables based on observed evidence, making BBNs valuable tools for modeling, reasoning, and conducting probabilistic inference in complex systems. By describing causal interactions between system components in probabilistic terms, BBNs can explicitly account for uncertainties in knowledge that are inherent to complex systems. They can be developed using empirical data from models, direct observations, expert knowledge, or a combination of these (Bruce G. Marcot 2012). As such, BBNs are practical in situations where empirical data is lacking and for integrating data of different quality (Uusitalo 2007). In respect to the latter, integrating knowledge across domains assists with understanding complex management problems in a more comprehensive way (Cain 2001). Additionally, established BBNs can be updated when new information becomes available, allowing for iterative scenarios analyses, which is useful for adaptive management approaches (Uusitalo 2007).

There are many examples in the literature of participatory BBNs being applied to support agricultural management, especially in the European context. Henriksen et al. (2007) used a BBN to explore complexity and uncertainties when assessing the impacts of pesticide management actions on agricultural economics and groundwater and drinking water quality on the national Danish scale. Along with stakeholders, Carmona et al. (2011) worked on developing a decision support system combining an agro-economic model and object-oriented BBN to study different management options for groundwater management in Spain, focusing on the trade-offs between agriculture and the environment. Duspohl and Doll (2016) used a participatory BBN approach to identify implementable strategies for promoting renewable electricity generation in a German county. In a pre-Alpine region in Switzerland, Celio and Gret-Regamey (2016) applied a BBN approach for land-use modelling to understand the influence of farmers on land-use change in a spatially explicit manner. Finally, Salliou et al. (2017) used a BBN with stakeholders in Southwest France to model ambiguity in perceptions of different stakeholders in the context of biological pest control in apple orchard cultivation. The diversity of applications in which participatory BBNs have been employed speaks to their overall usefulness as a participatory modelling approach. However, no studies have - to our knowledge - used participatory BBNs in the context of modelling the impacts of agricultural digitalization till now.

2.2 Selecting system variables and indicators with stakeholders

The selection of system variables and respective indicators is a crucial step in assessing sustainability since it affects what is measured, how it is measured, and what conclusions can be drawn from the findings (Pope et al. 2004). Here, stakeholder involvement is seen as a key criteria for conducting a nuanced impact assessment and developing indicators that are relevant, meaningful, and reflective of the local context (Binder et al. 2010; Latruffe et al. 2016). In our study, we involve stakeholders in identifying system variables and respective indicators through the creation of a causal network (i.e. in the form of a BBN) following the commonly used DPSIR approach (more on this in Section 2.4.1) (Niemeijer and Groot 2008; König et al. 2013). By engaging stakeholders in this process, their knowledge and perspectives are incorporated, ensuring that the chosen system variables and indicators capture the diverse aspects of sustainability that are important to the region under study (Reed 2008). This leads to a better understanding of the interconnectedness between indicators and the complex relationships within the system (Chopin et al. 2021)

2.3 Case study area: Brandenburg, Germany

The federal German state of Brandenburg covers 29,640 km^2, of which 45% of the land area is dedicated to agricultural production (Amt für Statistik Berlin-Brandenburg 2016). Within the utilized agricultural area, 77% comprises of cropland and 23% of permanent grassland (Troegel and Schulz 2016). The agricultural landscape is characterized by homogenization and intensified production, which are implied to have detrimental effects on biodiversity, soil and water quality (Thomson et al. 2019). This is despite existing economic incentives from the EU's Common Agricultural Policy (CAP) for sustainable land management practices (Wolff et al. 2021).

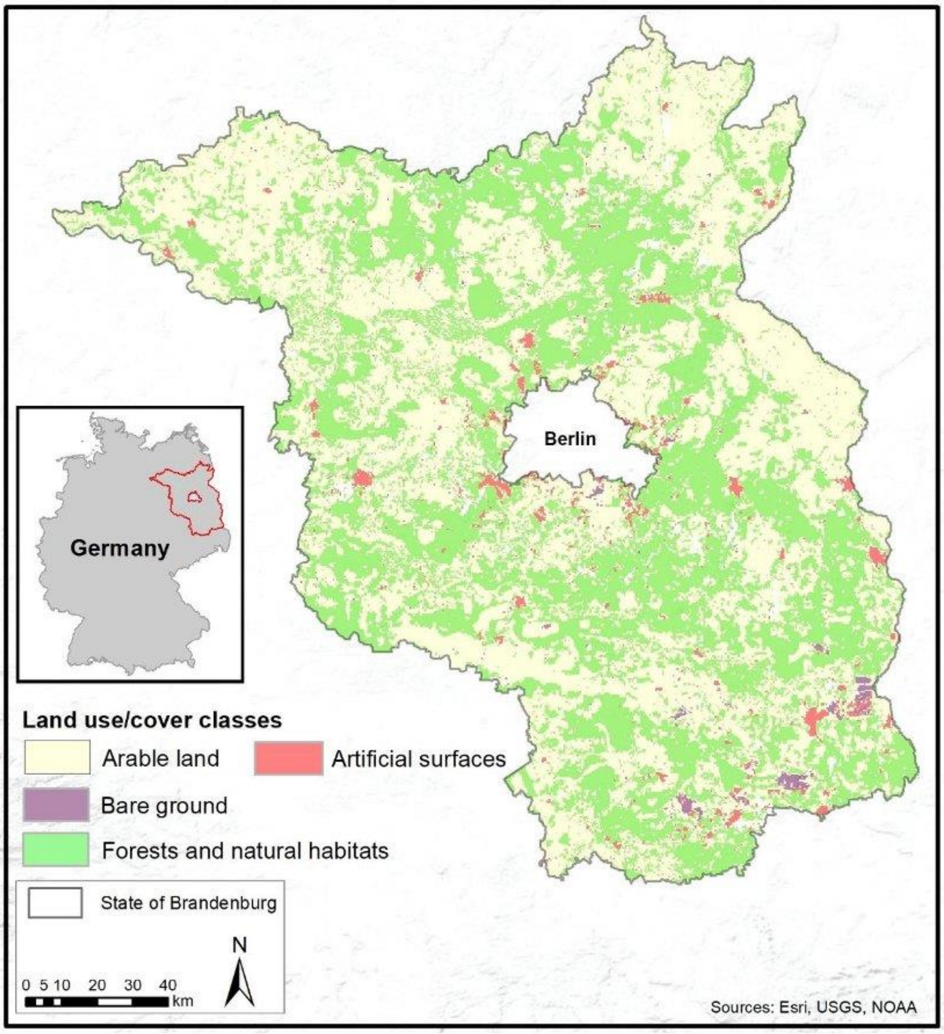

Figure 1. Map depicting the location and major land use classes of the German Federal State of Brandenburg, the case study region.

The main crops grown in Brandenburg are wheat, maize, rye, and barley (Gutzler et al. 2015; Amt für Statistik Berlin-Brandenburg 2021). Agricultural enterprises are relatively large, having an average farm size of 242 hectares, or four times the German average (Gutzler et al. 2015; Troegel and Schulz 2016). These enterprises tend to be highly mechanized and make intensive use of fertilizers and agrochemicals (Gutzler et al. 2015).

Regarding natural conditions, the region is characterized by low-quality soils, from which almost two-thirds are sandy and sandy-loamy (Wolff et al. 2021). Rainfall is also low, being on average less than 600 mm/year with the tendency to decrease even further in the future. Combining these two factors explains in part the high input and mechanization of agricultural enterprises. For a more detailed description of Brandenburg's agricultural landscape, Wolff et al. (2021) provided an analysis of landscape metrics indicating agricultural landscape structure, diversity and management using plot-based agricultural data.

2.4 Digital agriculture and state of adoption

Agricultural digitalization is a rapidly emerging trend, intertwined with varying concepts, such as Precision farming, Smart Farming, Agriculture 4.0 and Digital Agriculture, which are often used interchangeably (Klerkx et al. 2019). Digital agriculture is a form of managing and optimizing agricultural systems (e.g. production, value chains, and food systems) by leveraging data-driven techniques and technologies. In agricultural production, in-situ sensors offer real-time data on soil and crop conditions (Pedersen and Lind 2017; Wolfert et al. 2017), while remote sensing technologies like satellites and drones provide similar data over larger areas (Gao et al. 2020). Artificial intelligence analyzes large datasets for pattern detection, aiding in crop monitoring and yield prediction (Wolfert et al. 2017). Variable Rate Technologies (VRT) adjust inputs based on soil and crop variations, enhancing resource efficiency (Finger et al. 2019; Späti et al. 2021). GPS technology enables precise field mapping and vehicle guidance, reducing input wastage (Fielke et al. 2019; Godoy et al. 2012). More recently, although still a fringe development, agricultural digitalization has expanded to include the deployment of robotics and artificial intelligence for enhanced mechanization and automation of production activities, such as field crop robots that can work in fleets (Sparrow and Howard 2021; Spykman et al. 2021; Lowenberg-DeBoer et al. 2020). Utilizing data gathered from various sources, computer software like, or Farm Management Information Systems (FMIS), integrate data analytics and modelling techniques to manage agricultural enterprises and provide farmers with decision support on complex tasks, such as crop management, irrigation scheduling, fertilizer application, risk assessment (Tummers et al. 2019). These devices are connected through the internet, also known as the Internet of Things (IoT), allowing them to gather and communicate data among themselves.

Mobile phone apps have become ubiquitous throughout the world, providing farmers with information on things such as crop protection, crop selection, weather forecasts, market prices and entry points, e-learning, and communication with other farmers and consumers, as well as promoting citizen science (Daum et al. 2018; Dehnen-Schmutz et al. 2016). Digital technologies facilitate enhanced information exchange among suppliers, producers, consumers, and governments Within agri-food value chains and food systems (Poppe et al. 2013). RFID chips and blockchain contribute to heightened transparency and traceability throughout food supply chains (Kamilaris et al. 2017). These advancements aid farmers in securing added value for their products while empowering consumers to make informed choices and bolstering food safety measures for governments.

The instrumentalization of digital agriculture, or the objectives for which it is being used to achieve, depends on the underlying paradigm it is associated with (Metta et al. 2022). When viewed through the lens of sustainable intensification, digitalization is often seen as a means to mitigate environmental pollution and land expansion pressures by enhancing efficiency and productivity through improved input management (Lindblom et al. 2017). On the hand, from the angle of conventional agriculture, the potential efficiency and productivity gains of digitalization are typically considered from a profit-maximization perspective, with less thought for wider impacts on sustainability (Lajoie-O'Malley et al. 2020). From an alternative perspective, where efficiency and productivity gains are less in focus, digitalization can be seen through the lens of agroecology as a tool for facilitating better spatial planning and promoting multifunctional and diversified agriculture (Mouratiadou et al. 2023), taking advantage of ecological processes (Hilbeck et al. 2022). In this context, digital agriculture technologies can be divided into three broad functional categories: monitoring, decision support systems, and communication (Mouratiadou et al. 2023). Monitoring technologies of biodiversity and ES provision can be used for gaining transparency on complex cause-effect relationships within agroecosystems. In this case, monitoring not only facilitates a deeper understanding of these relationships, but also enables the establishment of result-oriented policy measures aimed at promoting sustainable agricultural practices. Decision support software can help navigate multifunctional and diversified agricultural landscapes, where various targets such as improving yields, ecosystem services, and biodiversity conservation need to be consolidated. In communication among stakeholders and land use actors, digital technologies can improve information exchange regarding societal demands on biodiversity and ecosystem services. This communication could help to reduce conflicts over the future use of agricultural land by fostering a shared understanding of the importance of ecological resources along the entire value chain, leading to their valorization.

There is not much evidence available about the level of adoption of digital agriculture across Europe, and most of the research is country-specific, showing that there are significant regional variations in adoption. In a survey of farmers from 7 EU countries (n=287), Kernecker et al. (2020) found that about 50% were adopters of smart farming technologies, with higher levels of adoption correlating with increased farm size and arable cropping systems compared to livestock or mixed cropping systems. Although it should be noted that they used a purposive sample, so the rates of adoption in across the EU are probably lower in reality.

In Germany, higher levels of adoption also correlate with larger farms, which points to future growth in adoption rates due to the continuing structural change in the rural sector (Paustian and Theuvsen 2017). In a survey of 500 farmers, Rohleder et al. (2020) found that 8 out of 10 farmers make use of digital technologies in Germany. However, the necessary infrastructure for a wide adoption, such as broad network connectivity and speed, is still lacking, although it is probably a question of time until German rural areas are fully connected (Bernhardt et al. 2021).

Brandenburg is characterized by large farm sizes, so adoption of digitalization should therefore be more likely there. No data is available, however, on the current state of adoption among farmers in Brandenburg, although there is ongoing discussion about the future of digitalization, especially considering the unlocked possibilities coming with the expansion of the 5G mobile network (Land Brandenburg 2019). The state government has its own digital strategy and claims that it wants to expand Brandenburg’s leading role in digital agriculture and forestry, as well as the digitalization of companies and value chains (Landesregierung Brandenburg 2021). There are also ongoing research projects specifically focused on agricultural digitalization considering the regional context (Bellingrath-Kimura 2019).

Our research is a component of the BMBF-funded DAKIS (Digital Agricultural Knowledge and Information Systems) research project, which is – among other things - developing a Decision Support System (DSS) to allow farmers and advisors to incorporate ecosystem services and biodiversity in farm-level agro-economic planning (Mouratiadou et al. 2023). The DAKIS DSS executes models and simulations that are supplied with high resolution real-time, site-specific data from in-situ measurements and remote sensing.

Based on these models, the project is also anticipating the integration of field robots within its DSS infrastructure. Taken as a whole, the DAKIS research project is a state-of-the-art example of how digital agriculture technologies can be applied to optimize agricultural productivity while fostering the provision of multiple ecosystem services. Most of the project's activities are located within the German Federal State of Brandenburg. Therefore, Brandenburg was chosen as the case study area for testing our participatory approach and developing the BBN.

2.4 Stakeholder workshops

In this study, a participatory modelling approach using a BBN was used to identify and assess the potential impacts of agricultural digitalization in the future (i.e. in a 10 years' time period) in Brandenburg, Germany. We designed our protocol based partially on those developed by Cain (2001) and Bromley et al. (2005) through engaging a group of stakeholders in a series of workshops and iterative consultation to co-construct a BBN. The following subsections describe the methodological approach used to construct our

Bayesian network. For a graphical overview of the methodology, see Figure 2.

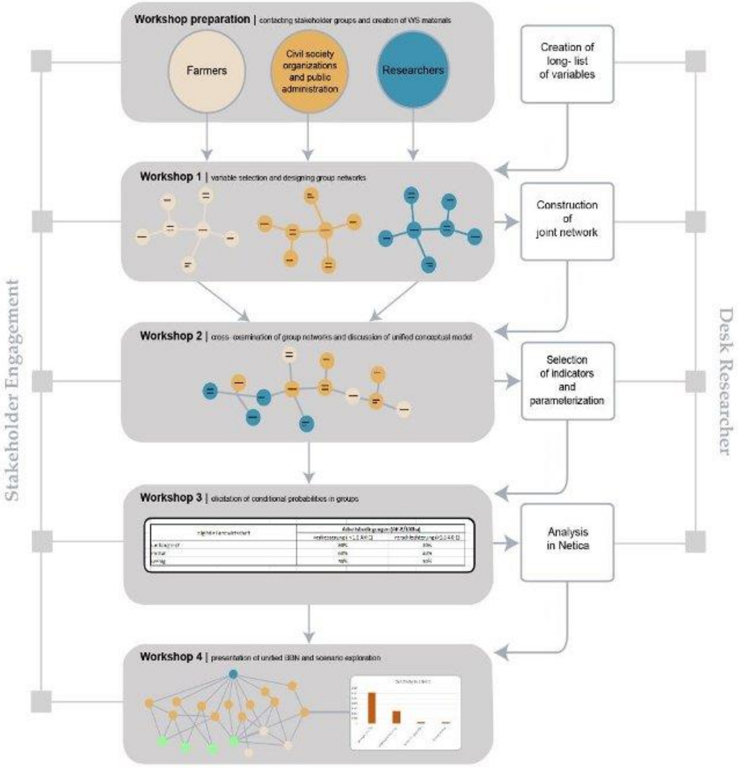

Figure 2 Overview of methodological workflow of the participatory modelling process to construct the BBN.

During three online workshops (each 3 hours long), stakeholders were led through a stepwise process to co-construct a BBN. The main tasks of the workshops were to select relevant system variables and arrange them into a graphical network, elicit conditional probability estimates (e.g. quantification), and to discuss the resulting BBN with the participants. The workshops were spread out over a six-month period in 2021-2022 and conducted online to comply with the COVID-19 regulations at that time. Workshop materials were prepared on the collaborative whiteboard software MURAL as well as with MS Excel. Data obtained from the workshops were later entered into Netica (Netica V5.18 2015), a Bayesian network modelling software package, for analysis.

For our case study area, we identified four stakeholder groups of interest, namely: farmers, researchers, civil society organizations and public administration. We considered these groups because farmers offer firsthand insights into the tangible effects of digital technologies on their livelihoods, while researchers provide technical expertise and guidance on innovations. Civil society organizations ensure alignment with societal values and potential externalities, and public administration contributes perspectives on regulation and policy-shaping. By involving this diverse range of stakeholders, a well-rounded assessment of digitalization was ensured. The public administration and civil society groups can both be seen as expressing the broad viewpoint of the general public, thus we felt that they could be combined into one group, which we named the 'civil society group' for the purpose of this study. Based on this grouping, we non-randomly identified potential participants using personal contacts and Google search. We sought out participants that were experts in their fields and that were familiar with regional agricultural conditions in Brandenburg. Within each group, we sought to include individuals with different backgrounds and experience to harness diverse and contrasting expertise.

Due to the high time requirements for developing the BBN and to consider the shorter attention span of online workshops compared to face-to-face workshops, it was necessary to divide the participatory modelling process across multiple days. It was therefore crucial that participants were able to attend all workshops as to ensure their continuous collaboration throughout the process. In this way, a smaller group of workshop participants was more feasible in terms of achieving continuous participation as well as more desirable for the in-depth discussions required for the study. Fourteen stakeholders participated in the workshops, most of which were able to attend all three workshops. In cases where a participant was not able to attend a subsequent workshop, they were requested to send a substitute representative to attend the workshop in their stead. For an overview of participants and their backgrounds as well as their attendance in the workshops, please see Supplementary Material I.

2.4.1 Workshop 1: variable selection and construction of conceptual models

The primary objective of the first workshop was to collect insights into how different stakeholder groups perceive the impact of digitization on agricultural systems by guiding them in the selection of relevant system variables and the creation of conceptual models (Figure 3). In this workshop, each stakeholder group acted in parallel to develop their own conceptual model, as recommended by Cain (2001), which allowed for in-depth discussions and intra-group consensus-building. Before network construction, it was necessary for each group to identify and select the system variables (i.e. relevant agricultural system components such as productivity, working conditions, and biodiversity, for example) to be included in their models. Therefore, each group first systemically selected variables from a list of pre-selected variables. The pre-selected list of variables was compiled from objectives outlined in policy strategy documents, including the EU F2F Strategy (European Commission 2020), the German National

Sustainability Strategy (Deutsche Bundesregierung 2018), and the 2035 Arable Farming Strategy (BMEL 2019), as well as indicators from agricultural sustainability assessment frameworks and models, including SAFA (FAO 2013), RISE (Grenz et al. 2012), KSNL (Breitschuh 2008), MODAM (Zander and Kächele 1999), and ViSA (Shaaban 2022). Additionally, relevant scientific literature (Wolfert et al. 2017; Walter et al. 2017; Finger et al. 2019) was used to derive variables specific to agricultural digitalization and precision agriculture. Each of the abovementioned sources were thoroughly reviewed by the authors before being entered into the pre-selected list of variables. Also, during this workshop, participants were given the option of 'writing-in' new, additional variables they felt were missing from the pre-selected list. See Supplementary Material I for an overview of the pre-selected list of variables used in the workshop.

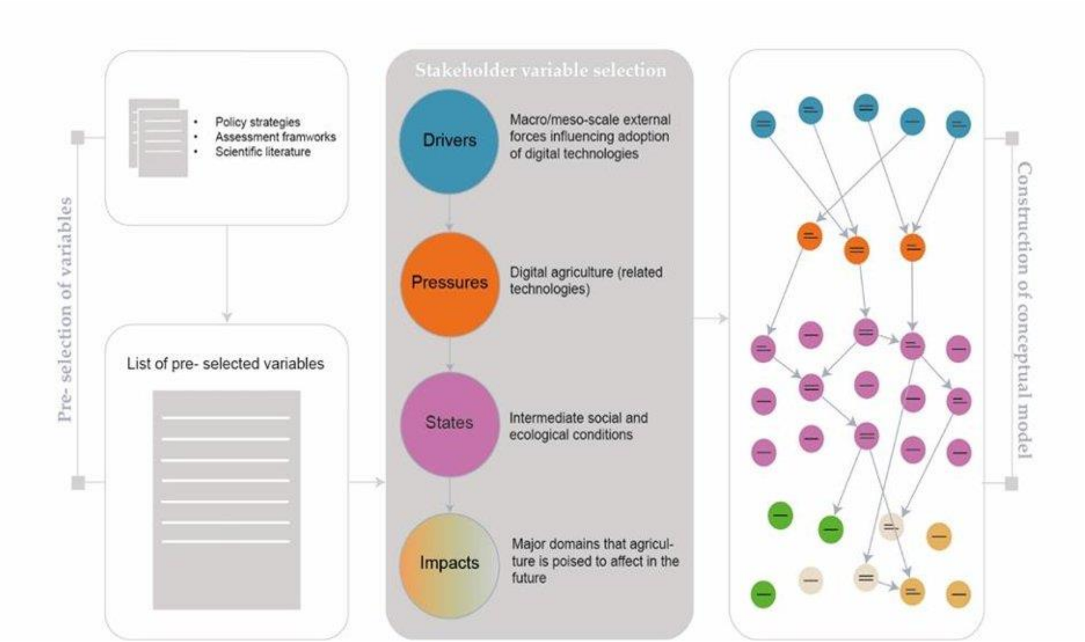

Figure 3 Variable selection and construction of conceptual models using the DPSIR framework.

The list of pre-selected variables were categorized according to the DPSIR framework as a means to structure the variable selection and model construction processes (Tscherning et al. 2012; Bosch and Gabrielson 2003; Niemeijer and Groot 2008). Consisting of Drivers (D), Pressures (P), States (S), Impact (I), and Response (R), the DPSIR framework analytical tool highlights cause-effect relationships in nature-human interactions (Bosch and Gabrielson 2003). In our study, the Drivers category represented macro- and meso-scale external factors (e.g. subsidies, producer prices, costs of digital technologies) influencing the adoption of agricultural digitalization. The Pressures category was used to represent digital agricultural management as an intervention. The States category represented intermediary social and ecological conditions (e.g. ecosystem connectivity, wages, health hazards) that lead to Impacts. The Impacts category represented major domains of influence that agriculture is expected to have in the future (e.g. biodiversity, food security, regional identity). The Response category represents actions taken by society to affect impacts by influencing other elements, including Drivers, Pressures and States within the system. These actions commonly involve policy measures related to compensation, prevention and adaptation. To facilitate a focused analysis of the impacts arising from digital agriculture and streamline the assessment process, the study deliberately excluded responses from consideration.

Given the complexity of interactions in agricultural systems, it was necessary to narrow down the range of variables considered for developing the BBN to a manageable number. Considering this and in order to stay within the time limits of the workshops, we imposed constraints on the number of variables each group was allowed to select. The focus of the study was on identifying Impacts (differentiated with 9 variables) of digital agricultural management (Pressure, differentiated with 3 variables). However, we recognize there may be a multitude of intermediate processes that connect digital agriculture management with impacts. Therefore, we decided to allow for a higher limit on the maximum number of States, or intermediate variables, that could be included in the model (20 variables). Lastly, we allowed for 5 variables to differentiate the Drivers. The decision on the number of variables stem from earlier experiences with participatory assessment workshops (König et al. 2013; Hermanns et al. 2017; Hamidov et al. 2022). To provide a familiar means to the workshop participants for conceptualizing system components, the variables in the Impact and State categories were divided according to environmental, economic and social dimensions. To promote a fair and balanced approach to selecting Impacts, we instructed the participants to choose three Impact variables from each of the three dimensions of sustainability, with the aim of ensuring that each dimension is given equal consideration in the modelling process.

After completing the variable selection process, the groups were instructed to arrange their variables into network diagrams using arrows to indicate causal relationships between the variables. With the help of a moderator, the group participants were encouraged to draw as many connecting arrows as possible, while explaining the reason behind these connections as they were made. The conceptual models of each stakeholder group can be seen in the Supplementary Material III.

2.4.2 Desk analysis: construction of a unified conceptual model

After the first workshop, the three individual conceptual models of the stakeholder groups were merged into a unified conceptual model. To limit model size and complexity, only variables that were common to two or more of the three stakeholder group models were included in the unified conceptual model. All connecting arrows between these common variables as found in the individual conceptual models were included in the first elaboration of the unified conceptual model.

2.4.3 Workshop 2: Discussions of individual group models and joint conceptual model

In the second workshop, similarities and differences between the individual stakeholder conceptual models were highlighted and mixed-group discussions were held to allow for in-depth exchanges on viewpoints between groups. After that, the participants were divided back into their respective stakeholder groups, where they were presented the unified conceptual model. The participants were then requested to review the model for logical consistency, such as clarifying the reasoning behind connections, while identifying superfluous and missing connections. Their feedback was then later incorporated into the second elaboration of the unified conceptual model. The unified conceptual model of the three stakeholder groups can be seen in Supplementary Material III.

During this workshop, participants were also introduced to the Digital agriculture variable (i.e. Pressure) and the specific digital agricultural technologies encompassing it, as selected by the groups in the first workshop. To simplify, these technologies were bundled under one variable, which was assigned varying degrees of digital integration: intensive digitalization, moderate digitalization, and limited digitalization (corresponding to business-as-usual) (Table 1). The delineations for these distinct degrees of digitalization were partially drawn from the work of Dönitz et al. (2020) and were employed to provide comprehensive descriptions and a common understanding among participants.

Table 1 Different levels of digitalization as used in the BBN for Digital agriculture variable.

Degrees of digital integration	
Intensive	Sensors and automated decisions (artificial intelligence) are fully integrated at every stage of production. Drones and small autonomous robots are widespread. Farmers are contractually integrated into larger systems/associations, and management is carried out at a higher level with the support of artificial intelligence. Precise use of inputs and environmental impacts are monitored in real time.

Moderate	Mixture of large, manually operated machines and small autonomous robots. Precision farming is used to reduce environmental impacts. Some sensors and robots are used to monitor plant and animal health and soil moisture. Farmers use apps and other decision support systems to follow real-time developments.
Limited (BAU)	Only certain parts of the cultivation process are digitized and most of the processes are analog, performed by humans and large machines (e.g. tractors with GPS-RTK). Digital technology is only used to support analog processes. This scenario represents business as usual.

2.4.4 Desk analysis: indicator selection for unified conceptual model

Following the second workshop, the system variables of the unified conceptual model were assigned indicators. This was done for two reasons: first, to transfer the qualitative conceptual model into a quantitative one and, second, to become more precise about the variables and their interactions for the next workshop. Through a review of the literature, policy documents and expert consultations, a set of Brandenburg-specific indicators for the variables in the unified conceptual model was produced. This set of indicators was then sent via email to the workshop participants for their feedback. After receiving and incorporating their feedback, the authors assigned discrete values to each indicator in order to reasonably describe a condition the variable could possess in the case study region. This was also done through literature analysis. Additional information, including sources, on the indicators used in the BBN is available in Supplementary Material II.

2.4.5 Workshop 3: quantifying probabilities

In the third workshop, probability estimates were elicited from the stakeholder groups for quantifying the conditional probability distributions of the variables in the network. For each group, a set of blank CPT formulas were provided where they were requested to input percentage probabilities that aligned with their expertise and knowledge. Due to time limitations, it was not feasible for each group to derive estimates for all CPTs. Instead, the groups were assigned a limited number of CPTs to complete. Certain CPTs were completed by all three groups, specifically focusing on variables and connections that were shared among their conceptual models. Estimates from CPTs that were common to each group, were summed and averaged as input for the final model.

2.4.6 Desk analysis: analysis of workshop results in Netica

The elicited network structure and CPTs obtained from the workshops were then entered into Netica. We then ran scenario analyses on the Bayesian network using different degrees of digitalization to observe marginal changes in probabilities of nodes, allowing us to identify areas of certainty and uncertainty in the model.

2.4.7 Workshop 4: Presentation of results and reflection on process

In the fourth and final workshop, the participants were presented the final BBN and a short demonstration was conducted using Netica. An open discussion was held where the participants were given the chance to express their views on the BBN and the overall modelling process.

3. Results

Using the procedure outlined above, each stakeholder group developed a conceptual model to determine crucial agricultural system components affected by digitalization as well as the relationships that lead to these effects. The commonalities between the various conceptual models were then used to construct a unified BBN (Figure 4), portraying the three stakeholder groups' shared understanding of the impacts of agricultural digitalization. The unified Bayesian network included a total of 28 variables, consisting of 1 Pressure variable (i.e., digital agriculture), 4 Driver variables, 14 State variables and 9 Impact variables. The network contained a total of 47 causal relationships (i.e., conditional dependencies) between variables and 272 unique probability values quantifying these relationships.

Table 2 provides a comprehensive overview of the characteristics of variables within the Impact category, including indicators, corresponding values, and probability estimates for different degrees of agricultural digitalization. Table 3 presents the same respective details for variables within the State category, while Table 4 lists the Drivers and their corresponding indicators and values.

In the following sub-sections, we outline key findings based on the analysis of the unified BBN related to Impacts, States, Pressures and Drivers. For the Impacts and States categories, we describe a scenario with an intensive degree of digitalization as compared with a limited degree of digitalization (i.e., business as usual). To assess the level of certainty regarding the effects of digitalization for each variable, we adopted a categorization technique. This involved categorizing the variable range of probabilities, derived from the percentage point difference between intensive and limited degrees of digitalization, which spanned from 0% to 56%, taking all variables into account. The resulting categorization scheme consisted of three equally partitioned levels: low certainty (0-18%), medium certainty (19-38%), and high certainty (39-56%).

3.1 Impacts

A total of nine Impact variables and respective indicators were included in the unified BBN, representing the key impact areas that agriculture in Brandenburg is likely to influence in the future (Table 2). According to the stakeholders in our study, digitalization is perceived to have a positive impact on *Resource use efficiency* (with medium certainty), specifically in terms of reducing the carbon footprint per product. This is primarily attributed to two main factors: decreased energy consumption of diesel fuel and reduced usage of synthetic fertilizers, both of which contribute to greenhouse gas emissions (e.g., regarding the usage of fertilizers, the indirect emission associated with their production is emphasized). *Economic stability*, or variability in revenue from crop production, is expected to be positively impacted by digitalization (with medium certainty), primarily through increased product diversification and decreased variability of yields, two factors that are strongly influenced by improved risk management. *Water quality*, specifically the nitrate concentrations in water wells, is expected to improve (with medium certainty) through the reduction of nitrogen fertilizer inputs as a result of site-specific fertilizer application. Digitalization was perceived to have a marginal positive effect on *Food quality and security* (with low certainty). The impacts of digital agriculture on *Biodiversity*, particularly farmland bird abundance, and *Regional value chains*, measured by the share of agricultural products marketed locally, are unclear. Regrettably, due to time limitations in the workshops, it was not possible to obtain the CPTs for the Impact variables on *Societal appreciation for the agricultural sector*, *Soil quality*, and *Productivity*.

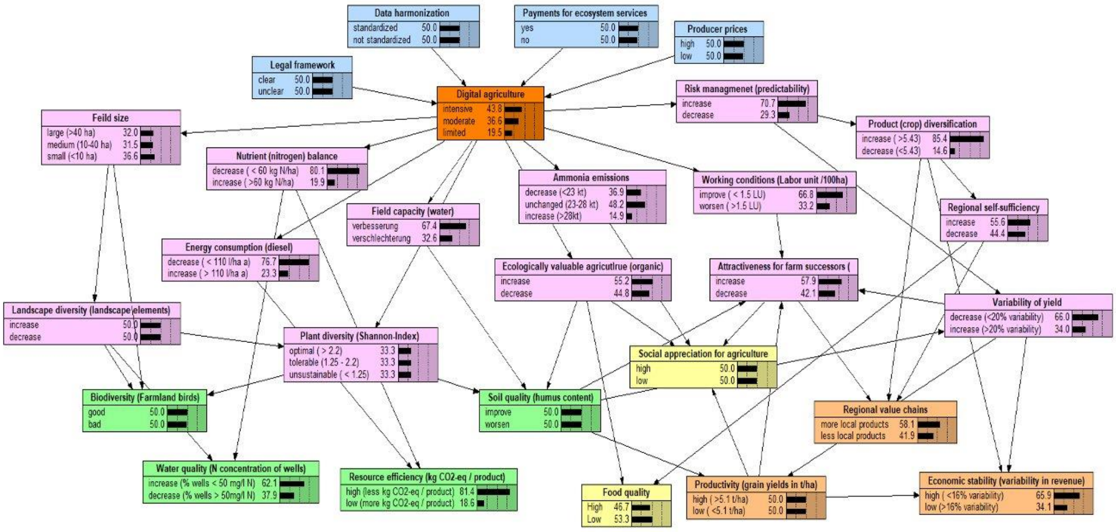

Figure 4 The unified Bayesian belief network (BBN) in Netica. Blue variables = Drivers; orange variable = Pressure; pink variables = States; Green/Yellow/light Orange = environmental/social/economic impacts.

Table 2 Impact variables, corresponding indicators, values and probabilities under different degrees of digitalization.

Impacts			**Degree of digitalization**			
Variable	**Indicator**	**Value**	**Limted (BAU)**	**Moderate**	**Intensive**	**Level of certainty**
Biodiversity	Farmland bird occurrence	Good	50,2%	50,2%	50,2%	Low
		Bad	49,8%	49,80%	49,8%	Low
Economic stability	Variability in revenue from crop production (€/ha UAA)	High (<16% variability)	47,2%	70,0%	75,2%	Medium
		Bad (>16% variability)	52,8%	30,0%	24,8%	Medium
Food quality	Not defined	High	41,2%	44,6%	50,9%	Low
		Low	58,8%	55,4%	49,1%	Low
Productivity	Yield in t/ha (only grains)	High (> 5.1 t/ha)	N/A			
		Low (< 5.1 t/ha)				
Regional value chain	Share of agricultural products that are marketed locally/regionally	More local products	50,9%	58,4%	61,0%	Low
		Less local procucts	49,1%	41,6%	39,0%	Low
Resource efficiency	kg CO_2-eq/product	High (fewer kg CO2-eq/product)	60,0%	78,8%	93,2%	Medium
		Low (more kg CO2-eq/product)	40,0%	21,2%	6,8%	Medium
Social appreciation of the agricultural sector	Not defined	High	N/A			
		Low				
Soil quality	Humus content	Good	N/A			
		Bad				
Water quality	Share (in %) of wells with a nitrate concentration of 50 mg/L	Increase (% wells < 50 mg/l N)	43,9%	59,4%	72,3%	Medium
		Decrease (% wells >50 mg/l N)	56,1%	40,6%	27,7%	Medium

3.2 States

The unified BBN encompassed fourteen state variables and their corresponding indicators, effectively capturing the intermediate processes that link digital agriculture to its impacts (Table 3). The analysis highlights the considerable positive influence of digitalization on *Risk management* (with high certainty), specifically through enhanced risk predictability, facilitated by data-driven decision support tools and Artificial Intelligence (AI). This improvement in risk management is expected to have positive impacts on *Product diversification*, measured by the average number of crops per farm, and the mitigation of *Variability of yield* for a typical crop rotation in Brandenburg (with medium certainty). Furthermore, the BBN suggests that *Nutrient balance* will improve (with medium certainty) by optimizing the application of synthetic nitrogen fertilizers using data-driven, site-specific approaches of precision farming. Moreover, by substituting diesel-powered machinery with electric-powered field robots, digital agriculture is likely to decrease *Energy (diesel) consumption* (with medium certainty). A shift towards automation will also contribute to improved *Working conditions* for farmers (with medium certainty), allowing farmers to work larger areas of land in less time, positively impacting the *Attractiveness of farming as a profession for successors* (with low certainty). Additionally, the utilization of lightweight field robots instead of heavy machinery is expected to mitigate soil compaction, resulting in an increase in *Field (water holding) capacity* (with medium certainty). Digitalization and site-specific fertilization were not anticipated to have a significant effect on reduction in *Ammonia emissions* (with low certainty). There was only a slight inclination towards smaller *Field sizes* (with low certainty) through the adoption of autonomous crop machines. The impact of digitalization on variables such as *Regional self-sufficiency*, *Ecologically valuable agriculture*, *Plant diversity*, and *Structural diversity of landscapes* remained uncertain.

Table 3 State variables, corresponding indicators, values and probabilities under different degrees of digitalization.

State variables			**Degree of digitalization**			
Variable	**Indicator**	**Value**	**Limited (BAU)**	**Moderate**	**Intensive**	**Level of certainty**
Ammonia emissions	NH_3 emissions (in kt) from the agricultural sector	Decrease (< 23,7 kt)	27,8%	32,8%	44,4%	Low
		Unchanged (23-28 kt)	51,1%	51,1%	44,4%	Low
		Increase (> 28 kt)	21,1%	16,1%	11,2%	Low
Attractiveness for farm successors	Share (%) of farm managers under 55 years old	Increase	47,5%	56,6%	63,5%	Low
		Decrease	52,5%	43,4%	36,5%	Low
Ecologically valuable agriculture	Share (%) of organic farms in the total agricultural area	Increase	46,7%	50,0%	63,3%	Low
		Decrease	53,3%	50,0%	36,7%	Low
Energy consumption	Average diesel consumption in L/ha-a	Decrease (< 110 L/ha-a)	53,3%	73,3%	90,0%	Medium
		Increase (> 110 L/ha-a)	46,7%	26,7%	10,0%	Medium
Field capacity (water)	% Vol. of water available to plants in the root area up to 100 cm	Increase	46,7%	63,3%	80,0%	Medium
		Decrease	53,3%	36,7%	20,0%	Medium
Field size	Average field size in hactares	Large (> 40 ha)	58,3%	48,7%	43,8%	Low
		Medium (10 – 40 ha)	23,1%	25,6%	25,7%	Low
		Small (< 10 ha)	18,6%	25,7%	30,5%	Low
Nutrient balance	Nitrogen balance	Decrease (< 60 kg N/ha)	56,7%	76,7%	93,3%	Medium
		Increase (> 60 kg N/ha)	43,3%	23,3%	6,7%	Medium
Plant diversity	Shannon index (HS)	Optimal (>2.2)	37,5%	37,5%	37,5%	Low
		Tolerable (1.25 - 2.2)	31,2%	31,2%	31,2%	Low
		Unsustainable (<1.25)	31,2%	31,2%	31,2%	Low
Product diversification	Average number of crops per farm	Increase (> 5.43)	65,0%	85,0%	93,3%	Medium
		Decrease (< 5.43)	35,0%	15,0%	6,7%	Medium
Regional self-sufficiency	Percentage of food produced and consumed in a region	Increase	49,5%	56,0%	58,0%	Low
		Decrease	50,5%	44,0%	42,0%	Low
Risk management	Risk predictability	Increase	30,0%	73,3%	86,7%	High
		Decrease	70,0%	26,7%	13,3%	High
Landscape diversity	Share (%) of the area of landscape elements in the total agricultural area	Increase	50,0%	50,0%	50,0%	Low
		Decrease	50,0%	50,0%	50,0%	Low
Working conditions for farmers	Labor Unit per hectare	Decrease (< 1.5)	50,0%	60,0%	80,0%	Medium
		Increase (> 1.5)	50,0%	40,0%	20,0%	Medium
Variability of yield	Coefficient of variation for typical crop rotation	Decrease (< 20%)	39,5%	67,6%	76,4%	Medium
		Increase (> 20%)	60,5%	32,4%	23,6%	Medium

3.3 Pressures

In order to highlight the diverse array of technologies falling under the umbrella of digital agriculture, eight specific technologies were identified between the three stakeholder groups: artificial intelligence, DSS, variable rate technologies, sensors, GPS, satellites, yield maps, and robotics. These technologies were subsequently bundled together under a single pressure variable named *Digital agriculture* in the unified BBN with varying degrees of digital integration (see Table 1 in Section 2).

3.4 Drivers

The Drivers category includes several key variables that influence the adoption and implementation of digital agriculture (Table 4). Based on agreement between the stakeholder groups, four drivers were included in the unified BBN. One important driver of agricultural digitalization is *Data harmonization*, which involves the standardized exchange and integration of data across digital devices and databases. Another driver is the *Legal framework* surrounding agri-digital practices. For example, clear and encouraging agri-digital laws can promote the widespread adoption of digital technologies in agriculture, while unclear and discouraging laws may hinder their progress. *Payments for ecosystem services* also play a role in driving the adoption of digital agriculture. For example, subsidies that support technology-assisted agricultural measures can incentivize farmers to adopt these practices and support ecosystem service provision. Lastly, *Producer prices*, measured by the producer price index, impacts the revenue and cost situation in agriculture¸ thereby affecting a farms ability to invest in new equipment and machinery.

Table 4 Selected Drivers, indicators and values of agricultural digitalization.

Drivers

Variable	**Indicator**	**Value**
Data harmonization	Standardized data	Standardized Not standardized
Legal framework	Agri-digital law	Clear, supportive Unclear, unsupportive
Payments for ecosystem services	Subsidies	Yes No
Producer prices	Producer price index	High Medium Low

4. Discussion

Our study highlights potential impacts of digital agriculture as perceived by key stakeholder groups from the Brandenburg region. Through a participatory BBN approach, system knowledge and uncertainties regarding the impacts of digitalization were made explicit, including a set of indicators to further describe these impacts. The participants in our study agreed that resource efficiency and economic stability will benefit from digitization. These features appear to be strongly supported by precision farming and improved risk management, respectively. However, the effects of digitalization on biodiversity-related factors appear to be more ambiguous, with impacts to landscape diversification acknowledged but unclear. By successfully establishing a co-learning environment and enabling in-depth exchange of viewpoints on digitalization, our method for developing a group model using a BBN approach has demonstrated its value as a participatory modelling tool.

4.1 Digitalization and resource savings

The stakeholders of our case study perceived that digital agriculture will lead to a more efficient use of resources, such as fuel, fertilizer, and labor, which is consistent with the majority of research and asserted benefits on the topic (Basso and Antle 2020; Finger et al. 2019; Balafoutis et al. 2017 Schimmelpfennig 2016). It is not unexpected that stakeholders held this opinion given that some farmers in the area, including those involved in our study, have been using precision farming technologies such as GPS guidance and yield mapping for many years now (Rohleder et al. 2020). Additionally, specific precision farming technologies, such as variable rate spraying, have been accessible in the market for quite some time, though their adoption remains low (Nowak 2021). More importantly, stakeholders also pointed out the value of these technologies in relation to addressing broader environmental, social, and political challenges the region's agriculture sector is currently facing.

For instance, the group of farmers brought up a concern regarding the use of nitrogen fertilizers and expressed that the agriculture industry is under constant political pressure to decrease N-fertilizer inputs, as mandated by the EU Nitrates Directive 91/676/EEC. To address this issue, the group of farmers suggested that digitization could play a role in ensuring regulatory compliance through improved data analytics and minimizing nitrogen fertilizer usage by enhancing the efficiency of site-specific fertilizer application methods. However, it is important to note that workshop participants also expressed skepticism about the use of nitrate concentration in water wells as an appropriate indicator for assessing progress toward reducing N fertilizers inputs because nitrate leaching into groundwater is a non-point source of pollution that occurs gradually over decades, making it difficult to attribute nitrogen pollution of groundwater to a specific farming practice at a specific time (Bijay-Singh and Craswell 2021). It was also suggested in the workshop that linking digital agriculture to surface water discharge of nitrates would present similar challenges (Steidl et al. 2022). This point generally suggests that in some cases the quantifiable environmental benefits of digital agriculture may need to be considered over longer time horizons than that of the current study and that utilization of diverse data sources, such as those derived from modelling outcomes, may be more suitable for estimating variable impacts of environmental measures at larger scales (Ehlers et al. 2021).

Given persistent labor shortages of farm workers (permanent and seasonal) in the case study region (Prause 2021), our group of stakeholders had a favorable impression of the potential labor-saving aspects as well as improved working conditions that digitalization could entail. For instance, it was mentioned by the workshop participants that automation would reduce the amount of a farmer's working hours, which would improve attractiveness of the farming profession and, thereby, attract permanent workers and farm successors. It was also mentioned that a higher degree of automation (e.g. self-driving tractors) would make certain tasks easier, reducing the amount of skills needed for performing certain tasks and thereby attracting capable workers. These results somewhat contradict arguments made in the literature, where there has been a significant deal of concern over the 'de-skilling' and displacement of workers due to digitalization (Carolan 2020; Rotz et al. 2019; (Zscheischler et al. 2022; Prause 2021). However, it should be highlighted that the majority of studies on labor displacement frequently focus on seasonal laborers and, more specifically, horticulture systems that rely heavily on low-skilled, manual labor. The difference in viewpoints here is because large-scale arable farming (mainly grains, maize, rape seed) is the predominant mode of production in our case study region, which necessitates a certain level of expertise and training to operate relatively complex farm machinery such as tractors and harvesters. Of course, for farmers to operate more advanced machinery, they will also be required to learn new (digital) skill sets. Here, we should expect that the quality of work would change for farmers, as they would take on new roles in managing their enterprise, which could also impact job satisfaction (Rose and Chilvers 2018). Overall, this indicates that when examining the potential implications of digitalization on labor, a differentiated assessment of local labor markets, potential alternatives and pertinent farming operations is required.

In light of rising oil prices and mounting public pressure to halt climate change, digitalization may be advantageous (Pearson et al. 2022). Participants in our case study believed that digital agriculture, e.g. electrification, field robots and precise fertilizer application, would result in fuel savings (diesel) and lower carbon emissions per product. However, as it was not taken up in the BBN, it is important to note that a highly digitalized agriculture at scale and the energy required to power data centers, drones, robots, sensor networks and electric tractors require significant amounts of energy, which, depending on the source, may not result in a substantial overall reduction of carbon emissions (Leroux C 2020). Similarly, indirect rebound effects from digitalization should also be considered (Lange et al. 2020). Although it falls outside the boundaries of this study, it is worth mentioning that while evaluating the carbon footprint of digital agriculture, it is also important to take into consideration the fact that the manufacture and disposal of electronic equipment also entail carbon emissions (Singh and Ogunseitan 2022). A clearer understanding of whether digital agriculture would ultimately result in lower carbon emissions from farming activities could be obtained through Life Cycle Assessment (LCA). However, to date, there appears to be a research gap on LCA studies applied to digital agriculture technologies and digital agricultural systems.

While there is currently a lack of studies focusing on how digital agriculture could affect soil water retention, there is evidence that tractor-induced soil compaction reduces water infiltration (Keller et al. 2019). This concern was raised by the stakeholders in our study. It was proposed that lighter-weight autonomous machinery could replace heavy, manually-operated tractors, thus decreasing soil compaction (i.e. soil bulk density) and improving infiltration and soil water-holding capacity. Although time constraints prevented us from deriving probability estimates for the Soil quality variable, it is key to emphasize the importance of soil water holding capacity for soil quality, particularly for farmers in our case study region, as decreasing precipitation and increasing severity of droughts continues to be a major issue affecting productivity and plant health (Reyer et al. 2012; Wolff et al. 2021). This suggests that digitalization could have important ramifications for soil health and climate change adaptation in the future, meriting further scientific exploration.

4.2 Supporting economic robustness through digitalization

In our study, stakeholders acknowledged the potential of digital agriculture to contribute to regional economic stability by mitigating major sources of uncertainty associated with environmental and market risks. Data-driven decision-making has the capacity to improve risk management and foster economic resilience during phases of market instability (McFadden et al. 2022; Wolfert et al. 2017). Specifically, in terms of weather risks, the utilization of agri-climatic databases in conjunction with big data analytics (AI) can assist farms in adapting to climate change and identifying hazards related to weather extremes, thereby enhancing production stability at specific sites (Martinez-Feria and Basso 2020). Considering the impact of increased weather extremes on production (Webber et al. 2020) and the (in-) stability of crop yields in the region (Macholdt et al. 2021; Döring and Reckling 2018), it was logical for the stakeholders in our workshop to recognize the potential of leveraging digital technologies to address such risks.

Similarly, a farmer's willingness to diversify their production systems may also be constrained by production risks. In this regard, digital agriculture could improve risk management related to crop diversification (Hernández-Ochoa et al. 2022). The participants agreed that better decision support could reduce production risks associated with introducing new crops as well as provide better market analytics on consumer demand for new products. In turn, crop diversification could improve economic stability (von

(Czettritz et al. 2023) and ecosystem functionality (Tamburini et al. 2020). However, due to region-specific policies in Germany subsidizing the production of certain types of energy crops, more diverse crop portfolios do not necessarily translate into a higher stability of income for farmers (Weigel et al. 2018). That means that regions characterized by larger farms specializing in energy crop production may not benefit from increased crop diversification. Considering this and given the relatively large farm sizes and high levels of energy crop production in Brandenburg, digitalization to facilitate crop diversification may have limited impact on reducing economic risks and promoting regional economic stability. On the other hand, as pointed out by the stakeholders in our study, higher crop diversity within a region can promote regional value chains and regional self-sufficiency (Vicente-Vicente et al. 2021). However, both factors are strongly dependent on regional consumption habits (Zasada et al. 2019), a driving factor not explicitly included in the unified BBN.

4.3 Uncertainties concerning the impacts of digitalization on landscape diversification

Uncertainty is pervasive regarding how digitalization will affect the structural diversity of landscapes. On the one hand, the stakeholders in our study perceived that digital agriculture, specifically autonomous crop machines, could lead to smaller average field sizes. On the other hand, it was not clear whether smaller field sizes would result in an increase or decrease of landscape elements and structures, since automation might open what was once considered unproductive, marginal land to more intensive agronomic management, thereby reducing the amount of land available for semi-natural habitats. Similar results based on stakeholder perceptions were shown in other studies (Zscheischler et al. 2022). However, digitalization might boost productivity per unit of land, reducing the amount of land required to generate the same quantity of output, freeing up — or at least maintaining — land for natural features that support habitat quality (Daum 2021).

Historical context may help shed light on the source of this ambiguity. For example, in the past, technological innovation, specifically mechanization and economies of scale, have resulted in ever-larger field and farm sizes, monocultures and a notable reduction of landscape elements in the case study region (DBB 2001). If digitalization is seen as a continuation of this historical tendency toward increasing mechanization and economies of scale, then it is reasonable to believe that productivity- and efficiency-driven digitalization could lead to more of the same (Lajoie-O'Malley et al. 2020). However, recent political and social developments indicate movement in the opposite direction. As pointed out by the stakeholders in our case study, policymakers and consumers today are becoming more aware of the detrimental consequences that conventional, large-scale agriculture has on the environment, and as a result, they are placing more pressure on farmers to operate sustainably and to ‘think’ on smaller scales. Moreover, there appears to be a growing trend among farmers in the region to embrace funding from the EU's Common Agricultural Policy by incorporating greening measures. However, the success of such measures till now has been limited and varies according to region (Gocht et al. 2017). Ehlers et al. (2021) suggested that digitalization may significantly lower costs related to monitoring such agri-environmental policy instruments in the future and lead to new forms of results-based payments tailored to local conditions. In this respect, digitalization could be an important tool for promoting biodiversity-related societal objectives under the right political guidance and legal framework (MacPherson et al. 2022; Garske et al. 2021). Additionally, building on practical research in this field could facilitate the implementation of greening measures in the future (Mouratiadou et al. 2023).

It is important to reiterate that the impacts on biodiversity resulting from digitalization may manifest over longer time periods than that used for modeling in the current study (i.e. 10 years), which could partly account for the ambiguity of stakeholder perspectives in our study surrounding this topic. In other words, while the rapid digitalization of agriculture is a plausible scenario, its effects on biodiversity through, for example, changes in landscape elements, may not be immediately observable due to time lags (Fahrig et al. 2011). Overall, the findings suggest that the impacts of digitalization on biodiversity-related factors are not obvious to stakeholders, which may be due to lack of evidence base (Finger et al. 2019), or insufficient communication between researchers and other stakeholders.

4.4 Reflections on the method

The construction of the BBN encouraged collaboration among the stakeholders in our case study by giving them a platform to exchange ideas and knowledge. In this way, through the graphical representation of the BBN and the quantification of uncertainties of causal effects via probabilities, stakeholders were able to transparently see how their knowledge was incorporated in the BBN model. By representing system components and their interactions in a graphical structure, it was easier for the stakeholders in our study to communicate their understanding of agricultural digitalization to others, which helped with facilitating discussion and learning (Barbrook-Johnson and Penn 2022). Consequently, the BBN served as a 'boundary object' (Kenny and Castilla-Rho 2022), bridging the different perceptions of the participants, allowing us to develop a mutual understanding on the issues at hand, while helping to mitigate emotion to the greatest possible extent during discussion. Similarly, by utilizing indicators as selected by our group of stakeholders, it was possible to attain greater clarity and mutual understanding, thus further mitigating emotions. While indicators are frequently applied in quantitative studies, their incorporation of stakeholder perspectives often remains limited. In contrast, qualitative studies often deal with themes or topics that are broad and less well defined. Through the substantiation of variables with quantitative indicators, the combined strengths from both quantitative and qualitative domains can be utilized, as demonstrated by this study. Nevertheless, it is essential to acknowledge that the indicators employed in our BBN are tailored to the unique circumstances of Brandenburg. Therefore, it is important to recognize that utilizing the same approach as ours in a different location would necessitate the use of a distinct set of indicators.

There was a startling lack of negative impacts resulting from digitalization included in the BBN. This finding is unexpected considering the numerous concerns raised in existing literature and the initial skepticism expressed by participants in our study regarding digitalization. However, this outcome can be explained through the drivers that our stakeholders selected, as they essentially lay the foundation for optimizing the use of digital technologies. For example, without supportive agri-digital regulations in place, farmers face the risk of losing control over their data (Härtel 2021). This could subsequently create power imbalances between farmers and larger agri-tech companies (Birner et al. 2021; Clapp and Ruder 2020), a concern voiced by the farmers' group in our workshop, thus potentially leading to lower adoption rates and negative externalities.

The selection of representative stakeholders is indeed a critical aspect of participatory modeling because it directly influences the success and relevance of the model's outcomes. Here, the primary objective was to establish a selection that accurately reflects the diverse range of local interests. Hence, in our study, we aimed to engage farmers, for example, who represent the general agricultural landscape in Brandenburg, including those engaged in large-scale arable farming, two of which practicing conventional methods, and one who recently transitioned to organic farming. Interestingly, all farmers in our workshop reported using some sort of digital technologies in their daily business operations, including the use of farming apps, GPS-guided tractors, and engagement with social media. However, at least during the initial stages of the workshop series, there were varying and somewhat emotional opinions concerning the subject of digitalization within the farmers group. For example, some participants held skepticisms regarding the effectiveness of digital technologies, questioning their ability to match the value of traditional experience and expertise. Yet, simultaneously, these individuals believed that digital tools could simplify certain tasks in the future. It is challenging to discern the extent to which these farmers' pre-existing beliefs influenced related uncertainties and the model's ultimate outcomes. Nonetheless, we were pleasantly surprised by the level of engagement exhibited by our stakeholders throughout the workshops, as well as the favorable feedback received from farmers when we presented them the final BBN.

We would also like to acknowledge some limitations of the study. While the co-development process placed a strong emphasis on iterative and in-depth discussions to select variables and explore their causal interactions, it is important to recognize the potential presence of latent variables not explicitly accounted for in the BBN model, which might contribute to ambiguities in perceptions and, consequently, uncertainties in model outcomes. This is linked in part to the broad level analysis of the case study region, which limited the level of specificity and detail contained in the BBN. Here, it is important to note that unique characteristics and dynamics of landscape scale interactions may have been overlooked, undermining the generalizability of the outcomes from our study. Future research may therefore benefit from applying the same participatory BBN approach on a sub-regional or smaller scale, while using the results of this study as a foundational reference for exploring societally relevant questions regarding the impacts of digitalization. That being said, however, through using conditional probabilities in BBNs it is still possible to capture elements from the wider system in the analysis and discussion, even if not explicitly included in the network. Non-zero probabilities in certain scenarios, such as the occurrence or non-occurrence of outcomes given specific interventions, represent the influence of "everything else going on in the system," providing an important aspect in the elicitation process (Barbrook-Johnson and Penn 2022). This highlights the notion that participatory BBNs are better suited as a tool for facilitating discussions and co-learning, rather than serving as a decision support tool (Cain 2001). However, it is worth mentioning that participatory BBNs have been utilized in both capacities many times in the past (Duespohl et al. 2012).

Another important limitation of the study should be mentioned. Although it was possible to derive probability estimates for the majority of CPTs within the given timeframe of the workshops, several CPTs were left blank due to time limitations. To overcome this, we suggest the use of alternative elicitation methods. For example, 3-point elicitation methods may reduce fatigue of participants by simplifying the probability estimation process (Cain 2001). Use of improved elicitation methods will enhance data completeness, maintain participant engagement, and ultimately improve the overall quality and reliability of results.

5. Conclusions

The transition to digital agriculture is poised to bring about significant systemic changes that will have far-reaching impacts on production, consumption, governance, and the environment of agricultural systems. Therefore, the objective of this study was to investigate the impacts of digitalization on agricultural systems by engaging stakeholder knowledge and values, specifically focusing on the Brandenburg region. To achieve this, our study employed a participatory modelling approach to co-construct a Bayesian belief network with key stakeholder groups from the area, including farmers, researchers and representatives from civil society organizations and public administration.

Through our study, we found that there is a significant amount of uncertainty among stakeholders regarding aspects related to landscape heterogeneity and resulting impacts on biodiversity. There is need, therefore, for additional empirical research to assess the impacts of enhancing landscape heterogeneity on biodiversity through the lens of digitalization. Once more evidence is ascertained on this topic, it will be important for research and policy endeavors to effectively communicate these effects to stakeholders. Here, effective communication between research and the public still seems to be lacking. However, there was more certainty regarding the socioeconomic benefits of digitalization, specifically in terms of promoting economic stability through enhanced risk management, as well as knock-on effects of improved resource use efficiency on certain environmental factors. Therefore the alignment of stakeholders' perceptions with the existing literature regarding resource use efficiency and economic robustness validates general claims already made. Overall, the consensus among stakeholders regarding the interplay between digitalization, risk management, and diversification warrants closer attention, as it could potentially serve as a strong lever for utilizing digital technologies to promote economic robustness. To date, however, there has been a limited amount of research examining this relationship.

Our study also makes important contributions to our understanding of the various perspectives about digitalization according to key stakeholder groups in the region, which can direct future research initiatives in conveying the possibilities and implications of digital agriculture to a larger societal audience. In general, by recognizing and addressing differing perspectives, we can bridge the gap between stakeholders and researchers, facilitating a more inclusive and informed dialogue and, consequently, promoting research that is socially and environmentally more responsible.

Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Supplementary Material

Supplementary Material I

Table 1. List of work workshop participants and their backgrounds

Stakeholder groups	Background
Farmers	1. Conventional arable farming 2. Conventional arable 3. recently switched to organic arable farming
Researchers	1. Agroforestry/soil science *(ZALF)* 2. Agricultural economics *(ZALF)* (only 1st and 2nd workshop) 3. Hydrology *(ZALF)* 4. Biodiversity in agricultural systems *(ZALF)*
Civil society	1st workshop: 1. Representative from Brandenburg's Ministry of Rural Development *(Ministerium für Ländliche Entwicklung, Umwelt und Landwirtschaft des Landes Brandenburg)* 2. Representative from the Office for Agriculture and Environment of the Märkish-Oderland district *(Landkreis Märkisch-Oderland Amt für Landwirtschaft und Umwelt)* 3. Representative of the German Association for Landscape Conservation *(Deutscher Verband für Landschaftspflege)* 4. Representative of the German Conservation Union in Brandenburg *(NABU Brandenburg)* 2nd and 3rd workshop: 1. Same representative from Brandenburg's Ministry of Rural Development *(Ministerium für Ländliche Entwicklung, Umwelt und Landwirtschaft des Landes Brandenburg)* 2. A different representative from the Office for Agriculture and Environment of the Märkish-Oderland district *(Landkreis Märkisch-Oderland Amt für Landwirtschaft und Umwelt)* 3. The mayor of a village in the region

Table 2. List of impact areas the stakeholders had to select from in the first workshop, with the original terms in German.

Impact areas *(Wirkungsbereiche)*	
Environment *(Umwelt)*	Adaptation to climate change *(Klimaanpassung)* Biodiversity *(biologische Vielfalt)* Climate change mitigation (CO2 sequestration) *(Klimaschutz (CO2 Speicherung))* Erosion protection *(Erosionsschutz)* E-waste production *(Elektroschrottproduktion)* GHG emissions *(Treibhausgasemissionen)* Nature conservation areas *(Naturschutzflächen)* Resource efficiency *(Ressourceneffizienz)* Soil quality *(Bodenqualität)* Unforeseeable environmental damage *(unvorhersehbaren Umweltschäden)* Vulnerability to weather extremes *(Anfälligkeit für Wetterextreme)* Waste production *(Abfallaufkommen)*

	Water availability *(Wasserverfügbarkeit)* Water quality *(Wasserqualität)*
Social *(Sozial)*	Animal welfare *(Tiergerechtheit)* Attractiveness of the agricultural profession *(Attraktivität des landwirtschaftlichen Berufs)* Cooperation *(Kooperation)* Cybersecurity, data abuse *(Cybersecurity, Datenmissbrauch)* Food security and quality *(Ernährungssicherheit und –qualität)* Gender equality *(Geschlechergleichheit)* Health (OSH) *(Gesundheit (Arbeitsschutz))* Job satisfaction (Arbeitszufriedenheit*)* Landscape attractiveness *(Landschaftsattraktivität)* Regional identity *(regionale Identität)* Social appreciation of the agricultural sector *(Wertschätzung für Landwirtschaft)* Structural change *(Strukturwandel)* Traceability *(Rückverfolgbarkeit)* Traditions *(Traditionen)* Trust *(Vertrauen)* Vocational training *(Berufsausbildung)* Volunteer engagement *(ehrenamtliche Engagement)*
Economy *(Ökonomie)*	Business investments *(Geschäftsinvestitionen)* Economic incentives for ecosystem services *(wirtschaftliche Anreize für Ökosystemleistungen)* Economic independence, power symmetry *(wirtschaftliche Unabhängigkeit, Machtsymmetrie*) Economic stability *(wirtschaftliche Stabilität)* Growth (GDP) *(Wachstum (BIP))* Local economy (tourism, upstream and downstream sectors) *(lokale Wirtschaft (Tourismus, vor- und nachgelagerte Sektoren))* Profits *(Gewinne)* Rebound effects *(Rückkopplungseffekte)* Regional supply chains *(regionale Wertschöpfungsketten)* Yield *(Ertrag)*

Table 3. Pre-selected list of State variables used in the first workshop with the original terms in German.

Environmental (Umwelt)		
Nurtient balance (Nährstoffbilanz)	Plant diversity (Pflanzenvielfalt)	Locally adapted sort and races (lokal angepasste Sorte und Rassen)
Soil compaction (Bodenverdichtung)	Insect abundance (Insektenvorkommen)	Ecosystem connectivity (Ökosystem-Konnektivität)
Wild pollinators (wilde Bestäuber)	Pollutants in water (Schadstoff-konzentration im Wasser)	Bird abundance (Vogelvorkommen)
Use of animal residues (Verbrauch von Rückständen aus der Tierhaltung)	Landscape diversity (Strukturelle Vielfalt der Landschaft)	Nitrate leaching (Nitratauswaschung)
Nitrogen fertilizer use (N-Dünger Verbrauch)	Crop land area (Ackerlandfläche)	Phosphate fertilizer use (P-Dünger Verbrauch)

Field size (Feldgröße)	Water erosion (Wassererosion)	Linear landscape elements (lineare Landschafts-elemente)
Water use for irrigation (Wasserverbrauch für Bewässerung)	GHG emissions (Treibhaugasemissionen)	Fuel from plant origins (Treibstoff pflanzlicher Ursprung)
Wind erosion (Winderosion)	Ammonia emissions (Ammoniak-emissionen)	Energy use (Energieverbrauch)
Soil organic matter (Organische Substanz im Boden)	Abundance of earth worms Vorkommen von Regenwürmer)	Field water holding capacity (Nutzbare Feldkapazität (Wasser)
Wild game abundance (Wildvorkommen)	Grassland area (Grünlandfläche)	Cooling effects (Kühlungseffekt)
Use of crop residues Verbrauch von Ernterückständen)		
Economy (Ökonomie)		
Debt to income ratio for farms (Schulden-Einkommens-Verhältnis von landwirtschaftlichen Betrieben)	Net income (Nettoeinkommen)	Grassland yield (Ertrag (grassland))
Crop yield (Ertrag (Acker))	Transport costs (Transportenkosten)	Risk managment (Risikomanagement)
Stability of agricultural inputs (Stabilität lanwirtschaftlichen Inputs)	Wages (Lohn/Gehalt)	Yield stability (Ertragsstabilität)
Yield from livestock (Ertrag (Tierhaltung))	Job creation (Schaffung von Arbeitsplätzen)	Long-term investments (langfristige Investition)
Financial liquidity (finanzielle Liquidität)	Data ownership (Dateneigentum)	Dependency on digital technologies (Abhängigkeit von digitalen Technologien)
Product diversification (Produkt-diversifizierung)	Economic independence (wirtschaftliche Unabhängigkeit)	
Social (Sozial)		
Health hazards via dust (Gesundheitsgefahr durch Staub)	Health hazards via pesticide use (Gesundheitssgefahr durch Pestizide)	Negotiation channels (Verhandlungskanäle)
Contact with animals (Kontakt zu Tiere)	Atractivness for farm successors (Attraktivität für Hofnachfolger)	Working hours/free time (Arbeitstunden/Freizeit)
Landscape planning (Planung auf Landschaftsebene)	Rural exodus (Landflucht)	Regional self-sufficiency (Regionale Selbstversorgung)
Working conditions for farmers (Arbeitsbedingungen für Landwirte)	Stress (stress)	Ecologically valable agriculture (ökologisch wertvolle Landwirtschaft)

Table 4. Pre-selected list of Pressure variables (digital agricultural technologies) used in the first workshop with the original terms in German. Categorical delineations taken from MacPherson et al 2022.

Monitoring and analytics (Analytik)		
Citizen science apps	Citizen science applications (Citizen science apps)	Sensors (Sensoren)
Yield maps (Ertragskarten)	Digital soil maps (digitale Bodenkartierung)	Census data (Census data)
Drones (Drohnen)		
Management		
Artifical intelligence (künstliche Intelligenz (KI))	Robots (Robotik)	Radio frequency identification devices (RFID)
Internet of Things (Internet der Dinge)	Electronic field recors (elektronische Feldaufzeichnungen)	GPS-RTK
Precision farming (Präzisions-landwirtschaft)	Cloud computing	E-commerce
DSS Software		
Communication (Kommunikation)		
Blockchain	Social media (soziale Medien)	QR-code

Table 5. Pre-selected list of Drivers used in the first workshop with the original terms in German

Internet access and security (Internetzugang und -sicherheit)	Data harmonization (Daten-harmonisierung)	Agri-digital law (Agrardigitales Recht)
Producer prices (Produktpreise)	Costs of digital technologies (Kosten digitaler Technologien)	Payments for ecosystem services (Zahlungen für Ökosystemleistungen)
State of the economy (Wirtschaftslage)	Population (Bevölkerung)	Climate change (Klimaveränderung)
Input costs (Input kosten)	Advisory services (Beratungsdienste)	Training services (Aus- und Weiterbildungsdienste)
Consumer demand (Verbrauchernachfrage)	Data ownership (Dateneigentum)	Data protection (Datenschutz)
Experience of other farmers (Erfahrungen anderer Landwirte)	Work force offer (Arbeitskräfte-angebot)	Repair network (Reparaturnetzwerk)
Funding for technologies (Förderung für Technologien)		

Supplementary Material II

Table 1. Selection of impact areas contained in the joint BBN with their respective indicators, values and descriptions.

Impact Areas		
Variable	**Indicator**	**Value**
Biodiversity	Farmland bird occurrence	Good Bad
Description: Within the framework of the National Biodiversity Strategy, farmland birds are used as an important indicator of the overall biological diversity in agricultural landscapes. In recent decades, due to increasing pressure from agriculture (e.g. loss of habitat structures), farmland bird populations have declined sharply. In Brandenburg this affects species such as Skylark, Corn Bunting, Lapwing, Whinchat, Red-backed Shrike, Yellowhammer, and Woodlark (Glemnitz et al. 2015).		
Economic stability	Variability in revenue from crop production (€/ha UAA)	Good Bad
Description: Variability of all income from the sale of agricultural products (arable and grassland), horticultural products in field cultivation and natural extraction. Lower variability in revenue ensures a stable economy and reasonable growth.		
Food security and quality	Not defined	High Low
Description: Availability of food that is of high nutritional quality, as well as safe and affordable for consumption. In the context of Brandenburg, quality in terms of nutritional values and food safety is more relevant than food availability, i.e. security.		
Productivity (yield)	Yield in t/ha (only grains)	High (> 5.1 t/ha) Low (< 5.1 t/ha)
Description: In Brandenburg, mainly grain is produced. From 2015 to 2020, the average grain yield was 5.1 t/ha (Amt für Statistik Berlin-Brandenburg 2021b).		
Regional value chain	Share of agricultural products that are marketed locally/regionally	Good Bad
Description: Food that is grown, processed and marketed in a region. Regional foods are in higher demand with consumers. Promoting the regional value chain strengthens the local economy, closes material cycles, shortens transport routes and, potentially, preserves cultural landscapes.		
Resource efficiency	CO_2-eq/ product	High Low
Description: The agricultural sector in Brandenburg is characterized by high input and high efficiency. However, due to mechanization and the use of synthetic mineral fertilizers, agriculture in Brandenburg contributes significantly to greenhouse gas emissions (CO_2, CH_4, N_20), through indirect emissions from fertilizer production, farm management and through direct emissions from the soil (Landesamt für Umwelt 2022). *Note: To account for direct and indirect emission resulting from agricultural production, it was suggested by the stakeholders in our study to use an indicator describing emissions per product.*		
Social appreciation of the agricultural sector	Not defined	High Low
Description: Harsh working conditions, unstable prices, extreme weather events, environmental regulations and pressure from environmental groups make farming a difficult task. Farmers not only		

produce essential food, but are also responsible for protecting the environment. However, farmers' social reputation/acceptance is somewhat impaired, partly because of the public perception regarding environmental impacts stemming from the sector. (Gerlach 2020; Deter 2019).		
Soil quality	Humus content	High low
Description: The humus content in the soil is linked to many essential ecosystem services, such as filtering and storing water, building and maintaining the soil structure, securing the nutrient supply and fixing and breaking down pollutants. The desired humus content varies depending on the location. In sandy soils that can only build up little permanent humus, as in the case of Brandenburg, it is 1 to 2% (Düwel et al. 2007).		
Water quality	Share (in %) of wells with a nitrate concentration of over 50 mg/L	Good Bad
Description: There is a connection between nitrate concentration in groundwater and agriculture, e.g. the application of nitrate fertilizers and nitrate leaching. Elevated nitrate concentrations in groundwater can adversely affect human health and aquatic ecosystems. In Märkisch-Oderland, 10-20% of the wells have a nitrate content of more than 50 mg/l - the acceptable threshold values of the EU nitrate directive 91/676/EEC (VSR-Gewässerschutz e.V. 2021).		

Table 2. Selection of state variables contained in the joint BBN with their respective indicators, values and descriptions.

State variables		
Variable	**Indicator**	**Value**
Ammonia emissions	NH_3 emissions (in kt) from the agricultural sector	Increase (> 28 kt) Unchanged (23-28 kt) Decrease (> 23,7 kt)
Description: By reacting with other air pollutants, ammonia emissions lead to the formation of harmful particulate matter and, through the input of nitrogen, to eutrophication. Further conversion processes can result in soil acidification, groundwater pollution and indirect nitrous oxide emissions. The most important source of NH_3 emissions in agriculture is manure (slurry, manure, liquid manure, but also fermentation residues from biogas plants). In 2019, 23.7 kiloton NH_3 was emitted in Brandenburg. The amount has been decreasing since 2015, but has always been in the 23-28 kiloton range since 1991. (Rösemann et al. 2021).		
Attractiveness for farm successors	Share (in %) of farm managers under 55 years old	Increase Decrease
Description: Securing a farm successor is a decisive factor for agricultural businesses if they want to maintain their existence. In Brandenburg, the search for a farm successor has become more difficult. As a result, farm managers have become older on average in recent years. In Brandenburg, between 2010 and 2020, the proportion of farm managers under the age of 55 fell by 12% (Statistisches Bundesamt 2021).		
Ecologically valuable agriculture	Share (in %) of organic farms in the total agricultural area	Increase Decrease
Description: Organic farming is generally environmentally friendly, animal-friendly and resource-friendly. For 2030, the German sustainability strategy calls for a share of agricultural land under		

organic management of at least 20%, and 30% was agreed in the coalition agreement of the new federal government. The proportion in Brandenburg was 15,5% as of 2021 (Ministerium für Landwirtschaft, Umwelt und Klimaschutz 2022b).		
Energy consumption	Average diesel consumption in L/ha-a	Increase (> 110 L/ha-a) Decrease (< 110 L/ha-a)
Description: The average diesel consumption of farms in Germany is 110 l/ha-a. More than half of the diesel consumption is used for tillage and sowing (Verband der Landwirtschaftskammern e. V. 2009).		
Field capacity (water)	% Vol. of water available to plants in the root area up to 100 cm	Improvement Worsening
Description: Field capacity is the amount of water that is available to the plants in the rooted soil space. Because the water availability in Brandenburg is the limiting factor for plant growth, this indicator is essential for productivity. Although the field capacity is typically limited by natural soil conditions, it can be influenced by management such as tillage, humus creation and compaction through the operation of heavy machinery on field.		
Field size	Average field size in ha	Large (> 40 ha) Medium (10 – 40 ha) Small (< 10 ha)
Description: Field size refers to the area of the field that is treated or cultivated uniformly or approximately uniformly in terms of crop rotation. Large-scale cultivation increases the risk of soil erosion and at the same time has the consequence that the proportion of ecologically important landscape elements such as field hedges, field woods, field borders and paths decreases. In 2017, the average field size in Brandenburg was 8.11 ha (Invekos, 2017). However, when considering just the most common crops, such as grains and oil seeds, the average field size is 14.2 ha (Invekos, 2022).		
Nutrient balance	Nitrogen balance	Increase (> 60 kg N/ha) Decrease (< 60 kg N/ha)
Description: The nitrogen balance is calculated from the difference between nitrogen supply and nitrogen removal per hectare of agricultural land. In 2018 the nitrogen area balance surplus in BB was 60 kg/ha for agricultural area (Wey et al. 2020).		
Plant diversity	Shannon index (HS)	Optimal (>2.2) Tolerable (1.25 - 2.2) Unsustainable (<1.25)
Description: The Shannon Index (HS) is widely used in agricultural studies as an indicator of species diversity and agrobiodiversity. Based on experience with farm-related surveys in a large number of farms in Germany, Breitschuh et al. (2008) propose the following interpretation of the HS in studies at farm level: HS values > 2.2 are considered optimal, between 2.2 and 1.25 as tolerable and below 1.25 as unsustainable. The average HS for farms in Brandenburg is 1.06 (Breitschuh et al. 2008; Uthes et al. 2020).		

Product diversification	Average number of crops per farm (only arable land + share of crops in arable land >5%)	Increase (> 5.43) Decrease (< 5.43)
Description: The diversification of crop production means that new crops are introduced into the cultivation system to generate additional profits for the farm. In 2017, in Brandenburg the average number of crops per farm was 5.43 Invekos		
Regional self-sufficiency	Percentage of food produced and consumed in a region	Higher Lower
Description: Brandenburg produces more than enough grain (376%, as of 2011), vegetable fats (536%, as of 2011) and eggs (>100%, as of 2020) to be regionally self-sufficiency. On the other hand, not enough legumes (34%, 2011), potatoes (26%, 2011), meat (28%, 2011), vegetables (20%, 2011) and fruit (7%, 2011) are produced to be regionally self-sufficient (Amt für Statistik Berlin-Brandenburg 2021a; Kögl 2011).		
Risk management/assessment	Risks predictability	Increase Decrease
Description: Farmers face production risks (unpredictable weather, crop disease), market risks (price fluctuations). Anticipating these risks is a crucial aspect for the long-term success of farms and a stable agricultural sector.		
Structural diversity of the landscape	Share (in %) of the area of landscape elements in the total agricultural area	Increase Decrease
Description: Landscape elements contribute to structural diversity. They are, for example, hedges, flower strips, rows of trees, copses, individual trees, wet areas and ponds, field margins, clearing stone walls, rock and stone blocks. In BB the share is 0.35% and in MOL 0.27% (Invekos).		
Working conditions for farmers	Automation: Labor Unit per hectare	Improvement (> 1.5) Worsening (< 1.5)
Description: Automation can reduce physical workload, take over monotonous tasks and save time, which can lead to better working conditions. In Brandenburg there are 1.7 labor units per 100 ha (Ministerium für Landwirtschaft, Umwelt und Klimaschutz 2022a).		
Yield stability	Coefficient of variation for typical crop rotation in BB e.g. winter wheat - winter barley - winter rapeseed	Higher (> 20%) Lower (< 20%)
Description: A high stability of crop yields is a central goal in plant production and breeding, especially when considering climate change (e.g. increased heavy rainfall and more pronounced dry periods). The yield variability in Brandenburg has increased in recent years, reaching currently about 20% (Notz et al. 2021).		

Table 3. Selection of drivers contained in the joint BBN with their respective indicators, values and descriptions.

Drivers		
Variable	**Indicator**	**Value**
Data harmonization	Standardized data	Standardized Not standardized

Description: Data harmonization enables the exchange of data between digital devices and the integration of data in databases. One way to facilitate this process is through data standardization or the use of a common methodology or standard for data collection and sharing. Currently there are no common standards for data in the agricultural sector, although there are many initiatives addressing this issue.		
Legal framework	Agri-digital law	Clear, encouraging Unclear, discouraging
Description: Laws can promote or prevent the spread of digital technologies in agriculture.		
Payments for ecosystem services	Subsidies	Substantial Medium Little
Description: Funding for technology-assisted/digital agricultural measures that support ecosystem services.		
Producer prices	Producer price index	High Medium Low
Description: The price indices illustrate the revenue and cost situation in agriculture. If the producer price index rises, farms can achieve higher revenues with the same yields and expenses.		

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Supplementary Material III

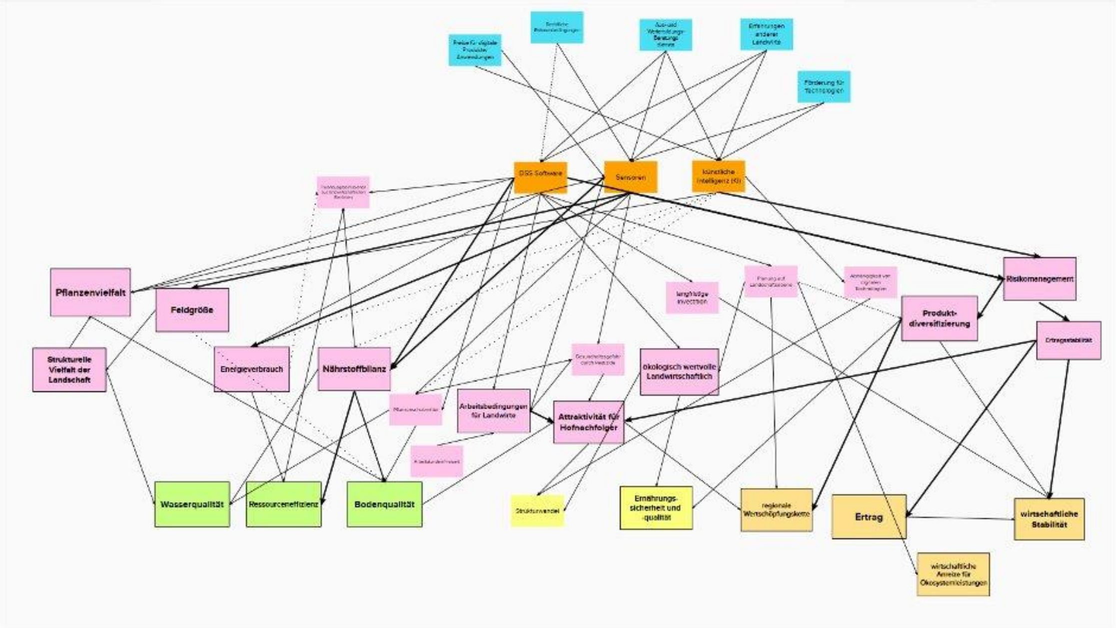

Figure 1. Conceptual model of scientist group (variables in German).

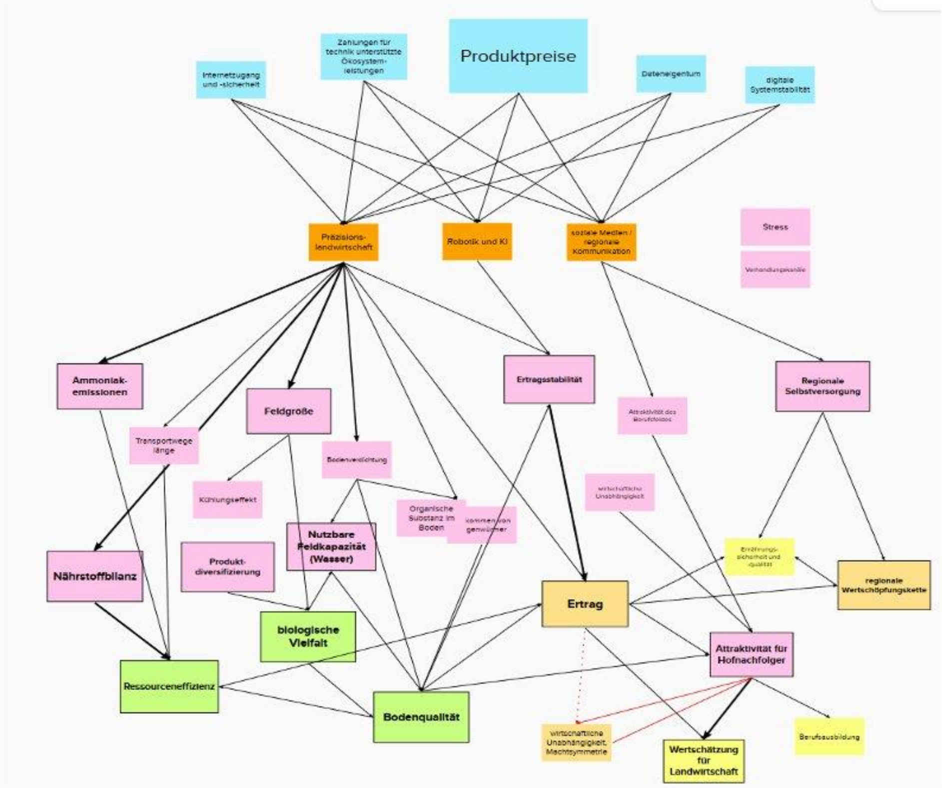

Figure 2. Conceptual model of farmer group (variables in German).

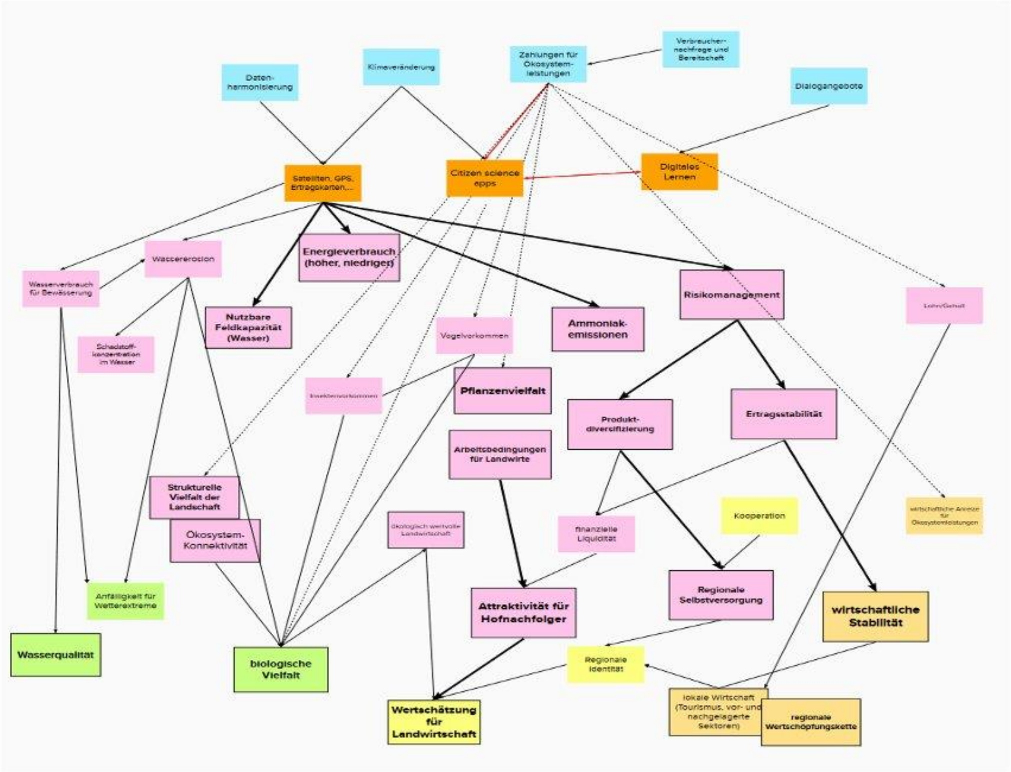

Figure 3. Conceptual model of CSO group (variables in German).

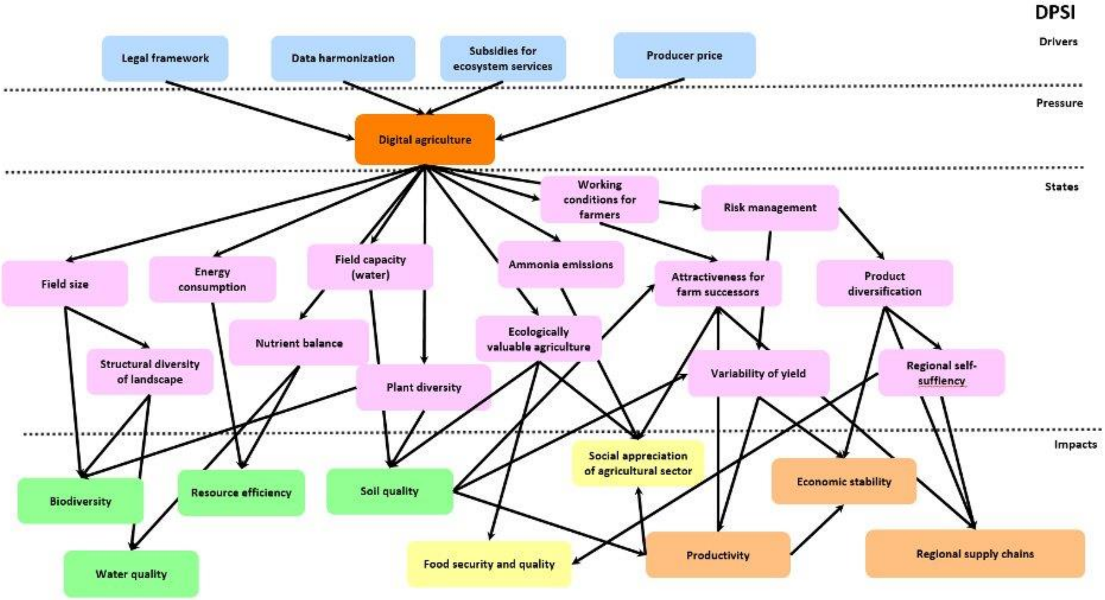

Figure 4. Unified conceptual model organized along the DPSI framework (variables in English).

5. Synthesis

Assessing agricultural sustainability is a challenging endeavor as it entails considering social, economic, and environmental factors, while recognizing their interconnectedness within systems. It involves combining quantitative analysis with qualitative dimensions such as norms, values, and politics, while evaluating the long-term viability of agricultural measures, policies, or projects by assessing their impacts on current and future generations. It involves bridging scales between farm level activities, their effects on landscape ecosystems, and their contribution to sustainability goals, national and global. It requires integration of concepts, techniques, and stakeholder knowledge to balance trade-offs, identify synergies and navigate uncertainties of complex agricultural systems. Finally, agricultural sustainability assessment requires adaptation to evolving and context-specific knowledge, values, and goals to ensure its effectiveness in guiding transformative change towards a more sustainable and resilient agriculture in the future.

In fulfilling the overall aim of this thesis, the work produced insights into integrative concepts and methods for enhancing agricultural sustainability assessment. First, in Chapter 2, analysis was performed on diverse farm-level SA tools and models to determine their potential contribution and characteristic for sustainably managing ES and achieving sustainability goals. Chapter 3 demonstrates a novel, interdisciplinary approach, combining policy, law, and foresight analysis, to understand the broader implications of digital agriculture on sustainability. Finally, based on the thematic insights on agricultural digitalization obtained from Chapter 3 and the methodological insights on sustainability assessment methods derived from Chapter 2, Chapter 4 conducted a SA engaging stakeholder knowledge to assess the perceived impacts of digital agriculture in the German federal state of Brandenburg.

This chapter provides a synthesis of the key findings and addresses the research questions outlined at the beginning of the thesis. It underscores the connections between the individual chapters, demonstrating how they build on one another, as well as discusses how common challenges related to uncertainty, comprehensiveness and standardization in SA were addressed, while making suggestions for improvements. In conclusion, an outlook and recommendations are offered based on the findings of the work.

5.1 Results

5.1.1 Assessing the integration of ecosystem services and Sustainable Development Goals in farm-level sustainability assessment tools and models

Numerous tools and models have emerged for evaluating the sustainability of farms and agricultural systems. While such tools and models may not have been designed explicitly to address ES and SDGs, their thematic scope may still latently encompass these aspects to varying degrees. Thus, in addressing Research Question 1: *To what extent can agricultural assessment tools and models integrate the ES concept and contribute to the Sustainable Development Goals (SDGs)?*, several generic farm-level assessment tools and models were examined and analyzed in Chapter 2. The results indicate that SAFA had the most extensive coverage of ES and SDGs, followed by RISE and KSNL. Compared to models, SA tools were found to have greater potential latent coverage of ES and SDGs, attributed to their larger and more comprehensive indicator sets covering the three dimensions of sustainability. In terms of ES, provisioning services were comprehensively addressed across the tools and models reviewed, whereas regulation and maintenance ES were covered broadly across farm-level tools and varied across models. Potential coverage of cultural ES was lacking across all models and tools. Generally, the reviewed farm-level tools and models do not explicitly articulate the ES concept thoroughly. In terms of SDG coverage, SAFA had the highest latent coverage, which can be explained due to its affiliation with the UN. RISE exhibited a similar coverage of SDGs due to recent harmonization efforts with SAFA. Models showed a low coverage of SDGs altogether.

The disparity of ES and SDG coverage between SA tools and model can be explained by the broader (i.e. covering economic, social, and environmental dimensions) and more extensive sets of indicators featured in farm-level tools, enabling them to accommodate the multifunctional and integrated nature of the ES concept and SDGs. This can ultimately be traced to the intended purpose and design of tools and models: models are typically tailored to address specific research questions and policy issues requiring a high level of precision, data, and time requirements, while tools focus on broader geographical and practical applications with lower precision, time, and data requirements. Thus, a trade-off emerges, where tools excel in the potential coverage of ES and SDGs but lack precision, while models excel in precision but lack potential coverage. Moreover, as sustainability issues vary significantly based on geography, climate, culture, and socio-economic setting, the rigid indicator frameworks of top-down generic tools and models constrains their capacity to consider normative aspects as well as capturing both the supply and demand of ES of (often highly) specific local contexts. Neglecting to consider such local context and normativity may hinder the ability to conduct relevant and effective SA, thereby limiting uptake and implementation of sustainable management.

Acknowledging that SA tools are designed primarily for ex-post evaluation at the farm level, it became apparent that they would not be suitable for assessing the potential future impacts of digitalization at a regional level. In this context, the capacity of models to conduct ex-ante simulations and explore 'what-if' scenarios make them more adept at addressing this problem. However, it was also acknowledged that the reviewed models would pose certain limitations. For instance, they lacked the scope to perform SA comprehensively, and their high data requirements would pose a hurdle to assessing the impact of digital agriculture given current data scarcity on the topic. Therefore, in Chapter 4, a participatory modeling approach to enable a forward-looking SA, while addressing the challenges related to capturing local perspectives and sustainability issues, as well as those related to data requirements and limitations.

The indicators from the tools and models reviewed in Chapter 3 were used as the basis in Chapter 4 to construct a comprehensive and amendable ‘long list’ of variables from which stakeholders could choose. The aim of this was to streamline the assessment process while including indicators in the SA that have already been validated by the scientific community.

5.1.2 Policy and legal landscapes: investigating the potential of digital agriculture for sustainability

Digital agriculture has garnered attention in academic and policy circles due to its potential to improve sustainability within food systems. Yet, there is a lack of research examining potential contributions of digital agriculture to policy initiatives and larger societal sustainability goals This knowledge gap was addressed in Chapter 3 through answering Research Question 2: *how is digital agriculture currently embedded in preeminent global, EU, and German policy, and what links can be drawn between digital agriculture technologies and to wider sustainability principles outlined in these policies? How could* *future trends in the agri-food sector influence the adoption and use of digital technologies? How does the current legal setting surrounding digital technologies impact agriculture?* To answer this question, a review was conducted of prominent sustainability policies at the German national, European Union (EU), and global scales, analyzing connections to digital agriculture. Additionally, the current legal framework concerning digital agriculture technologies at EU and German national levels was analyzed. This was followed by foresighting and scenario analysis to explore how future frame conditions might affect the instrumentalization of digital agricultural for achieving sustainability.

The results show that some policies (F2F Strategy, German Arable Farming Strategy, German Bioeconomy Strategy) articulate the potential benefits of digital agriculture, albeit to a limited extent. These policies mainly focus on the capacity of digital agricultural technologies to enhance resource efficiency and productivity, while neglecting their potential benefits for environmental improvements, including biodiversity conservation, soil protection, and climate change adaptation and mitigation. By addressing these deficits, the study draws a link between potentials applications of digital technologies and policy, demonstrating how various on-farm management, monitoring, and communication technologies could be applied for achieving a broad range of agriculture-related sustainability goals. Further, the legal analysis reveals a fragmented yet evolving body of law that could impact agricultural digitalization. Looking into the future, the foresighting and scenario analysis demonstrates that a highly digitalized future dominated by retailers could lead to structures of information flows and data ownership regimes that may negatively affect sustainability. This suggests that as data becomes more central in the future agri-food sector, whoever controls this data will have immense influence on dictating to which ends it is being used, including how and if it used for achieving sustainability principles.

Overall, the results of Chapter 3 reveal the potential of leveraging digital agriculture for attaining sustainability goals under proper political and legal guidance, which speaks to the importance of good governance in promoting sustainability (Purvis et al. 2019). However, to fully capitalize on this broad proposition and provide policy and decision makers with necessary strategic intelligence, more empirical research is needed to comprehensively assess the potential impacts of digital agriculture. This requires conducting SA to examine the potential effects of digital agricultural technologies, qualitatively and quantitatively, going beyond the analysis of known productivity and efficiency enhancements to consider more closely social and environmental aspects. As Chapter 3 shows the potentially controversial and far-reaching systemic changes that agricultural digitalization could entail, SA should therefore promote public participation and dialogue while also balancing competing interests (Klerkx and Rose 2020). Following this logic, Chapter 4 engaged stakeholders to assess their perceptions on the impacts of digital agriculture.

5.1.3 Exploring the impact of digitalization on agriculture: insights from participatory modeling in Brandenburg

While Chapter 3 examined the broader scope of potential high-level policy implications of digital agriculture on sustainability, Chapter 4 took a deeper look into the specific sustainability impacts of digital agriculture at a local level. The study begins with the premise that there is limited empirical evidence regarding the broad-scale impacts of agricultural digitalization, leading to uncertainties and ambiguities in perceptions among stakeholders. Thus, Chapter 4 addressed Research Question 3: *What are the anticipated impacts of agricultural digitalization according to stakeholders?* To investigate this, a PM approach was employed wherein a diverse range of stakeholders collaborated to construct a BBN for assessing the impacts of digital agriculture in 10 years, with the German federal state of Brandenburg serving as a case study region.

The results show that stakeholders agree that resource efficiency and economic stability will benefit from agricultural digitization. These features appear to be strongly supported by precision farming technologies and improved risk management, respectively. However, the effects of digitalization on biodiversity-related factors appear to be more ambiguous, with impacts to landscape diversification acknowledged but unclear. For instance, there was some degree of certainty regarding the likelihood of automation and field robots to allow for smaller field sizes in the future, but it was uncertain if this would lead to the incorporation of biodiversity enhancing landscape features (i.e. hedgerows, grassland buffer, flower strips). From a theoretical point of view, digitalization has the potential to increase productivity per unit of land, thereby decreasing the land needed to produce the same output quantity, thus increasing—or at least maintaining—land for natural features that contribute to habitat quality. However, past technological innovations leading to larger field sizes and monocultures suggest that if digitalization is viewed as a continuation of these historical patterns towards mechanization and economies of scale, it is likely that similar productivity and efficiency-driven outcomes will ensue, resulting in less emphasis on promoting diversified landscapes.

The stakeholder perspectives in Chapter 4 corroborated policy considerations in Chapter 3 regarding efficiency improvements through digitalization. However, in terms of the impacts of digitalization on biodiversity, the lack of consideration in policy (Chapter 3) and uncertainty among stakeholders (Chapter4) points to a significant knowledge gap and the potential risk of negative environmental spill-over effects. This knowledge gap most likely stems from inadequate communication between research and society, as well as a lack of available data on the impacts of digital agriculture on landscape structure and biodiversity thus far.

5.2 Challenges for agricultural sustainability assessment

5.2.1 Uncertainty

Uncertainty is an inherent and emergent property of complex agriculture systems and thereby agricultural SA as well. It emerges in assessments, for instance, that incorporate more extensive thematic coverage, extend farther into the future, utilize participatory techniques, and attempt to consider indirect impacts (Hacking and Guthrie 2008). Currently, uncertainty is seldom addressed in generic agricultural SA frameworks, thereby giving a false impression on the confidence of such results (Olde et al. 2018; Schader et al. 2019). As uncertainty is unavoidable in SA, it is worthwhile to address not only for the sake of scientific transparency but for improving the robustness of assessment outcomes as well (Schaubroeck et al. 2020). Various methods exist for managing and reducing uncertainty in agricultural SA (Ciuffo et al. 2012). This thesis employed qualitative scenarios, addressing broad-scale uncertainties of digital agriculture on policy (Chapter 3), and a participatory BBN approach in to address local-scale uncertainties of digital agriculture from the standpoint of stakeholders (Chapter 4).

In Chapter 3, scenario-based foresighting was used to investigate the long-term effects of digital agriculture on sustainability. In this context, scenarios aided in dealing with the complexities and unknowns of future conditions by exploring different combinations and interactions between drivers, trends, and potential outcomes. The process of organizing and contextualizing uncertainties facilitated reflection on sustainability risks associated with agricultural digitalization. For example, by comparing possible outcomes, it allowed for pinpointing differentiated sources of risk and uncertainty across the scenarios, e.g. alternative structures of future information flows and data ownership regimes could lead to contrasting sustainability outcomes. Although scenarios provide rich details on probable futures, they are, of course, based on speculations about what could happen (Voros 2003). Indeed, the inherent ontological uncertainty of the future renders it impossible to anticipate all factors and changes that might emerge, particularly when extending timeframes farther into the future. Therefore caution should be used when drawing conclusion from scenarios (Fleming et al. 2021). Nevertheless, Chapter 3 showed the usefulness of employing this approach in agricultural SA as analytical tools for reflecting on long-term impacts and incorporating uncertainty for strategic thinking.

Moving beyond the broad approach of addressing uncertainties through scenarios as just described, Chapter 4 sought to manage and reduce uncertainties more directly and quantitatively though participatory modeling using a BBN. Here uncertainty was addressed in three ways. First, the collaborative process of developing the BBN facilitated consensus building by bridging the diverse perspectives of stakeholders, thereby reducing uncertainty related to ambiguities in their perceptions. In this way, the BBN essentially formed a boundary object, allowing for the stakeholders to effectively communicate with each other (Kenny and Castilla-Rho 2022). This is especially relevant in the context of digital agriculture, as limited empirical evidence and contrasting opinions on its desirability has fueled much uncertainty and debate regarding its sustainability implications (Klerkx and Rose 2020). Second, as with other participatory methods, the co-construction of the BBN leveraged stakeholder knowledge by tapping into their implicit and explicit knowledge, while synthesizing their diverse expertise, insights, and experiences (Barbrook-Johnson 2022). Hereby, the epistemic uncertainty arising from incomplete data regarding the impacts of digitalization on agricultural systems was reduced through a collaborative learning process and harnessing the collective intelligence of stakeholders (Gray et al. 2020). Third, in a more direct sense of addressing uncertainties, employing a BBN facilitated an explicit account of uncertainty in stakeholder knowledge through quantifying their perception of impacts and causal processes using probability distributions. Modelling different scenarios and observing marginal changes in the posterior probability distributions of output variables were used to assess node-specific uncertainties. Through this approach, a range of possible outcomes from agricultural digitalization could be identified. Overall, the BBN and the participatory process behind its construction help to articulate and reflect on uncertainties, offering a structured and quantitative approach to addressing it within SA. Such approaches can be considered beneficial in the pursuit of adaptive management strategies in innovation settings (Klerkx et al. 2010), including agricultural digitalization, which can help lead to better decision-making under uncertainty.

It should be noted that bias in prior stakeholder knowledge could have had a significant impact on the estimation of uncertainty within the BBN. For example, stakeholders' prior technical knowledge of digital agriculture, or lack thereof, may lead to overestimation or underestimation (Kuhnert et al. 2010), affecting the reliability and validity of the uncertainty estimates derived from the BBN outputs. For example, the stakeholders consulted in Chapter 4 were familiar with basic digital tools like farming apps, GPS-guided tractors, and social media. However, it remained uncertain to what extent they were familiar with more advanced digital technologies such as robotics, artificial intelligence (AI), or remote-sensing-driven data prior to the modeling exercise. To address this potential bias, measuring confidence of stakeholder knowledge on digitalization before the PM exercise could help assess the level of influence of stakeholder bias on uncertainty estimates represented in the outputs of the BBN.

5.2.2 Comprehensiveness

It was highlighted in Chapter 2 that tools and models that include comprehensive sets of indicators covering multiple sustainability dimensions are better suited to encompassing the integrative frameworks of the ES concept and SDGs. Yet, because these tools primarily aim to standardize and streamline assessments for making performance comparisons, their indicators are most often intentionally fixed (apart from SAFA) and may have low applicability toward location-specific conditions. As a result, their ability to address local sustainability issues are restricted. Essentially, in generic tools and models, sustainability objectives and the methods for measuring progress towards these objectives are determined from the top-down by external experts. This goes against the premise that sustainability is a normative and ‘situated concept’ (Rigby and Caceres 1997) as well as calls for greater stakeholder inclusion (Reed 2008), raising doubts about the effectiveness of such approaches for generating tangible sustainability improvements. Although resource intensive, bottom-up SA that explicitly accounts for local environmental, social, economic and cultural factors offers a potential solution to this problem by providing more contextually relevant and comprehensive representations of complex agricultural systems and sustainability issues (Olde et al. 2018). Additionally, in order to gain knowledge on local systems and include local discourses, involving stakeholders in the assessment process is strongly advised (Moreau et al. 2023; Binder et al. 2010).

Building on these insights, Chapter 4 adopted a participatory approach where a structured procedure was used to collaboratively select a set of sustainability themes and indicators. However, to avoid making assessments overly complex and challenging (Olde et al. 2018), it's important to establish limits and prioritize which themes and indicators are most relevant for the context of the SA. In Chapter 4, prioritization was achieved through a method that employed multiple rounds of group discussions and voting. Through this approach it was possible to select the most relevant indicator set for the SA to fit the specific context, akin to materiality analysis methods as used in the GRI standards (Whitehead 2017). However, there are several drawbacks to grounding SA and indicator selection based on local conditions through a participatory approach. One of the limitations is that the outcomes derived from context-specific assessment are not easily transferable to other locations and therefore lack generalizability. Additionally, for any given SA, the relevance of themes and indicators most likely will change over time with evolving values, norms and biophysical conditions (Paul and Helming 2019). In this context, adaptive and iterative SA are needed.

Participatory approaches have the potential to introduce bias into the indicator selection process if individuals recruited for the assessment do not adequately represent the interests and perspectives of key stakeholder groups specific to the location and system under study. Integrating stakeholder mapping approaches before the outset of SA can help reduce this type of bias by ensuring a balanced selection and composition of stakeholders for the assessment (Reed et al. 2009).

In response to the challenge of balancing the trade-off between comprehensiveness and precision of SA as pointed out in Chapter 2, participatory modelling, as employed in Chapter 4**,** can offer a possible solution. Using the PM approach, comprehensiveness is upheld through the integration of modeling techniques that translate qualitative expert opinions (e.g. norms and values) into quantitative outputs. This approach allowed for assessing the interaction between variables and indicators that might typically be excluded from an assessment due to insufficient empirical data, e.g., the effects of digital agriculture on working conditions and attractiveness of the farming profession.

5.2.3 Lack of standardized indicators

Top-down agricultural SA as reviewed in Chapter 2 are intended to streamline monitoring and benchmarking, which can provide information on performance comparisons across farming systems, identify areas for improvement, and inform strategic decision-making processes (Binder et al. 2010). However, the existence of numerous tools and lack of harmonization with an international indicator framework makes performance comparisons across farming systems, conducting meta-analyses, and scaling up of local assessments to broader levels challenging (Schader et al. 2014; Olde et al. 2017a). Efforts are being made to address these issues, specifically with recent standardization efforts of the SAFA Guidelines (FAO 2013). The SAFA Guidelines are intended to provide “a harmonized taxonomy” and “clear and common language” (FAO 2013) for assessing sustainability. The effects of this could be seen in Chapter 2, where the RISE tool, which has recently harmonized its indicators with those of SAFA, provides a comparable level of coverage of agriculturally related ES and SDGs. Although the coverage of ES and SDGs was largely indirect in that study, this type of standardization offers the potential for facilitating comparison of results across tools and, ultimately, supporting concerted actions aimed at advancing the sustainable management of ES and achieving the SDGs. Other generic SA tools have also advocated for a globally consistent approach by embracing the SAFA Guidelines as a conceptual framework (Schader et al. 2019). In a similar vein, Chapter 4, sought to utilize SAFA indicators and themes to align with this international standard and facilitate consistency. Recognizing the SAFA indicators are intended for broad geographic applicability, they may or may not be relevant depending on which part of the world the assessment is conducted. However, global challenges like climate change and biodiversity loss, which necessitate collective international efforts, can benefit from such endeavors towards standardization.

Similar undertakings toward standardizing terminology can be observed in relation to the ES concept, as demonstrated by the development and utilization of the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young 2018). While CICES stands as the most comprehensive classification system for ES up to now (e.g. 83 distinct classes of ES), not all ES classes are relevant to the agricultural context. Therefore, Chapter 2 developed a list of agriculture-related CICES classes, recognizing that defining a sub-set of context relevant CICES classes is an important first step forward toward standardizing the assessment of ES (Paul et al. 2021). However, since there is no common indicator framework for measuring CICES classes, comparing and upscaling assessments based on the CICES framework is still a major challenge. The abundance and variety of existing indicators utilized for assessing ES encompassed within CICES (Paul et al. 2022; Czúcz et al. 2018) shows how difficult developing a standardized indicator framework would be in this regard.

In relation to the SDGs, although there are targets, indicators, and reporting mechanisms in place for measuring progress towards achieving them at the national level, understanding how actions at lower levels contribute to their attainment remain difficult to assess. This stems from the considerably broad, universal nature for which the SDGs and targets were designed. Addressing this, Chapters 2 and 3 attempted to operationalize the SDG framework and targets through linking them to the indicators of farm-level tools and model as well as agricultural management i.e. digital agriculture. While achieving an international consensus on lower-level indicators is highly unlikely, directionality holds greater significance in this context. After all, the SDGs are not binding mandates but rather serve as societal orientation (Jossin and Peters 2022). However, defining sub-sets of agricultural SDGs can help refining the scope of assessments and make them more relevant and manageable, as shown in Chapter 2.

5.3 Outlook and future research

Technological innovation, as a catalyst of transformation, offers hope by addressing the many issues afflicting the current agri-food system (Herrero et al. 2020). This type of techno-centric solutionism is not new and has sparked considerable criticism (Fielke et al. 2022; Huesemann and Huesemann 2011). Indeed, while past technological progress has yielded significant benefits, it has also brought about substantial repercussions for both society and the environment, forming the very foundation of several of the contemporary challenges we find ourselves facing. In light of this, the development of technological innovations, such as digital agriculture, should be accompanied by well-defined missions that align with societally-determined sustainability objectives (Klerkx and Rose 2020; Herrero et al. 2021). This approach serves to counteract unintended adverse effects of technological innovations, while simultaneously addressing societal needs. In this context, policy can provide guidance to steer collective efforts towards fostering more sustainable agriculture, as it is highly influential in determining technological innovation and adoption through shaping public discourse, directing public funding for research and development, as well as setting subsidies and regulations. However, as it was shown in Chapter 3, there is currently no unified policy explicitly dedicated to digital agriculture at the global, EU, or German national level. Instead, it is treated in these policies as a peripheral concern or a driver. Given the widespread anticipation of digitalization as a potentially transformative force in agriculture (Rose et al. 2021; Klerkx and Rose 2020), there is need for policy to play a more proactive role in guiding this transition. This is especially true to avoid outcomes that could lead to more social and environmental degradation of agricultural systems by reinforcing conventional modes of production. Increasing rural access to high-speed internet and creating a statutory framework that puts farmers in control of their data would be a positive initial step in guaranteeing an equitable distribution of the benefits derived from digital agricultural technologies.

In addition to the potential environmental benefits of agricultural production, digitalization could also provide an opportunity to help connect farm to fork. As agri-food value chains become more digitalized, consumers and producers will become more connected through increases in bilateral data flow, leading potentially to better management of ES (Voglhuber-Slavinsky et al. 2023). Future studies should examine how various digital technologies along the value chain could promote the sustainable management of ES. Additionally, depending on the country of interest, policy development and the digital transformation of agriculture may look very different (Fleming et al. 2021). This means future studies could explore how policy and digital agriculture is taking shape in other regions to assess and compare impacts of digitalization under different socio-cultural conditions.

The results of this thesis can be used as a reference for exploring and researching societally relevant questions regarding the impacts of digitalization. For example, Chapter 4 pointed to the significant amount of uncertainty among stakeholders surrounding the impacts of digitalization on biodiversity, necessitating more empirical research and better communication between science and other stakeholders. Chapter 3 outlined the potential importance of data flows and data ownership for instrumentalizing digital agriculture for achieving sustainability goals. In this context, collaboration between legal experts and other disciplines will be key to develop a coherent and adaptive legal framework that incentivizes innovation while balancing various sustainability objectives in the coming digital transformation of agriculture.

As shown in Chapter 2, the integration of the ES concept into agricultural SA tools and models has been noticeably constrained thus far. Therefore, there is an ongoing need for better articulation and integration of the ES concept in farm-level tools and models. Consensus on terminology and standardized metrics for measuring agricultural ES would be a first step in this direction. As the understanding of the interactions between agricultural management and ES develops, SA tools and models must evolve to reflect this advancement. The emergence of digital technologies, such as *in-situ* and remote sensing will aid in this process by providing more data on agriculture-activities and related ES, which will improve monitoring and prediction of ES supply and demand (Mouratiadou et al. 2023).

Participatory modeling serves as a valuable method for accessing both implicit and explicit knowledge of stakeholders as well as building consensus on sustainability issues. However, challenges persist in involving large groups in participatory modeling (Voinov and Gaddis 2017). Utilizing online methods could be beneficial in addressing this issue, since barriers to participation are smaller compared to in-person workshops. Building on this, the experiences obtained from Chapter 4 led to the development of a web-based participatory tool[1] (not covered by the work in this thesis) designed to select context-specific sustainability themes and indicators by tapping into the collective mental models of stakeholder groups. The concept is that by systematizing and streamlining the indicator selection process online, broader inclusion becomes possible, and the representativeness of samples is improved.

While significant progress has been made in advancing SA methodologies over the years, there remains a need for increased inclusion and participation. While generic assessments (Chapter 2) and socially determined objectives (Chapter 3) can shift society toward greater sustainability, an important aspect lies in acknowledging the local conditions of sustainability issues (Chapter 4). Simply relying on overarching objectives without considering contextual factors can pose challenges in garnering broad societal support and commitment to achieving sustainability. This is because stakeholders often hold diverse yet equally legitimate perspectives on what constitutes agricultural sustainability. Thus, since agriculture heavily relies on stakeholders' demands and actions, achieving sustainability hinges on their perspectives.

The integration of multiple perspectives, methodologies, and frameworks in sustainability assessments of agricultural systems contributes to a more comprehensive and nuanced understanding of sustainability challenges and opportunities. In this context, insights gained from this thesis point to several recommendations for improving agricultural SA through:

- Involving stakeholders and their knowledge: By engaging stakeholder values and knowledge, SA can simultaneously address issues of normativity and data limitations. Here, participatory modelling tools are recommended as a process for synthesizing implicit and explicit knowledge of stakeholders in quantitative ways as well as deriving consensus of values through collaborative learning and negotiation.

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[1] https://psim.variat.studio/

- Addressing uncertainty: By confronting the inherent uncertainty of conducting agricultural SA, a clearer understanding of the confidence level of potential sustainability outcomes is provided, which enhances transparency of the assessment. This, in turn, allows for improved reflexivity in SA by exposing potential risks and opportunities, thereby strengthening decision-making capacities for managing alternative outcomes. Depending on data availability, uncertainty in SA can be managed quantitatively by delineating outcomes using probability distributions, or qualitatively through foresight and scenario analysis, particularly when SA extends into the distant future.
- Incorporating policy and legal frameworks: Including policy and legal considerations in SA can provide guidance to ensure that assessment outcomes align with societally relevant goals, objectives, and regulations. Moreover, where feasible, SA should integrate indicators provided by policy to improve communication and legitimacy of SA results. This can contribute to informed policy development and fostering socially responsible decision-making in pursuit of sustainable development goals.
- Integrating the ES perspective: By incorporating the ES concept in SA, the representation of complex ecological processes underpinning agricultural systems is enhanced. The ES perspective has the potential to capture the multifunctionality of agriculture systems in more detail, surpassing generic assessment methods and metrics, leading to a more integrated coverage of sustainability dimensions. Integrating the terminology of the CICES framework in SA is recommended as a starting point.
- Harmonizing indicators: To facilitate performance comparisons among different farming systems, meta-analyses, and the expansion of local assessments to wider scales, generic SA tools and models should aim to integrate with globally recognized indicator frameworks. Considering its international recognition and the recent alignment efforts of other SA tools with it, it is recommended to utilize the FAO SAFA Guidelines.

In conclusion, agricultural SA would benefit from a more explicit consideration of ES and the SDGs. By doing this, future assessment tools and models will be better equipped to reflect new paradigms of sustainable agriculture. For generic SA tools and models, further harmonization with standard metrics and indicators, as per SAFA, will promote up scaling of analyses and allow for more informed policy. High-level policy should be future-oriented, anticipating a greater role of digitalization not only in agricultural production but also in governance, retail, and consumption. This shift in thinking about agriculture, driven by digitization, may blur traditional lines in agri-food systems through higher connectivity. Finally, recognizing and integrating differing perspectives in SA will help bridge the gap between stakeholders and researchers, facilitating a more inclusive and informed dialogue, and promoting socially and environmentally responsible research.

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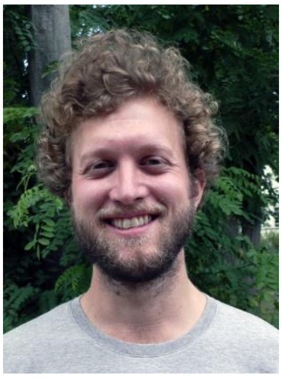
Curriculum Vitae



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List of Publications

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