Stakeholder perspectives on the contribution of digital technologies to improve the sustainability of fruit production – a case study on the Lake Constance region in Germany

Dissertation to obtain the doctoral degree of Agricultural Sciences (Dr. sc. agr.)

Faculty of Agricultural Sciences

University of Hohenheim

Institute of Social Sciences in Agriculture

Dept. Societal Transition and Agriculture

Karlsruhe Institute of Technology

Institute for Technology Assessment and Systems Analysis

submitted by

Kirsten Gaber (Moore)

Born in Toronto, Canada

2024

Dean of the faculty of Agricultural Science: Prof. Dr. Ralf Vögele

Date of the oral examination: May 13, 2025

Examination Committee

Prof. Dr. Claudia Bieling
Prof. Dr. Jana Zscheischler
Prof. Dr. Andrea Knierim
Prof. Dr.-Ing. Stefan Böttinger (Chairperson of the oral examination)

Acknowledgments

This dissertation has played a considerable role in my life over the last 5 years and it has accompanied me through numerous life milestones. I am incredibly grateful to the people who have helped to give this work its vitality and supported me along its course.

I am deeply thankful to my doctoral supervisor, Prof. Dr. Claudia Bieling, for her sweeping and comprehensive expertise, unfailing guidance and moral support, and for always having an answer to my questions or a guiding question that leads me to my own. Thank you to Prof. Dr. Jana Zscheischler and Prof. Dr. Andrea Knierim for kindly agreeing to act as reviewers and examiners for the doctoral proceedings. For her valuable mentorship and collaboration over many years, for supporting my decision to complete a doctorate from the very beginning, and for enabling me to see the work through to its end, I thank my external mentor and colleague, Dr. Christine Rösch.

As an external PhD candidate, I had the unique opportunity to be part of two excellent collegial groups: I am thankful to my wonderful colleagues at both the Institute of Technology and Systems Assessment (ITAS) at the Karlsruhe Institute of Technology (KIT) and at the Institute of Social Sciences in Agriculture at the University of Hohenheim for their intellectual and moral support and motivation. For the financial support and guiding theoretical frameworks, I am thankful to the Horizon 2020 project DESIRA and to my research institute, ITAS-KIT.

Without the engagement of the stakeholders within this doctoral work, I would not have material to work with, nor a reason to do the work; I am grateful to the 34 stakeholders who donated their time and effort to the interview series and especially to those who welcomed me into their offices, farms, and homes in the Lake Constance region.

Finally, I am eternally grateful to my parents for their love, encouragement, and for always believing in me; to my husband, for his constant, pragmatic, and loving support; and to my son, the light of my life.

Table of contents

Executive Summary

Fruit cultivation is facing numerous sustainability challenges including climate change, weather extremes, and societal pressures surrounding the use of agricultural inputs. The value of fruit cultivation extends beyond the production of food, as the places of production are regionally important for ecology, recreation, tourism, and socio-cultural values; thus, sustainability issues threaten not only the future production of fruit, but also the cultural landscape as such. Digitalization in agriculture is progressing at a rapid pace and is frequently heralded as a solution to the current pressures surrounding modern food production. Increased productivity, efficiency gains, and improved transparency along the food value chain, enabled through the implementation of digital technologies, may lead to environmental and socio-economic benefits. Meanwhile, a divide is growing between supporters of digitalization and skeptics who are concerned with the technologies and their short- and long-term impacts. Digital solutions are not always suitable across agricultural sectors and regions due to differences in crop management activities, land-use types (e.g. perennial crop area like orchards versus arable land area for temporary crops), and physical barriers and infrastructure.

At the face of these challenges and the rapid development of digitalization, stakeholder perceptions regarding the influence of digitalization on the sustainability of fruit cultivation must be understood in order to enable a sustainable further development of digital technologies. Particular to the case study region of this dissertation, the Lake Constance region in southern Germany, research on stakeholder perspectives at the interface of sustainability in fruit production and digitalization does not exist. There is a large knowledge gap regarding the attitudes and practical understandings of the stakeholders impacted by the digital transformation of fruit cultivation, as well as what measures are required to support a more user-oriented development. Technology development without the consideration of barriers, user abilities, and user expectations may lead to an imbalanced transformation that may favour certain agricultural sectors, farm sizes, or production systems over others, which may consequently create a regional, demographic, and/or sectoral digital divide.

To this end, this cumulative doctoral work sought to explore the knowledge and views of stakeholders regarding the contribution of digital technologies to improve the sustainability of fruit production by using an empirical and qualitative case-study approach within the setting of sustainability research. The case-study region was the Lake Constance region in Germany, characterized by organic and integrated production (IP) fruit production on small- to medium-sized family farms. This region is the second-largest fruit growing area in the country and plays a critical role in the regional, national, and international food supply. The research questions that have guided this doctoral thesis are as follows: (1) What is the state of the art on digital technologies in fruit production? (2) How do stakeholders perceive digitalized fruit production, adoption and barriers to adoption of the technologies, and do these perceptions differ based on production system or farm size? (3) Do farmers (and other stakeholders) believe that digital technologies can tackle the environmental and social/societal sustainability challenges of fruit production, in both conventional and organic production, and if yes, how? In order to answer these questions, the author comprehensively reviewed over 200 digital tools that can be used by farms in the context of fruit production and conducted a qualitative analysis of 34 interviews with stakeholders along the fruit value chain. The three research articles that form the basis of this cumulative dissertation synergistically answer these questions through the research findings and surrounding scientific literature-based discussions.

Overall, the development of digital tools for this case study region appears to be unsuitable and knowledge on digitalization is uneven. Based on the findings, opportunities for technological development to overcome reported barriers and therefore support a user-oriented transformation include the development of tools that are cost-efficient, such as tools with multifunctionalities or that are hireable services, and that offer technical support in the local language. Marketing of technologies must be improved, as misguided marketing and inadequate information in the fruit sector may hinder implementation. Political frameworks should prioritize supporting the inclusion of small farms and equal efforts for development and implementation across production systems. The reduction of agricultural inputs and lack of societal acceptance of agriculture were the most frequently reported sustainability challenges for regional fruit production. Stakeholders believed both environmental and socio-economic challenges could be mitigated by digitalization in fruit production, particularly through increased efficiency and improved transparency. However, perceptions of digitalization’s chances and challenges varied among individuals, fruit production systems, and farm sizes. Furthermore, the majority of stakeholders believed that digitalization could change the public opinion about fruit production, either through on-farm use of the technologies or through improved transparency along the value chain. Both pathways were reported to potentially create positive or negative impacts; for instance, more transparency can lead to improved trust between farmers and consumers, but could also de-romanticize expectations or contradict the idea of naturalness in agriculture, especially in the case of organic farming. The discourse surrounding the use of digital technologies in fruit farming may be more influential on public opinion than their actual implementation.

According to stakeholders in the Lake Constance region, digitalized technologies can be used as tools to mitigate urgent sustainability challenges in fruit cultivation, but are not a cure-all solution. These technologies must be considered with caution, as they also risk worsening sustainability issues, particularly related to power inequalities and the growth paradigm of greater productivity and efficiency. Therefore, a reprioritization of digitalization focusing on mitigating urgent sustainability issues is required. This should include the supported development and implementation of user-driven technological design, hybrid (human-technological) intelligence for fruit cultivation tasks, and tools that prioritize building trust towards farmers and maintaining their autonomy. Future transdisciplinary research approaches are encouraged in order to meet many of the provided recommendations from this dissertation, such as enabling collaborative technology- and research design, improving foundational knowledge of involved groups through capacity-building measures like trainings, and building trust between actor groups. The results of this work will inform policy makers, researchers, and technology developers to support the fruit production sector to overcome current and future sustainability issues and enable fair, informed participation in the digital transformation of agriculture.

Zusammenfassung

Der Obstanbau steht vor zahlreichen Herausforderungen in Bezug auf die Nachhaltigkeit, darunter Klimawandel, Wetterextreme und gesellschaftlicher Druck im Zusammenhang mit dem Einsatz von Pestiziden und anderen landwirtschaftlichen Betriebsmitteln. Der Wert des Obstanbaus geht über die Produktion von Lebensmitteln hinaus, da die Produktionsorte für die Ökologie, die Erholung, den Tourismus und soziokulturelle Werte von regionaler Bedeutung sind; daher bedrohen die Herausforderungen der Nachhaltigkeit nicht nur die künftige Obstproduktion, sondern auch die Kulturlandschaft der Obstanbaugebiete als solche. Die Digitalisierung in der Landwirtschaft schreitet rasant voran und wird häufig als Lösung für die Nachhaltigkeitsherausforderungen der modernen Lebensmittelproduktion angepriesen. Produktivitätssteigerungen, Effizienzgewinne und eine verbesserte Transparenz entlang der Lebensmittelwertschöpfungskette, die durch den Einsatz digitaler Technologien ermöglicht werden, können zu ökologischen und sozioökonomischen Vorteilen führen. Gleichzeitig wächst die Kluft zwischen den Befürworter*innen der Digitalisierung und den Skeptiker*innen, die sich Sorgen über die Technologien und ihre kurz- und langfristigen Auswirkungen machen. Digitale Lösungen eignen sich nicht immer für alle landwirtschaftlichen Sektoren und Regionen, da es Unterschiede in der Bewirtschaftung, in der Art der Landnutzung (z. B. mehrjährige Anbauflächen wie Obstplantagen im Gegensatz zu Ackerflächen für Zwischenfrüchte) sowie in den physischen Barrieren und der Infrastruktur gibt.

Angesichts dieser Herausforderungen und der rasanten Entwicklung der Digitalisierung muss die Wahrnehmung der Stakeholder zum Einfluss der Digitalisierung auf die Nachhaltigkeit des Obstanbaus verstanden werden, um eine nachhaltige Weiterentwicklung der digitalen Technologien zu ermöglichen. Speziell für die Fallstudienregion dieser Dissertation, die Bodenseeregion in Süddeutschland, gibt es keine Forschung zu Stakeholder Perspektiven an der Schnittstelle von Nachhaltigkeit im Obstbau und Digitalisierung. Es besteht eine große Wissenslücke hinsichtlich der Einstellungen und des praktischen Verständnisses der von der digitalen Transformation des Obstbaus betroffenen Akteure sowie der Frage, welche Maßnahmen erforderlich sind, um eine nutzerorientierte Entwicklung zu ermöglichen. Eine Technologieentwicklung ohne Berücksichtigung von Hindernissen, Nutzerfähigkeiten und Nutzererwartungen kann zu einer unausgewogenen Transformation führen, die bestimmte landwirtschaftliche Sektoren, Betriebsgrößen oder Produktionssysteme gegenüber anderen begünstigt, was in der Folge zu einer regionalen, demografischen und/oder sektoralen digitalen Kluft führen kann.

Vor diesem Hintergrund wurden in dieser kumulativen Doktorarbeit das Wissen und die Ansichten von Akteuren in Bezug auf die Rolle digitaler Technologien für die Nachhaltigkeit der Obstproduktion erforscht, indem ein empirischer und qualitativer Fallstudienansatz im Rahmen der Nachhaltigkeitsforschung verwendet wurde. Die Fallstudienregion war die Bodenseeregion in Deutschland, die durch die ökologische und integrierte Produktion (IP) von Obst in kleinen bis mittelgroßen Familienbetrieben gekennzeichnet ist. Diese Region ist das zweitgrößte Obstanbaugebiet des Landes und spielt eine entscheidende Rolle für die regionale, nationale und internationale Lebensmittelversorgung. Die Forschungsfragen, von denen sich diese Doktorarbeit leiten ließ, lauten wie folgt: (1) Was ist der Stand der Technik bei digitalen Technologien in der Obstproduktion? (2) Wie nehmen die Beteiligten die digitalisierte Obstproduktion, die Akzeptanz und die Hindernisse für die Akzeptanz der Technologien wahr, und unterscheiden sich diese Wahrnehmungen je nach Produktionssystem oder Betriebsgröße? (3) Glauben die Landwirt*innen (und andere Beteiligte), dass digitale Technologien die ökologischen und sozialen/gesellschaftlichen Herausforderungen der Obstproduktion sowohl im konventionellen als auch im ökologischen Anbau bewältigen können, und

wenn ja, wie? Um diese Fragen zu beantworten, hat die Autorin über 200 digitale Tools, die von landwirtschaftlichen Betrieben im Rahmen der Obstproduktion eingesetzt werden können umfassend untersucht und eine qualitative Analyse von 34 Interviews mit Akteuren entlang der Wertschöpfungskette im Obstbau durchgeführt. Die drei Forschungsartikel, die die Grundlage dieser kumulativen Dissertation bilden, beantworten diese Fragen synergetisch durch die Forschungsergebnisse und die Diskussionen in der wissenschaftlichen Literatur.

Insgesamt scheint die Entwicklung digitaler Werkzeuge für diese Fallstudienregion ungeeignet zu sein und das Wissen über Digitalisierung ist uneinheitlich. Basierend auf den Erkenntnissen sind Möglichkeiten für die technologische Entwicklung zur Überwindung der berichteten Barrieren und damit zur Unterstützung einer nutzerorientierten Transformation die Entwicklung von Tools, die kosteneffizient sind, wie z. B. multifunktionale Tools oder mietbare Dienstleistungen, und die technische Unterstützung in der Landessprache bieten. Die Vermarktung von Technologien muss verbessert werden, da fehlgeleitetes Marketing und unzureichende Informationen im Obstsektor die Umsetzung häufig behindern. Politische Rahmenbedingungen sollten vorrangig die Einbeziehung von Kleinbetrieben und gleiche Anstrengungen für die Entwicklung und Umsetzung in allen Produktionssystemen unterstützen. Die Reduzierung der landwirtschaftlichen Inputs und die mangelnde gesellschaftliche Akzeptanz der Landwirtschaft waren die am häufigsten genannten Herausforderungen für die Nachhaltigkeit der regionalen Obstproduktion. Die Stakeholder waren der Meinung, dass sowohl ökologische als auch sozioökonomische Herausforderungen durch die Digitalisierung in der Obstproduktion entschärft werden könnten, insbesondere durch höhere Effizienz und verbesserte Transparenz. Die Chancen und Herausforderungen der Digitalisierung wurden jedoch je nach Person, Obstproduktionssystem und Betriebsgröße unterschiedlich wahrgenommen. Darüber hinaus glaubte die Mehrheit der Stakeholder, dass die Digitalisierung die öffentliche Meinung über die Obstproduktion verändern könnte, entweder durch den Einsatz der Technologien auf dem landwirtschaftlichen Betrieb oder durch eine verbesserte Transparenz entlang der Wertschöpfungskette. Es wurde berichtet, dass beide Wege positive oder negative Auswirkungen haben können; so kann beispielsweise mehr Transparenz zu einem größeren Vertrauen zwischen Landwirt*innen und Verbraucher*innen führen, aber auch die Erwartungen entromantisieren oder der Vorstellung von Natürlichkeit in der Landwirtschaft widersprechen, insbesondere im Fall des ökologischen Landbaus. Der Diskurs über den Einsatz digitaler Technologien im Obstanbau kann die öffentliche Meinung stärker beeinflussen als ihre tatsächliche Umsetzung.

Nach Ansicht von Akteuren in der Bodenseeregion können digitalisierte Technologien als Instrumente zur Entschärfung dringender Nachhaltigkeitsprobleme im Obstanbau eingesetzt werden, sind aber kein Allheilmittel. Diese Technologien müssen mit Vorsicht betrachtet werden, da sie auch das Risiko bergen, Nachhaltigkeitsprobleme zu verstärken, insbesondere im Zusammenhang mit Machtungleichheiten und dem Wachstumsparadigma der höheren Produktivität und Effizienz. Daher ist eine Neupriorisierung der Digitalisierung erforderlich, die sich auf die Entschärfung dringender Nachhaltigkeitsprobleme konzentriert. So sollten die Entwicklung und Umsetzung von nutzergesteuertem Technologiedesign, hybrider (menschlich-technischer) Intelligenz für Obstanbauaufgaben und Werkzeugen unterstützt werden, die den Aufbau von Vertrauen gegenüber Landwirt*innen und die Wahrung ihrer Autonomie in den Vordergrund stellen. Zukünftige transdisziplinäre Forschungsansätze werden angeregt, um viele der in dieser Dissertation gegebenen Empfehlungen zu erfüllen, wie z. B. die Ermöglichung eines kollaborativen Technologie- und Forschungsdesigns, die Verbesserung des Grundlagenwissens der beteiligten Gruppen durch kapazitätsbildende Maßnahmen wie Schulungen und die Vertrauensbildung zwischen den Akteursgruppen. Die Ergebnisse dieser Arbeit bieten Informationen für politische Entscheidungsträger, Forscher und Technologieentwickler, um den Obstproduktionssektor bei der

Bewältigung aktueller und zukünftiger Nachhaltigkeitsprobleme zu unterstützen und eine faire, informierte Teilnahme an der digitalen Transformation der Landwirtschaft zu ermöglichen.

List of figures

List of tables

List of acronyms

ACPS	Agricultural Cyber-Physical Systems
BCE	Before Current Era
CA	Controlled Atmosphere
CSA	Community Supported Agriculture
CWB	Climactic Water Balance
DESIRA	Digitization: economic and social impacts in rural areas
DGC	Digital Game Changer
DP	Demand-Pull (Model)
IOT	Internet of Things
IP	Integrated Production
ITAS	Institute of Technology and Systems Assessment
KIT	Karlsruhe Institute of Technology
PA	Precision Agriculture
PEU	Perceived Ease of Use
PPP	Plant Protection Product
PU	Perceived Usage
RWL	Real World Lab
SSC	Soluble Solids Content
SCOT	Social Construction of Technology
SFT	Smart Farming Technology
SOTA	State of the Art
TAM	Technology Acceptance Model
TDR	Transdisciplinary Research
TP	Technology-Push (Model)
TPB	Theory of Planned Behaviour
TSR	Transformative Sustainability Research
UAV	Unmanned Aerial Vehicle
UTAUT	The Unified Theory of Acceptance and Use of Technology

1. Introduction

1.1 General introduction and problem setting

1.1.1 Environmental and socio-economic challenges in fruit production

Agriculture is facing major challenges to meet the demands of a growing world population and, simultaneously, is threatened by sustainability issues such as climate change and species loss. At the same time, societal criticisms and changing consumer preferences place additional tensions on agricultural practices and practitioners. The fruit cultivation sector faces additional, unique challenges in the current setting: climate change and weather extremes create substantial concerns for fruit farmers by disrupting horticultural processes, altering growing conditions, and amplifying pest and disease pressures (Dierend, 2009; Krölling, 2021; Stöckle et al., 2011). For instance, the earlier begin and overall lengthening of the vegetation period through climate change can lead to increased blossom damage by exposure to frost (Krölling, 2021). Sustainability challenges for fruit threaten economic prosperity and self-sufficiency at various regional and federal scales. Orchards are valuable not just for their ecological role as habitats for plants and animals, but also for recreational and tourism purposes in the surrounding area (Lehr- und Forschungszentrum für Wein- und Obstbau Klosterneuburg, 2013). In Germany, fruit is cultivated in all 16 federal states (Dirksmeyer & Garming, 2022). Apples dominate national fruit cultivation: around 44% of the national fruit growing area (Muder et al., 2022) and 70% of the tree fruit area (Statistisches Bundesamt, 2023a) is dedicated to apple cultivation. While Germany generally imports more fruits and vegetables than it exports and is therefore considered a 'net importer', in the case of dessert or table apples (meaning mainly for direct consumption), Germany is considered to be self-sufficient with a self-sufficiency rate of around 60% between 2011 and 2021 (Garming et al., 2024). Small farms, such as those typical of the fruit production landscape in southern Germany, have been found to be more vulnerable than large farms to climate change pitfalls such as extreme weather and increased pressures from pests and diseases (Ebel et al., 2018). While an increased use of agricultural inputs may be seen as a mitigation strategy against the environmental pressures in fruit cultivation, the use of pesticides in fruit cultivation is under strict examination as political strategies have been formed as a reaction to environmental concerns. According to the European Green Deal and the Farm-Fork-Strategy the use of chemical pesticides must be reduced by 50% by the year 2030 (The European Commission, 2019b, 2019a). Of all the crops grown in Germany in 2020, apple cultivation was the most pesticide-intensive crop (Chemnitz et al., 2022). Specifically, apples had the highest value on the treatment frequency index, a commonly-used index by authorities to describe how often a crop has been treated with the maximum permitted application rate of a pesticide product over the entire cultivation area, in comparison to other German crop cultures (Chemnitz et al., 2022). The German government's goal of increasing their share of organic farming from 9.6% in 2020 to 30% by 2030 offers to make a significant contribution to reducing the amount of pesticides used (BMEL 2022; DESTATIS 2023). Generally, organic farming faces challenges of lower yields compared to conventional systems, certification barriers and challenges to access markets, and difficult soil nutrient management (Jouzi et al. 2017). Specific to fruit farming, organic pomaceous fruits produce less CO_2-equivalents per kg than conventional pomaceous fruits, yet more land is required to produce these organic products (Reinhardt et al. 2020; Treu et al. 2017).

Societal concerns and consumer expectations further complicate the fruit farming landscape. Historically, food shortages and threats to food security that were once commonplace were reduced through the progressive use of machines in agriculture as products of the individual industrial revolutions (von Veltheim & Heise, 2021). As basic concerns over food security eased in industrialized countries like Germany, other concerns such as the sustainability of common agricultural production methods gained more public attention and attracted criticism (Spiller et al., 2015; Voerste, 2008; von Veltheim & Heise, 2021), extending to negative effects on farmer trust and reputation (von Veltheim et al., 2019; von Veltheim & Heise, 2021). The resulting disconnect between farmers and consumers with the continued progression of industrialized agriculture (Duncan & Broyles, 2006; Zimbelman et al., 1995) has led to deficient agricultural literacy or knowledge among consumers (Rumble & Irani, 2016). Thus, in addition to environmental sustainability challenges, the future of farming is threatened by deficiencies in agricultural knowledge, as these could lead to misguided public support for political campaigns and inadequate understanding of price politics (Igo et al., 1999).

1.1.2 Digitalization in agriculture

To face the numerous sustainability challenges surrounding modern food production, digitalized technologies for agriculture may offer technical solutions. Digitalization in agriculture is complex, complicated further by the often-synonymous use of terms like precision agriculture, smart agriculture, Agriculture 4.0, and smart farming within media and scientific literature. However, the terminology are indeed non-synonymous and not all have neutral connotations; for instance, favourable word choice in media and public discourse such as ‘smart agriculture’ have promoted a positive technical fix for current agricultural and food system challenges (Soma & Nuckchady, 2021; van der Burg et al., 2019). Within this dissertation, as detailed later in Chapter 2, Agriculture 4.0 is considered the umbrella concept for digitalization in agriculture, under which various systemizations that are grouped into concepts of ‘precision farming’ and ‘smart farming’ exist (Gandorfer et al., 2017; Griepentrog, 2012; Munz, 2021). The digital connections of agricultural production processes are a central element of Agriculture 4.0 and aim to improve the efficiency and transparency of production, transport, storage, and marketing of agricultural products (Arvanitis & Symeonaki, 2020; Deichmann et al., 2016; Madushanki et al., 2019; Talavera et al., 2017; Zambon et al., 2019). Digital agricultural technologies can improve production efficiency through the reduced use of water, fuel, and fertilizer, enabled by precision techniques and the use of renewable energy (Haarlem, 2020; Miranda et al., 2019). As such, their implementation may aid in bridging the numerous gaps (e.g. labour requirements, price, societal acceptance, environmental impact) between organic and conventional production methods in agriculture, through for instance the use of non-chemical weeding robots to reduce the needs for biochemical inputs. Proponents mainly argue that digital agricultural technologies improve efficiency and productivity through which the socio-economic and environmental aspects of the food system are balanced (Basso & Antle, 2020).

In the case of fruit production, digital technologies have been and continue to be developed to complete functions specific to this agricultural sector or adapted from other sectors for use in orchards, tunnels, greenhouses, and other fruit cultivation settings. For instance, machine learning can assist in achieving a sustainable and competitive fruit and wine production through disease prognosis, harvest date suggestions, and early pest detection (Nordmark et al., 2021). Autonomous robots can harvest fruit (e.g. Baeten et al., 2008; Zhang et al., 2024), unmanned aerial vehicles and robots can manage farm tasks (e.g. Adarsch et al. 2018; Stefas et al. 2016; Zhang et al. 2021; Zhang et al. 2019), and artificial intelligence models can use deep learning approaches for fruit sizing (e.g. Miranda et al. 2023), early recognition of fruit diseases (e.g. Kodors et al., 2020), and fruit detection and segmentation (e.g. Barbole et al., 2022).

In Germany, the agricultural sector has been praised for leading national digitalization (Rentenbank, 2018) and farmers are portrayed as pioneers of digitalization (Bitkom, 2019). In a recent representative survey, 90% of German farmers reported using at least one of the digital technologies or processes named in the survey, including digital farm indexes or farm management systems (Rohleder & Meinel, 2024). Nevertheless, numerous barriers to adoption exist. Financial investment is a leading cause of apprehension in the adoption of digitalization among German farmers, followed by concerns surrounding data security and sovereignty and possible technical incompatibility between systems (Schleicher & Gandorfer, 2018). Similarly, the factors considered to most strongly hinder the digitalization of agriculture according to German farmers are high investment costs, worries that bureaucracy will increase rather than ease, insufficient standardized interfaces and system networking, and a lack of farmer involvement in the planning of political measures (Rohleder & Meinel, 2024). Overall, farmers are interested in incorporating digital technologies on their farms, with farm managers of larger farms showing a greater inclination to adopt these technologies, primarily due to their capital-intensive nature (Köhler, 2018).

1.1.3 Digitalization in agriculture: opportunity or threat?

Dichotomous to the opportunities seen by proponents of digital agriculture, threats emerge through the digital transformation. The history of technological development has demonstrated that, in addition to the anticipated positive effects, unintended negative side-effects, so-called ‘unseens’, occur (Scholz et al., 2018, 2021; Zscheischler et al., 2024). The claims of improved efficiency and productivity belong to the growth paradigm that has led to many of the sustainability issues facing agriculture today; for instance, intensive farming of monocultures has led to soil degradation and biodiversity loss (Lal et al., 1989; Tsiafouli et al., 2015). Environmental challenges may be worsened through digitalization’s disruptive character (Barth et al., 2023), such as its resource consumption (Del Río Castro et al., 2021) and its possible rebound effects, including higher energy usage through new technologies or the further intensification of agricultural and non-agricultural land (Chemnitz et al., 2022). The social sustainability impacts of digital technologies have notably received less attention than their environmental counterparts (Pfeiffer et al., 2021; Prause, 2021). As is common in socio-technical transitions, the socio-ecological effects are rarely predictable and are faced with great uncertainties (Hirsch-Kreinsen, 2016; Schweizer & Renn, 2019; Zscheischler et al., 2024). Various ethical concerns exist regarding digital agriculture, such as amplified social inequalities through agricultural robotic use (Ayris et al., 2024) and data sovereignty and farmer privacy from AI tool use (Dara et al., 2022; Gardezi et al., 2023; Ryan, 2023). Furthermore, technological lock-ins through debt (McKinnon 2019), dependence of farmers on corporate agro-industrial farming models (Hackfort, 2022) and the correlational loss of traditional knowledge (Carolan, 2017; Rotz et al., 2019) through digitalization create and re-enforce power relations.

While advancements in digital technologies for agriculture are rapid and ongoing, a divide is growing between supporters and skeptics, their costs and benefits, applications, and the short- and long-term impacts. Digital solutions are not always suitable across sectors and regions due to differences in infrastructure and crop management activities. Adoption rates vary across branches of agriculture and technology type (Groher et al., 2020) and agricultural systems, which can lead to inequalities in access to digital technologies (Barnes et al., 2019). Adoption of digital technologies in fruit cultivation is low (e.g. Rose & Bhattacharya, 2023) and lags behind adoption rates in arable farming (Ossevoort et al., 2016). The cost of technologies is not viable for all farmers, particularly small farms (Gkisakis et al., 2018; Wiggins et al., 2010). Managers of larger farms are more likely to adopt technologies than managers of smaller farms due to the greater amounts of work required on their land (Kernecker et al. 2020). Agricultural mechanization and increased access to information from advisor services were often found to be cost-effective only on larger fields (Batte & Ehsani, 2006; Binici et al., 2006; Ullah & Perret, 2014). The risks associated with uneven distribution of technology development and access to the technologies have been well-researched and include the social exclusion of farmers who do not have access to new technology, unevenly shaped technological development, unequal access to data, asymmetrical skills and resources required to benefit from digitalization (Bronson & Sengers, 2022; Hackfort, 2021, 2023; Klerkx & Rose, 2020; Martens & Zscheischler, 2022; Regan, 2019).

Digitalization and sustainability, referred to as the “twin transition”, are the two overarching narratives of the EU as of February 2022, as seen in the legislative packages the *Green Deal* and *Fit for the Digital Age*, respectively (Barth et al., 2023). Still, digitalization does not necessarily contribute to more sustainability on its own, but rather creates opportunities and risks for both environmental improvements and societal justice (Lange & Santarius, 2022). Considering the opportunities and threats of digitalization as a complex process of change, sustainability research is required, particularly stakeholder engagement and transdisciplinary approaches, to pinpoint the circumstances under which digitalization can support sustainable development (Barth et al., 2023). Agriculture 4.0 must include both the demand-perspective and the value chain-perspective of current sustainability issues to leverage technology, not just for the sake of innovation, but also to improve and meet actual consumer requirements and to re-engineer the value chain (De Clerqu et al., 2018).

1.1.4 Research and knowledge gaps

Digital technologies will undoubtedly change the culture of farming communities and agricultural stakeholders; nevertheless, until recently, the state of development was too immature to assess how these technologies will be perceived by stakeholders and evaluate their impact on societies (Balafoutis et al., 2017). Therefore, a large knowledge gap exists when it comes to practical understandings and attitudes of stakeholders affected by the digital transformation in fruit cultivation, how they perceive this transformation to impact sustainability issues, as well as how to integrate their views in the development of technologies and regulatory and financial framework conditions. Although the development of digital innovations is progressing in fruit cultivation, a characterization of the existing tools based on on-farm functions, which increases usability of the results, is lacking.

While studies on stakeholder perceptions of digital technologies in other German agricultural sectors exist, such as the dairy industry (e.g. Langer & Kühl, 2024) or across cropping systems (e.g. Knierim et al., 2019 and Pfeiffer et al., 2021), studies with a focus on stakeholders along fruit value chains in Germany are not represented within the literature. Particular to the case study region of this dissertation, the Lake Constance region in southern Germany, research on stakeholder perspectives on the potential contribution of digital technologies on the sustainability of fruit cultivation does not yet exist. The existing research gap on perspectives of fruit farmers and other stakeholders on digital technologies may lead to a regional, demographic, and/or sectoral digital divide, defined as the gap between those able to participate in the digital age and those who are not (Hilbert, 2011). It is critical to understand these perspectives given the speed at which digitalization in agriculture is advancing and the current environmental and socio-economic issues that threaten the future of fruit cultivation in this region, which plays a vital role in the local and national economy, food security, and socio-cultural landscape.

1.2 Research objectives and questions

This dissertation aims to contribute to the existing knowledge and research gaps by answering the following empirical research questions:

1. What is the state of the art on digital technologies in fruit production?
2. How do stakeholders perceive digitalized fruit production, adoption and barriers to adoption of the technologies, and do these perceptions differ based on production system or farm size?
3. Do farmers (and other stakeholders) believe that digital technologies can tackle the environmental and social/societal sustainability challenges of fruit production, in both conventional and organic production, and if so, how?

Each research question is reflected in at least one of the three scientific articles (Figure 1) that represent the core of this dissertation. Thus, the results of the articles synergistically meet the research objectives.

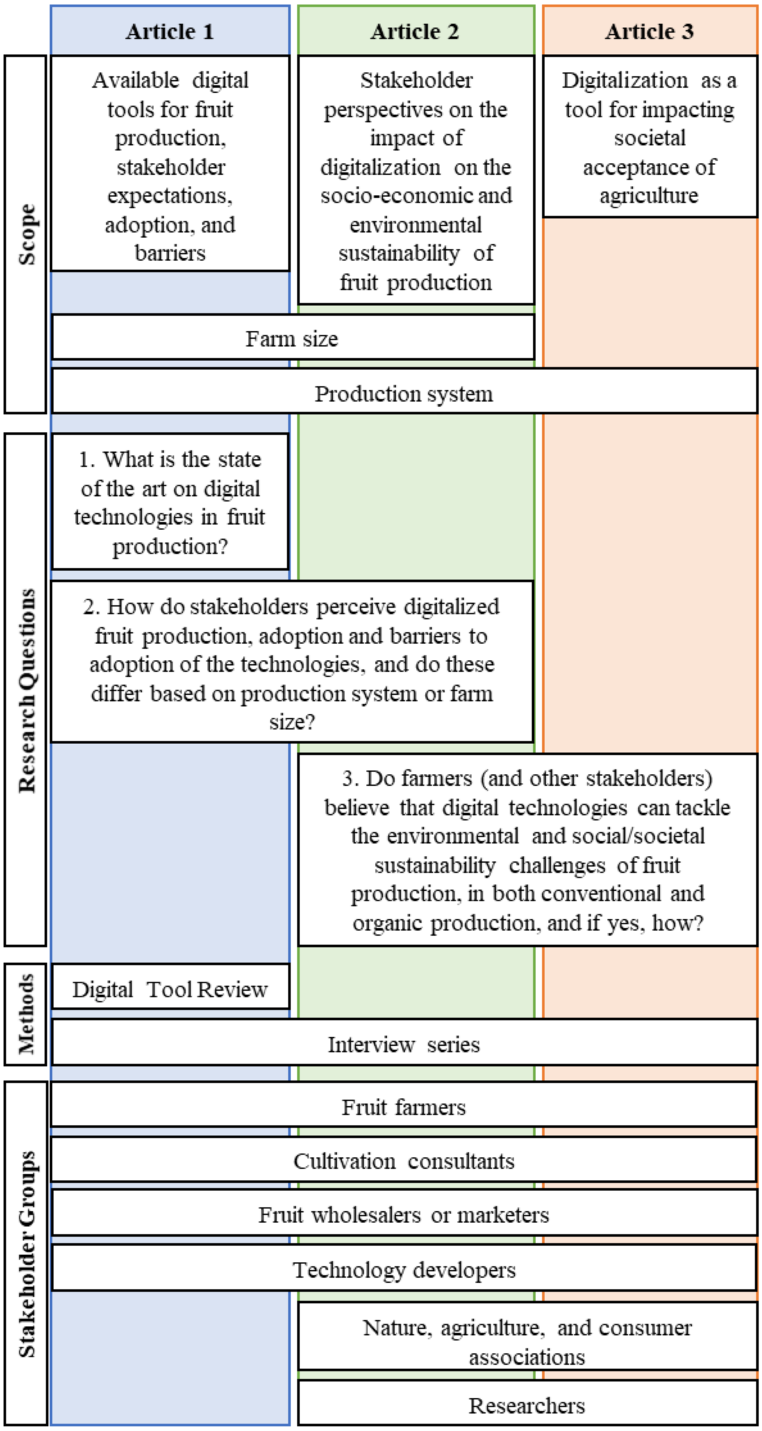

Figure 1: Overview of the scopes, research questions, methods, and stakeholder groups across the three papers within the dissertation

1.3 Outline of the dissertation

The outline of the dissertation is as follows: this introduction chapter to describe the problem setting and research objectives preceeds a section on the theoretical background. This section justifies how this work is embedded into an existing theoretical framework and provides context and knowledge on the topics of sustainability, Agriculture 4.0, and technology adoption and acceptance. From there, the methods used in this dissertation are summarized and described in detail in the corresponding articles. Chapter 5 presents an overview of the results and a table of the scientific articles and their publication statuses. Article 1 (Chapter 6) establishes a knowledge baseline on the existing digital technologies for fruit production for the dissertation, discusses adoption and barriers to adoption according to the case study stakeholders, and identifies commonalities and discrepancies between technology characteristics and stakeholder expectations. Article 2 (Chapter 7) continues from the established knowledge from article 1 towards the core of the dissertation, namely the perceived contribution of digitalization on the sustainability of fruit cultivation. Finally, article 3 (Chapter 8) dives deeper into a portion of the results from article 2, specifically the impact of digitalziation on societal challenges in fruit production. The discussion chapter synergizes the results and discussions of the three articles, critically appraises digitalization in the context of the results, and presents recommendations for future research and development of digitalization in fruit production. The dissertation closes with a conclusion chapter, which includes a summative section on policy implications.

2. Theoretical background

2.1 Sustainability and sustainable agriculture

Sustainability and sustainable development have been guiding concepts and principles for modern research. The document *Our Common Future*, otherwise known as the *Brundtland Report*, propelled a commonly- accepted concept of sustainability into everyday vocabulary. This report describes sustainable development to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987, p.37). Similarly, the three-pillar concept of sustainability – environmental, economic, and social – was first discussed in the Brundtland Report and has become ubiquitous (e.g. Purvis et al., 2019). While definitions of sustainability have varied over time and contexts, the term has remained rooted to the construct of time by prioritizing the longevity of a process. Sustainability goes hand-in-hand with sustainable development, and while often referred to as having the same meaning, sustainable development distinguishes itself by referring to the processes and pathways to achieve long-term sustainability (UNESCO, 2012). Sustainable development can be considered as an elaboration or an improvement of the traditional concept of the 'common good', in which the common good, which is generally understood as being opposite of private interests, is extended to the global population from a long-term standpoint (Hirsch Hadorn et al., 2006).

I have considered the Brundtland Report concept of sustainability as the most appropriate for the purposes of this dissertation. The pillars of environment and social sustainability are at the forefront of this research, and while the economic pillar is not directly addressed, the pillars are inherently interdependent and thus, the economic pillar cannot be completely excluded. For instance, as the cost of digitalized technologies in agriculture has been understood as playing a major role in adoption (e.g. Busse et al., 2014; Ferrari et al., 2022; Knierim et al., 2019), the economic aspects of the digital transformation must be considered when addressing sustainability.

Sustainable agriculture is a concept that, like sustainable development, has been defined and applied in a multitude of ways over time. Arguably, agriculture itself must be defined before defining sustainable agriculture (Smit & Smithers, 1993). The term has included a great spectrum of activities that are fundamental to agriculture and have their own descriptive terms (like domestication and horticulture), is often qualified by words (like extensive and intensive), and is frequently defined by different attributes (like soil type or animals) (Harris & Fuller, 2014). For the purpose of this dissertation, I look to the Oxford University Press' definition to use the term in its broadest, most inclusive sense, similar to Harris & Fuller (2014): "The practice of cultivating the soil, growing crops, or raising livestock for human use, including the production of food, feed, fibre, fuel, or other useful products. Also known as farming" (Oxford University Press, 2024, Quick Reference section, para. 1).

Overall, the concept of sustainable agriculture refers to ensuring the longevity of agricultural production and, therefore, food security, in a way that does not damage the natural resource base. Agricultural production systems and concepts such as organic farming, regenerative agriculture, permaculture, and agroforestry share foundational goals to conserve the planet's ability to sustain future generations while providing for the present civilization (Dubey, 2024). Looking at a European example, the European Parliament defines sustainable agriculture as "an integrated system of plant and animal production that will last over the long time, satisfy human food needs, enhance natural resources, use efficiently of non-renewable resources, sustain economic viability of farms and enhance the quality of life for farmers and society as a whole" (European Parliament, 2012, para. 1). Sustainable agriculture is considered a multidimensional concept which includes environmental, economic, and social components (Crosson, 1992; Smit & Smithers, 1993).

Along these lines, the Common Agricultural Policy (CAP) of the European Union (EU) is built around these three components as goals for a sustainable system of agriculture. The CAP uses a wide range of targeted actions to financially incentivize and support farmers in the transition towards sustainable agricultural production and contribute towards the goals of the EU Green Deal (The European Commission, 2024b). Incentivized actions in the CAP reform for 2023-2027 that are considered to work towards sustainable agriculture include: promoting organic farming and encouraging new technologies for environmentally-friendly pesticide application, expanding broadband coverage to improve rural infrastructure, offering specific payments to young farmers to encourage generational renewal, and helping farmers adapt to the challenges that come with a changing climate through targeted advising on new methods and technologies (The European Commission, 2024c, 2024a). Still, critics of the CAP claim that this latest reform falls short of EU commitments on sustainable development set under the EU Green Deal; for instance, risks to biodiversity and ecosystem services may instead worsen through increased land homogenization, and funding allocations do not focus enough on mitigating agricultural emissions (e.g. Cuadros-Casanova et al., 2023; Pe'er et al., 2020). Specific to digitalization, the EU recognizes the digitalization of agriculture as a strategy to support the sustainability of agriculture, particularly by increasing the efficiency and competitiveness of the farming sector through information processing, automation, and robotization, while also lowering the environmental footprint (The European Commission, 2023).

2.2 Agriculture 4.0

Presently, dynamic interactions of environmental and socio-economic factors are transforming agriculture on a global scale. These factors include changing demands of local and global markets, intensification and commercialization of agriculture, climate change, and urbanization (Kraatz et al., 2021). Agricultural transformation has been defined as "the process over time by which the agri-food system transforms from subsistence-oriented and farm centered into more commercialized, productive and off-farm centered" (FAO, 2019, p. 2). At the same time, a digital transformation is occurring within and beyond the agricultural sector. For the purposes of this dissertation, I have used the following definition of the digital transformation: “a fundamental and ongoing socio-technological change process in which digitization and digitalization increase over time.” (Zscheischler et al., 2022, p. 3). Throughout this dissertation, the terms “digital transformation” and “agricultural transformation” are used frequently to describe the current, ongoing agricultural revolution.

Waves of agricultural innovations, sometimes referred to as agricultural revolutions, have occurred since the 16th century, each of which improved and reinforced the methods created in the wave preceding it (Mottram, 2022). Each innovation wave involved interactions between new technologies, food production, and society, and survival of agricultural enterprises often required adoption of the innovations and practices. The most recent (and frequently considered as ongoing) agricultural revolution is commonly referred to as the fourth agricultural revolution, or Agriculture 4.0. This is associated with the fourth industrial revolution, or Industry 4.0, as farming is a major sector of the primary industry (Arvanitis & Symeonaki, 2020). The term ‘Industry 4.0’ was first introduced in Germany in 2013 (Kagermann et al., 2019) and is considered a product of the megatrend digitalization (Munz 2021). Digitalization is a paradigm that connects the digital and physical worlds through Cyber-Physical Systems, enhanced by the Internet of Things (Pereira & Romero, 2017) and is impacting ways of life and economic business by allowing large amounts of data to be observed and transferred at great speeds and without loss of quality (Bode, 1997; Naisbitt, 1982). Therefore, Agriculture 4.0, in which the digital connections of production processes along the agricultural value chain are a central element (DLG e.V. & Griepentrog, 2019), can improve the efficiency and transparency of production, storage, transport, and sales of agricultural goods (Arvanitis & Symeonaki, 2020; Madushanki et al., 2019; Talavera et al., 2017; Uwe et al., 2016; Zambon et al., 2019). In this way, digital agricultural technologies aim to use closed-loop control to positively impact the productivity of agriculture and to reduce environmental damage (Mottram, 2022). The many dynamic developments that have emerged within the umbrella concept of Agriculture 4.0 have led to various systematizations that are widely grouped into the management concept of “precision farming” and the knowledge-based approach of “smart farming” (Gandorfer et al., 2017; Griepentrog, 2012; Munz, 2021). Similar to the dissertation by Munz (2021), I found the 5-level categorization model of digitalization in agriculture by Porter and Heppelmann (2014) to be the most harmonious with my own understandings of the term. This model, which begins with ‘single products’ such as a tractor as the first level of digitalization, evolves step-wise towards the fifth level, known as ‘systems of systems’, in which different data from diverse sources network and merge to optimize the overall performance of an agricultural enterprise (Munz et al., 2020; Porter & Heppelmann, 2014). Level two includes the addition of intelligence to the single product, like a sensor for location-identification, to become a ‘smart product’, whereas level three introduces the concept of a ‘smart, connected product’ which would, for instance, use the identified location to apply area-specific fertilizer (Maleki et al., 2008; Munz et al., 2020). An ‘intelligent product system’ emerges as a fourth developmental level of digitalization which focuses on optimizing process chains in addition to single processes (Porter & Heppelmann, 2014). Finally, the previously described fifth level is most closely related to the state understood by the term ‘smart farming’.

In the first article of this dissertation (Chapter 6), it is noted how the terminology, depth of digitalization, and agricultural sector differ amongst the existing studies on digital agricultural tools. The synonymous nature of the terminology in this field, as well as the lack of a clear definition of tools, complicates the already complex nature of this agricultural revolution. For this dissertation, the terms *digital tools* and *digital technologies* are frequently used. Digital tools are defined by Bacco et al. (2020) as a “physical and/or virtual instance relying on digital technologies (or on a set of those, as in a digital paradigm) having a given function as defined in its design phase”. Digital technologies, therefore, are a combination of hardware and software to make use of digital data (Bacco, Brunori, et al., 2020). Further distinctions can be made within digital technologies, which are clearly defined by Birner et al. (2021) as:

1. embodied digital tools, which are precision farming technologies that are embodied into physical devices like sensors or machines, and
2. disembodied software tools, which are in contrast not embodied in a specific piece of agricultural equipment, but can be used on computers or smartphones, such as advisory apps or farm management software.

In addition to these definitions, it is important to consider that technology is not limited to the physical hardware and technical software, but also includes the knowledge and associations required to implement the technology (Bijker & Pinch, 1987; Vik et al., 2021). This consideration is the core assumption of the social construction of technology (SCOT) which involves a complex interaction between different social groups, each of which sees future technology as a solution to a problem technology (Bijker & Pinch, 1987). The perspectives that these groups have about new technologies differ due to their distinct interests. Therefore, the question of whether digitalization actually mitigates challenges in agriculture is not necessarily about technical rationality, but rather about the beliefs that affected stakeholders have on the ability of technical innovations to solve their problems. This underlines the importance of understanding the expectations and adoption tendencies of stakeholders along agricultural value chains.

2.3 Technology adoption and acceptance

The pathway to technology implementation is not determined solely by technology-readiness, but also by the ability and interests of users to adopt the technologies (Rose & Bhattacharya, 2023). Understanding why people accept new technologies may improve methods of predicting the reaction of the users to new technologies (Dillon & Morris, 1996), which could in-turn lead to better user-oriented development of technologies. User acceptance has been considered as the pivotal factor in determining the success or failure of any information system project (Davis, 1993). Still, the adoption of innovations is complex and involves a process that is dependent upon the views of the receiver regarding innovativeness (Olum et al., 2020; Rogers, 1995). A vast number of adoption models and theories exist, some of which have been touched upon in the first article of the dissertation (Chapter 6). For instance, the popular technology adoption theory, the Theory of Planned Behaviour (TPB) (Fishbein & Azjen, 1975) tests influencing factors to a potential user's decision regarding when and how new technology is used (Pierpaoli, 2013). The widely used Technology Acceptance Model (TAM) by Davis (1989) was derived from the TPB and focuses on the perception of potential users and connection of intended or unintended use of new technology. Similar to TAM, yet specific to offers in the digital economy, the acceptance model by Kollmann (1998) also focuses on the expected use of technologies in relation to the possible applications in order to draw conclusions about acceptance (Munz, 2021). The Unified Theory of Acceptance and Use of Technology (UTAUT) model by Venkatesh et al. (2003) was designed to predict technology acceptance and builds off of findings from other reputable acceptance research models. Adoption models for technology with an economic focus have been widely studied and applied, such as the induced innovation theory (Hicks, 1932), the Net Present Value analysis as a basic method for investment decisions (Gallardo & Sauer, 2018), or the diffusion model by Griliches (1957). These economic theories generally disregard human factors related to technology adoption, such as uncertainties in the decision-maker or investment choice. This is where empirical studies are advantageous. Furthermore, Dillon and Morris (1996) have noted that the likelihood of finding a single-variable answer for the acceptance level of an information technology is low, considering the complexity of technology acceptance among users. Along these lines, Taherdoost (2018) argues that more than one theoretical approach is necessary for a complete understanding of the issues involved in technology adoption and acceptance.

Technology adoption in agriculture has been considerably researched across sectors and regions to understand and predict users' behaviors (Taherdoost, 2018). Some of these studies have used technology adoption theories and models to explain the intended adoption. If we look at studies on German technology adoption, farmer adoption of digital technologies have been assessed using discrete choice models (e.g. Tamirat et al. 2018), econometric models (e.g. Michels et al., 2020), TAM (e.g. Mohr & Kühl 2021), and the UTAUT (e.g. von Veltheim & Heise 2021). Other studies, such as the majority of reviewed studies on farmer acceptance of robotics and UAVs by Degieter et al. (2023), did not base their methodology on existing adoption theories or models. Degieter et al. (2023) suggested that this limited number was due to the novelty of the technologies. Empirical approaches are common among studies on technology adoption in agriculture. However, limitations in the existing studies have been observed. Most studies on technology adoption in agriculture have focused on industrial cropping systems, tend to underrepresent factors that are frequently examined in other industries, and do not adequately describe the complex nature of adoption (Pathak et al., 2019).

Typically, farmers embrace most agricultural innovations (Olum et al., 2020). Among many factors, Olum et al., (2020) emphasize personal and social characteristics, as well as the need for innovation, as key elements influencing farmer adoption of innovations (Kamrath et al., 2019; Meijer et al., 2015; Rogers, 1995). Socio-cultural barriers, particularly demographic issues related to aging and sparsely-populated regions, were found to be the main barriers for adoption of digital technologies in a study for which 30 European cross-disciplinary experts on digitalization of rural areas were interviewed (Ferrari et al., 2022). Indeed, farmer age is a key characteristic that is expected to greatly influence technology and innovation adoption (Abadi Ghadim & Pannell, 1999) and has been observed to be a significant factor in farmers' adoption of new technologies (e.g. Barnes et al., 2019; Jithin Das et al., 2019; Knierim et al., 2019; Michels et al., 2020; Rijswijk et al., 2020). Younger farmers have been found to be more likely to adopt smartphones (Michels et al., 2020), cloud technologies (Jithin Das et al., 2019), and precision agriculture technologies due to higher interest in new innovations than older farmers (Tamirat et al., 2018).

Still, farmer perception and attitudes towards new technologies may bear greater weight in adoption tendencies than demographic factors (Kernecker et al., 2016; Tey & Brindal, 2012). Farmers may feel a societal pressure to adopt innovative technologies for the common good (Ryan, 2023). Farmers who have implemented innovative technologies are perceived as contributing positively to society, having foresight, and acting in a morally-admirable manner (Gardezi et al., 2023). On the other side, social needs and cultural aspects, such as fear of new technologies and lack of technical competence, are observed barriers that should not be overlooked (Ferrari et al., 2022). Rural development policies should focus on specific approaches to meet such socio-cultural needs in the adoption decision process (Bacco et al., 2020).

Cost is another well-researched factor in the adoption of technologies among agricultural practitioners. Access in relation to cost was found to be the largest barrier among European farmers (Kernecker et al., 2016), while German farmers in the study by Knierim et al. (2019) and European farmers in the study by (Kernecker et al., 2020) most frequently reported cost and compatibility as barriers to the adoption of smart farming technologies (SFT). Smaller farms may face the barrier of cost more than larger farms. Farmers of small farms in the study by Kernecker et al. (2016) reported that their farms were too small for the existing SFT and that the SFT were too expensive to implement. Similarly, Das et al. (2019) found cost to be the most significant factor in SFT adoption among 32 surveyed Irish farmers and found lower-cost technologies for small farms to be unavailable.

Insight into current German adoption:

A study on digitalization in German agriculture conducted by Bitkom, an association of the German information and telecommunications sector, provides insight into current perspectives and adoption tendencies among farmers. The representative study included 500 German farmers with farm sizes of at least 20ha in Western Germany and at least 100 ha in Eastern Germany. Overall, digitalization is perceived positively by German farmers: 79% of respondents saw digitalization as an area of opportunity for their farm (Rohleder & Meinel, 2024). Environmental benefits were particularly interesting for the surveyed farmers: 91% believed digital technologies help spare fertilizer, pesticides, and other resources, and 80% believed digital technologies make a more environmentally-friendly agricultural production possible (Rohleder & Meinel, 2024). Barriers to adoption are numerous among German farmers: 75% reported high investment costs to hinder digitalization in agriculture, followed by concerns over more bureaucracy (61%), insufficient standardized interfaces and system networking (59%), lack of involvement in the planning of political measures (52%), insufficient internet coverage (51%), and concern about loss of data sovereignty (49%). Nevertheless, 90% of surveyed farmers use at least one of the digital technologies or processes listed in the survey, such as GPS-guided machinery, digital farm indexes, or farm or herd management systems (Rohleder & Meinel, 2024). Drones (UAVs) and robotics were reported to be lower on the spectrum of adopted tools by German farmers at 23% and 5% respectively. Yet other literature contests these adoption rates: German farmers were found to have relatively high actual adoption, with one out of 5 farmers already using UAVs (Degieter et al., 2023; Michels et al., 2021; Michels et al., 2020b). Other information on the demographics of farmers in this study and their agricultural sector are not provided. Furthermore, farmers with farm sizes under 20ha, a category that nearly half of Germany's fruit farms fit into (Kösler, 2023), were not included in the representative survey by Bitkom. However, farm size is a recognized factor that impacts German farmer adoption tendencies (Michels et al., 2020a). When divided into farm-size cohorts, the smallest farm size group (20-49 ha) in the survey were the least optimistic about digitalization in agriculture: 60% of these respondents saw digitalization as an opportunity for their farm and 23%, the greatest percentage among cohorts, saw digitalization as a risk for their farm (Rohleder & Meinel, 2024). Over half of the surveyed German farmers (60%) believed that digital technologies are only worthwhile for larger farms (Rohleder & Meinel, 2024). Literature on German farmer adoption of precision agriculture technologies further emphasizes the role that farm sizes plays in adoption tendencies. Paustian and Theuvsen found that German farmers managing farms under 100 ha are less likely to adopt precision technologies (2017). Similarly, Tamirat et al. (2018) observed that German farmers operating farms under 250 ha are significantly less likely to adopt precision agriculture systems than operators of larger farms.

Development of digital solutions in fruit cultivation is slower than in other agricultural sectors (Ossevoort et al., 2016). Limited studies on farmer adoption of digital technologies in fruit cultivation exist, particularly in Europe. Rose & Bhattacharya (2023) found overall optimism among soft fruit growers in the UK on autonomous robots, but a number of critical barriers were identified, including cost and infrastructure challenges and concerns about data ownership, cybersecurity, and trust. A reported disconnect between the farmers and the technology developers led to farmers struggling to keep up with the latest developments, despite using various methods to inform themselves on robotic solutions. The authors found that rapid progress towards adoption of autonomous robots in horticulture is unlikely, regardless of technical readiness, because farmers are continuing to report the same constraining factors over time, implying that measures to overcome the barriers to adoption are not being taken seriously enough (Rose & Bhattacharya, 2023). To this point, studies on farmer adoption of digital technologies for fruit cultivation in China (e.g. Yue et al., 2023) and Vietnam (e.g. Hoang, 2020; Yap et al., 2023) further establish that cost, digital literacy, and infrastructure hinder adoption.

3. Investigation area

3.1 Connecting the dissertation to the EU-Horizon 2020 project DESIRA

This dissertation was conducted in part through the EU-Horizon 2020 project DESIRA (Digitization: economic and social impacts in rural areas) (DESIRA, 2019a). This project ran from 2019-2023. During this time, I was employed as a research associate and was tasked with specific research duties for the DESIRA project. One task was to assess the impacts of digitalization in agriculture, forestry, and/or rural areas through the formation of a living lab, a transdisciplinary group of stakeholders with common interests. Based on expressed interest by a fruit farmer's association in the Lake Constance region in Germany (Figure 2), I co-established a living lab in this region that participated in various participatory research activities throughout the length of the project. During the establishment phase of the project, I saw the opportunity to expand on the research that I would be conducting through the DESIRA project, or rather, deepen certain aspects of the methods and research focus, for this doctoral work. This connection and thematic expansion is visible, for instance, in the interview guideline: the guideline covers topics outside of those relevant for this dissertation, as these were formulated to meet the research goals of the DESIRA project. Nevertheless, discussing these topics during the interviews allowed me to gain a broad insight into the fruit farming landscape and the impact of digitalization beyond the interview questions of focus for the dissertation articles.

Figure 2: Apple orchard in the Lake Constance region, neighbouring the Lake of Constance (source: Kirsten Gaber)

3.2 Case study area

The Lake Constance region in southern Germany is the case-study area for this dissertation. This geographical region is comprised of the counties of Konstanz, Bodenseekreis, Ravensburg in the state of Baden-Württemberg, and the county of Lindau in Bavaria (Figure 3) (Genuss Bayern, 2024).

Figure 3: The counties surrounding the Lake of Constance (Bodensee) (Bundesamt für Kartographie und Geodäsie, 2021) © *GeoBasis-DE / BKG (2021)*

In 2023, the region had an annual average temperature of 10.8° C, 1,932 sunshine hours, and 1,099mm of precipitation (Kompetenzzentrum Obstbau Bodensee, 2023b). Land area around the lake varies from approximately 400-560 m in altitude above sea level (Bodensee.de, n.d.). The lake boasts a large surface area of 571.5 km² and is a natural ecosystem, representative and significant for plants and animals in central Europe (Hammerl & Trötschler, 2006). The lake itself has German, Austrian, and Swiss shorelines. Approximately 4 million inhabitants within 320 towns and communities are supplied with drinking water from the lake; thus, all economic activities in the catchment area must consider the important role of the lake as a drinking water reservoir (Hammerl & Trötschler, 2006). The proximity to the nation's largest drinking water reservoir requires stringent regulations to govern the use of agricultural inputs in order to reduce the risk of runoff and leaching into the reservoir (Bodensee-Wasserversorgung, 2022). At the same time, the climate around the lake creates heightened mildew pressures, adversely affecting fruit production (Bodensee-Stiftung, 2013) and increasing the reliance on agricultural inputs to mitigate these adverse effects. Still, the lake provides a relative temperature balance between day and night, as well as between seasons, as the large water area functions as a temperature reservoir (Bodensee.de, n.d.).

This area is known for their long-standing traditions and cultures that have been largely shaped by agriculture. Agriculture has thrived in the Lake Constance region for centuries. The landscape around the lake was shaped by the history of fruit cultivation (Bodensee-Obst-Museum Frickingen n.d.). First brought to the region by Romans and established in monastaries as a basis for feeding the local population in the 17th and 18th centuries, fruit cultivation continues to form the livelihoods of local people and communities today (Bund für Umwelt und Naturschutz Deutschland, n.d.; Wacker, 2023). Cereals, potatoes, corn, and specialty crops such as fruit, vegetables, and wine are the most valued regional crops (Grimminger et al., 2018).

As the second-largest fruit growing area in the country, the largest in the state of Baden-Württemberg (Bundesministerium für Ernährung und Landwirtschaft, 2016), and the largest national cultivation area for pomaceous fruit (Hammerl & Trötschler, 2006), the Lake Constance region is plays a vital role in the regional, national, and international food supply. About 1,600 fruit farms cover approximately 10,000 ha of land in the counties of Konstanz, Ravensburg, and Bodenseekreis (Hammerl & Trötschler, 2006; Statistisches Landesamt Baden-Württemberg, 2020d, 2020f, 2020e) (Table 1). Within the state of Baden-Württemberg, 17,640 ha are dedicated to tree fruit production, 11610 of which are for apple production (Statistisches Landesamt Baden-Württemberg, 2022f). Nearly 80% of the cultivated apples in the state are produced for fresh consumption (Statistisches Landesamt Baden-Württemberg, 2022f). Other important regional fruit crops include pear, sweet cherry, sour cherry, plums, mirabelle plums, wine, and berry fruits. Based on increased demand for seasonal, regional strawberries over the previous decades, farmers in the Lake Constance region have increased investments in strawberry farming (Statistisches Landesamt Baden-Württemberg, 2018). The state of Baden-Württemberg is considered the second largest strawberry growing region in Germany and has dedicated 2,543 ha to strawberry cultivation, from which 218 ha are in protected farming like foil tunnels, and from which 68 ha are organic (Statistisches Landesamt Baden-Württemberg, 2018).

Table 1: Land usage (ha) for fruit cultivation in the Lake Constance Region (2020-2023)

Land usage (ha)	Year	Konstanz	Ravensburg	Bodenseekreis	Lindau[5]	Lake Constance region totals
Total agricultural area[1]	2020	33003	85956	33060		152019*
Total fruit cultivation[1]	2020	1014	1675	7320		10009*
Orchards [2]	2022	875	1460	6.679	1330	10344
Apple	2022	769	1169	5.754	521	8213
Pear	2022	36	46	263	110	455
Sweet cherry	2022	21	142	252	13	428
Sour cherry	2022	1		84	1	86**
Plums	2022	25	77	280	8	390
Mirabelle plums	2022	3		8		11*,**
Vineyards[1]	2020	67		571		638*,**
Berries[3]	2023	16	129	96		241*
Black currant	2023	1	53	26		80*
Red and while currant	2023	3		11		14*,**
Raspberries	2023	5	7	4		16*
Strawberries[4]	2020	85	283***	241		609*

*Sources: [1](Statistisches Landesamt Baden-Württemberg, 2020d, 2020f, 2020e); [2](Statistisches Landesamt Baden-Württemberg, 2022a, 2022d, 2022c);[3](Statistisches Landesamt Baden-Württemberg, 2023a, 2023c, 2023b); 4(Statistisches Landesamt Baden-Württemberg, 2020a, 2020c, 2020b; 5(Bayerisches Landesamt für Statistik, 2018). *totals do not include values from Lindau due to missing data;**totals do not include values from Ravensburg due to missing data, ***data from 2012 due to missing 2020 data*

The region is experiencing structural change within the fruit cultivation sector. Within Baden-Württemberg, the total number of fruit farms reduced by 11% from 2017 to 2022, yet the number of organic fruit farms increased by 14% (Statistisches Landesamt Baden-Württemberg, 2022f). The organically cultivated state tree fruit area grew by 34% in this time period (Statistisches Landesamt Baden-Württemberg, 2022f). Approximately 3260 ha in Baden-Württemberg are dedicated to organically-certified fruit cultivation (Statistisches Landesamt Baden-Württemberg, 2022f). This equates to approximately 18% of the state's tree fruit cultivation area (Kösler, 2023), which is slightly less than the national share of tree fruit cultivation area under organically-certified management at 21% (Statistisches Bundesamt, 2023a, 2023b). Outside of fruit cultivation, a larger proportion of agricultural area in Lake Constance region is certified organic than at state and national scales (Table 22): approximately 17% of the total Lake Constance region land area is certified organic (Bayerisches Landesamt für Statistik, 2016, 2022; Landesanstalt für Landwirtschaft Ernährung und Ländlichen Raum, 2023), exceeding the share of organically cultivated land in the state of Baden-Württemberg (12%) (Kösler, 2023) and in Germany (11%) (Statistisches Bundesamt, 2024). The average national farm size is about 63 ha (Bundesinformationszentrum Landwirtschaft, 2020). Nearly half of Germany's fruit farms are considered small at less than 20ha and the average size in the Lake Constance region is 8.8 ha (Kösler, 2023).

Table 2: Utilized land area and number of farms for total agricultural production and organic production in the Lake Constance region counties

	Year	Utilized land area (ha)	Number of farms	Utilized organically farmed land area (ha)	Number of organic farms
Germany	2023	16585500	255010	1852700	28630
Baden-Württemberg	2023	1405000	37500	196000	4770
County: Konstanz[1]	2020, *2022	33003	791	5440*	107*
County: Bodenseekreis[1]	2020, *2022	33060	1412	5598*	152*
County: Ravensburg[1]	2020, *2022	85956	2250	17338*	419*
Bayern	2023	3086500	81560	423000	10810
County: Lindau	2022, **2016	17068[2]	756[2]	4034[3]**	159[3]**
Lake Constance region totals:	2016-2023	169087	5209	28376	678

*Sources:Statistisches Bundesamt, 2024; [1]Landesanstalt für Landwirtschaft Ernährung und Ländlichen Raum, 2023;[2]Bayerisches Landesamt für Statistik, 2022;[3]Bayerisches Landesamt für Statistik, 2016. Asterisks refer to the values in the tables associated with different years due to data availability. As shown in the 'year' column, *refers to data from the year 2022, and ** refers to data from the year 2016.*

3.3 Overview on fruit cultivation and production

Within this dissertation, 'fruit cultivation' and 'fruit production' are two common yet distinctly different terms to describe activities related to fruit farming. The distinction lies in the term boundaries: for the purposes of this research, *fruit cultivation* refers to agricultural activities on the field, including irrigation, soil care, and harvesting, while *fruit production* includes fruit cultivation activities as well as post-harvest and marketing activities. The German term *'Obstanbau'* was used in the interviews, which translates to fruit cultivation, fruit growing, or fruit farming. However, stakeholders also used this term to refer to activities that would fit to fruit production, like marketing, and therefore both 'cultivation' and 'production' are used in this dissertation.

Along with vegetables and ornamental plants, fruit cultivation belongs to the branch of plant agriculture known as horticulture (Herklots & Perrott, 2024). German fruits typically belong to one of three categories: pome fruit, stone fruit, and berries (Garming et al., 2024). Horticulture is an intensive form of land management and has a high added value compared to arable farming (Dirksmeyer & Garming, 2024). While horticultural activities are conducted on only 1.3% of German agricultural land, these activities generate about 12% of the gross value added and employ about 15% of the agricultural labour force (Dirksmeyer & Garming, 2024). Horticultural production systems are inclusive of open fields and protected cultivation (such as greenhouses or foil tunnels), perennial permanent crops and short crops of a few weeks, and cultivation in nutrient solutions, substrate, or soil.

The fruit crops of interest for this work are those most commonly grown in Germany, as described in section 3.1.1, namely pome tree fruits such as apple and pear; stone tree fruits such as sweet and sour cherries, plum, apricot, and peach; and berry fruits including wine grapes, currants, raspberries, blueberries, and strawberries (Bundesministerium für Ernährung und Landwirtschaft, 2019a). Apple cultivation dominates German fruit cultivation, and Elstar and Jonagold are the most important national apple varieties, as they constitute more than one-third of the harvested apples (Garming et al., 2024). Fruit cultivation in Germany is composed of two distinct production systems: integrated production (IP) and organic production. The choice of agricultural inputs, or plant protection products (PPPs), and the holistic nature of the production system differentiate the two systems (Das Grüne Lexikon Hortipendium, 2021; Landwirtschaftliches Technologiezentrum Augustenberg, 2023). While IP fruit cultivation aims to reduce the use of PPPs and thereby reduce the risks posed by their residues, organic fruit cultivation avoids the use of chemical-synthetic inputs by prioritizing natural resources, such as beneficial insects, and mechanical measures like hoeing to keep the tree strip free of harmful or competitive weeds (Bundesministerium für Bildung und Forschung, 2015). As perennial crops, orchards require unique management in comparison to arable land, which is defined as area under temporary crops, temporary meadows, and land temporarily fallow (World Bank Group, 2016). Typically, an orchard bears commercial crops only after its first seven to twelve years and, with careful management, continues to be economically productive for another 50-100 years (Bannier & Naturschutzbund Deutschland, n.d.).

Fruit cultivation has shaped cultural landscapes for thousands of years. The development of settled agriculture and the evolution of villages to urban centers between 6000 and 3000 BCE coincided with the emergence of fruit culture (Janick, 2005). This is due to the long-term commitment to a specific piece of land (in the case of perennial fruits) and could therefore be the link associated with territoriality, the creation of city-states, and nationhood (Janick, 2005). However, the domestication of fruit trees has received less attention than that of annual crops and the best-known pioneer studies deal mostly with Old World fruits such as figs and olives (e.g. Goldschmidt, 2013; Zohary & Spiegel-Roy, 1972). Today, fruits and vegetables are recognized as vital components of a healthy diet as rich sources of important vitamins and minerals, fibre, and antioxidants. Based on evidence linking low fruit and vegetable consumption to poor health and diseases such as cardiovascular diseases and some cancer types, the World Health Organization (WHO) recommends consuming more than 400 g of fruits and vegetables daily (World Health Organization, 2023). For reference, an medium apple weighs approximately 165 g (Hyson, 2011).

It is not possible to detail the complexities of each activity involved in the cultivation and production of each relevant fruit crop within the context of this dissertation synopsis. However, it is useful to provide at least a basic overview of fruit cultivation activities for the overall understanding of the role that digital technologies and digitalization could play in the fruit cultivation landscape. Thus, the following section provides an overview on the cultivation and production activities for orchard fruits as an exemplary and theoretical basis for the relevant digitalization functions described throughout the dissertation.

Orchard management categories for the cultivation of fruit can be defined as: monitoring, pruning, irrigation, soil care, weeding, pest and disease control, and harvesting, although not all activities must be executed in each season (Philadelphia Orchard Project, 2021). Following harvest, post-harvest activities such as sorting and storage, as well as marketing activities, are also relevant for this dissertation work. As a key challenge for horticultural value chains is the maintenance of highly perishable products like fruits and vegetables, the Thünen Institute, a leading scientifically independent research institution in Germany, suggests that analyses of digitalization in horticultural production systems should consider the entire value chain (Dirksmeyer & Garming, 2024). Still, considering that most fruit grown in Germany is not processed into products like alcohol but is rather sold and consumed as table fruit (Bundesministerium für Ernährung und Landwirtschaft , processing activities were not considered relevant for this work.

> *Monitoring* of the orchard enables the farmer to keep an eye on the health of the plants and consider any other important conditions in the management area (Philadelphia Orchard Project, 2021). With the emergence of imaging technologies and monitoring platforms in agriculture, digital orchard management began to compliment empirical monitoring conducted by farmers (Zhang et al., 2019). Popsecu et al. (2023) argue that acquisition and continuous processing of orchard data has become a necessity for modern orchard monitoring in order to achieve the highest yield and quality of fruit.
>
> *Pruning* controls plant growth through the cutting and disposal of branches (Philadelphia Orchard Project, 2021). Standard fruit trees should be pruned each year to promote their vigor and allows young trees to establish a long-term stable crown structure; otherwise, the trees may bear first yields more quickly, but their growth will decelerate and the trees will ultimately age prematurely (Bannier & Naturschutzbund Deutschland, n.d.).
>
> *Irrigation* requirements of plants depends on numerous factors such as climate, plant aspects (e.g. production system, leaf area, plant type), soil composition and moisture content, age of the plant, and time of year (Köhler & Immik, 2012). Due to changing precipitation conditions and increased temperatures in recent years, water management in the Lake Constance region has become a priority among fruit farmers and although few orchards in the region are irrigated, more farmers are investing in water storage possibilities like wells and irrigation systems (Kompetenzzentrum Obstbau Bodensee, 2023a).
>
> *Soil care* is critical for the overall health of the orchard. The pH and mineral values in the soil can be balanced through various practices, including fertilizer and compost application, and

choice of orchard floor management. Factors influencing the choice of fertilizer composition, nutrient requirement and application timing, and method of application are complex and require in-depth knowledge of the soil composition, plant health, and regulatory standards for fertilizers. Incorrect application, for instance during unfavourable weather conditions or incompatible mineral compositions, can easily lead to damage of the fruit and leaves (Dienstleistungszentrum Ländlicher Raum Rheinpfalz, 2016). ‘Greening’ between orchard rows, as opposed complete non-cultivation or barren soil, with crops such as clover or grass-flower mixes, enables better water penetration into the soil, protects against soil erosion, allows for better navigability in unfavourable weather conditions, suppresses rodent infestation, restores organic matter, and increases biodiversity (Kienzle et al., 2016; LaRue, 1989; Novara et al., 2021; Wiman et al., 2009).

Weeding in fruit production is one of the most important cultivation measures in fruit growing, as the increased competition for light, water, and nutrients negatively influences the yield and fruit quality, and can also increase pest pressure in the orchard through, for instance, enabling better hiding places for rodents from their prey (Werth et al., 2020). Rodents damage orchard trees by gnawing on the bark and sometimes roots of trees, which is particularly harmful for young tree stems (Sullivan et al., 2018). Although IP fruit cultivation allows for herbicide use for weed control, given the societal and political discussions surrounding the use of chemical inputs in agriculture, such as the controversial total-herbicide and crop desiccant glyphosate, mechanical measures already used in organic cultivation to partially or completely replace the use of herbicides are gaining popularity among IP farmers (Werth et al., 2020). These measures include hoeing, mulching, and finger-weeders (Deutsches Landwirtschafts-Gesellschaft et al., 2022).

Pest and disease control is the orchard management category that differentiates production systems (organic and IP) most greatly. Few chemical-synthetic pesticides are authorized for use in organic cultivation; instead, preparations such as those that include copper, sulfur, and insect-harming soaps are allowed under regulations (Bundesministerium für Bildung und Forschung, 2015). Copper is a commonly used element in organic and conventional fruit protection formulas and has been since the end of the 19th century, due to its ability to fight off numerous fungal and bacterial plant diseases (Bund Ökologische Lebensmittelwirtschaft e.V. et al. 2010). However, due to associated risks including negative impacts on soil quality and biodiversity, copper use is kept to a minimum wherever possible or replaced by less harmful substances (Diesner et al., 2014). The use of beneficial insects is common in IP and organic fruit cultivation in Germany, and measures such as anchor plants and cover crops between rows provide habitat for beneficial insects and increase biodiversity (Eben & Herz, 2022; Kienzle et al., 2016).

Harvesting of orchard fruit varies by plant type but typically occurs between spring and fall. Orchard fruits like apples are still primarily hand-harvested by seasonal farm employees, as mechanical harvesting options such as semi-automatic harvesters are known to damage the sensitive fruits (Bundesinformationszentrum Landwirtschaft, 2024; Zhang et al., 2016). Timing of harvest determines the quality of the fruit as a food product and is indicated by numerous cultivar-specific factors. Apples, for instance, should be harvested when mature but not yet fully ripe, and their maturity indices include weight, colour, firmness, soluble solids content (SSC), and respiration intensity (Kvikliene et al., 2011).

Post-harvest management includes activities of cleaning, washing, selection, grading, drying, packing, and storage, with the collective aims of removing undesirable elements from the food products, improving product appearance, and extending shelf-life (El-Ramady et al., 2022). Post-harvest activities take place on- or off-site, such as through wholesale companies or fruit distribution cooperatives. Technological innovations for the storage of fresh fruits and vegetables, such as controlled-atmosphere storage (CAS) which reduces oxygen and increases carbon dioxide to slow the rates of ripening and senescence (Rama & Narasimham, 2003), offer to extend the shelf-life of fresh produce, but also require space and energy to do so. Maintaining appropriate conditions to prolong the shelf life of perishable products following harvest greatly influences the overall sustainability of the fruit value chain. The FAO estimates food losses during post-harvest activities to comprise approximately 5% of the total 45% of the initial production lost or wasted along the supply chain for fruits and vegetables in Europe (Gustavsson et al., 2011).

Marketing of fruit is complex and governed by quality standards and consumer preferences. Within the EU, the General Marketing Standard applies to the majority of fresh fruit and vegetables, while the Special Marketing Standards apply to the ten fruits and vegetables with the highest market share, including apples, pears, strawberries, peaches and nectarines, and grapes (Bundesanstalt für Landwirtschaft und Ernährung, n.d.). These standards regulate qualities such as size, weight, cleanliness, appearance, and ripeness level. Further quality requirements exist on the side of the food retailers, driven largely by the aesthetic demanded by consumers and logistical aspects (Verbraucherzentrale Niedersachsen e.V. & Bundesministerium für Ernährung Landwirtschaft und Verbraucherschutz, 2022). Generally, fruit in Germany is sold through one of three channels: through food wholesalers, food retailers, or direct marketing. Fruit cooperatives and distribution companies also work to market and trade fruit between producers, retailers, and consumers. Organic fruit in Germany is marketed primarily through natural food wholesalers, although food retailers and direct marketing have been on an upward trend in recent years (Bundesanstalt für Landwirtschaft und Ernährung, 2017).

4. Methods

4.1 Research approach

In order to fulfill my research objectives, I conducted empirical research with a qualitative methodological approach, complimented by quantitative data like descriptive statistics. The temporal aspect of this research should be considered as in-situ, as the digital transformation of fruit production is ongoing. Thus, this research has been conducted at a critical point in the agricultural transformation and in the development of digitalized agriculture and the results of this work can aid in designing a more user-oriented way forward. The current and future needs of the users of digital technologies in agriculture must be considered to ensure a sustainable and fair technological development. Furthermore, the knowledge of actors and of society on the social acceptance of technologies can influence the sustainability of the transformation; therefore, involving stakeholders through, for instance, participatory research, is critical for a sustainability-oriented transformation.

According to Hirsch Hadorn et al. (2006), sustainability research is a setting that addresses issues by answering three basic and interrelated questions: (1) In which way do processes constitute a problem field and where are the needs for change? (2) What are more sustainable practices? (3) How can existing practices be transformed? Furthermore, Lang and Wiek (2016) describe sustainability research to address issues that threaten the viability and integrity of societies around the world. These authors argue that sustainability research can be divided into two research streams: (1) descriptive-analytical sustainability science and (2) transformational sustainability science, the former of which describes and analyses complexity, dynamics, and cause-effect relations of sustainability problems (Collins et al., 2011; Ostrom, 2009; Turner et al., 2003), while the latter focuses transforming the problems into solutions by providing evidence-supported solution options (Miller et al., 2014; Sarewitz et al., 2012; Wiek et al., 2015). Based on these descriptions of sustainability research, this dissertation involves descriptive-analytical research within the setting of sustainability research. Transformational sustainability science as a future research avenue is discussed in Chapter 9.

4.2 Overview of methods used within the dissertation

In order to answer the research questions of this dissertation, two key methodologies were used: a comprehensive digital tool review and an interview series with stakeholders. These methodologies are explained in detail in the corresponding sections of the articles and are contextualized with the appropriate stakeholder groups and papers in Figure 1.

While the digital tool review (article 1) established a robust knowledge basis on existing digital technologies for fruit production for which to continue the research, the methodological core of the dissertation was the stakeholder interview series. Therefore, it is valuable to take a closer look at this approach, particularly in relation to the overall research setting discussed in the previous section.

Participatory approaches generally enhance the feasibility of sustainability interventions and a solution orientation by integrating the values of different societal actors (Horcea-Milcu et al., 2019; Wiek et al., 2014). The individual perspectives of relevant stakeholders are instrumental for research on transformations: this type of assessment offers not only a time-stamped record of stakeholder perspectives during the ongoing development of digialization in agriculture, but also enables their percieved challenges and chances to be considered in the development of technologies for a more user-oriented future.

As described in detail in article 3, I have used the definition of a stakeholder as provided by Freeman (1984, p. 46): “any group or individual who can affect or is affected by the achievement of the organization’s objectives”. In order to answer the research questions of this dissertation, the ‘organization’ can be considered as the agricultural sector of fruit cultivation and the ‘objective’ would be the digitalization of the sector as a potential future scenario. A meticulous and reflective process for stakeholder selection, as detailed in the corresponding articles, ensured a nuanced understanding of the various viewpoints held by the Lake Constance region’s fruit farmers, providing insights on the complex dynamics of digital technologies and fruit production. Overall, stakeholder selection followed a purposive sampling approach (Bryman, 2012), guided by two key criteria: (1) stakeholders identified as either intended users or developers of digital technologies, and (2) stakeholders engaged in the fruit value chain, spanning farm-level participants, marketing and wholesale representatives, and those viewing the industry from a broader technology or research perspective.

As visualized in Figure 1 in section 1.3, not all stakeholder responses were used for each article. Selection was based on the relevance of the stakeholder groups to the research questions. In the case of article 3, the interview questions were formulated following the first interview in the interview series, as the importance of these questions became evident in the discussions with that digitalization expert, therefore this article includes the responses from all stakeholders except for the first.

Between February 2020 and April 2021, 34 stakeholders from six stakeholder groups, categorized by collective stakes (Table 3), participated in semi-structured interviews (guideline in synopsis Appendix). Descriptions of the stakeholder groups are provided in each article. 15 interviews were conducted digitally using video conference software, while 19 were conducted in-person. Stakeholder characteristics were collected during the interviews (Table 5 in the synopsis Appendix). The interview process adhered to the principle of free, prior, and informed consent from all participants. Each interview had an approximate duration of one hour and were recorded with consent. The recordings were anonymized, transcribed, and analysed using qualitative content analysis (Mayring, 2000) with the support of MaxQDA2020 software.

*Table 3: Stakeholder groups stakes, number of stakeholders, and proportion of the group within the total number of stakeholders. Descriptions of the stakeholder groups can be found in articles 1-3 (Chapters 6-8). *referred to as 'fruit cultivation and plant protection products 'PPP' advisors' in article 1 (Chapter 6); **referred to as 'agricultural machinery and digital innovation developers' in article 1 (Chapter 6); in these cases, the titles of the groups changed over the duration of the dissertation, but the stakes remained the same.*

Stakeholder group	**Stakes**	**#**	**%**
Fruit farmers	Farmers are considered as one of the main user groups in the development of digital technologies for agriculture. The digitalization of agriculture has the greatest influence on this stakeholder group and their ways of life.	8	24%
Cultivation consultants*	Functions of digital technologies for fruit farming can work to assist consultants with their advising duties, but may also threaten to replace the functions of this group.	5	15%
Fruit wholesalers or marketers	This group works at the interface between public and farmers and performs as a critical piece of the fruit value chain. Functions of existing digital tools offer to improve or obviate their professional tasks.	5	15%
Technology developers**	Technology developers directly affect the design of digitalized technologies in fruit production but are also therefore financially and professionally dependent on the continuation of digitalization.	5	15%
Researchers	Researchers function as neutral, objective assessors of their fields. They search for knowledge to solve problems. Researchers with in-depth knowledge on the listed fields offer valuable insights into the impact that digital technologies in fruit cultivation may have.	5	15%
Nature, agriculture and consumer associations	These stakeholders represent the interests of the relevant associations for the Lake Constance region and have professional, personal, and financial interests in maintaining sustainability of regional agriculture.	6	18%

4.3 Reflexivity and ethical considerations

Qualitative research celebrates the participants' personal and unique experiences, thus so too should those conducting the research reflect on their own experiences and roles as researchers and incorporate these viewpoints into the research process (Jamieson et al., 2023). Reflexivity in research is defined as "the conscious, active acknowledgement of one's own belief, bias, and judgement systems before, during, and after the actual research process" (Jamieson et al., 2023, p.2). As a researcher, I strive to take a neutral, objective stance in the research process. I strove to remain neutral during all stages of this research, to view all sides in this digital transformation, as well as options outside of the digital transformation, objectively towards mitigating the sustainability challenges. At the same time, I recognize that my culture, socialization, education, personal values and beliefs may unintentionally influence decisions during the research procedure, for instance phrasing of interview questions or coding of interview excerpts. Through methodological reflexivity (see e.g. Patnaik, 2013), standardized procedures were followed during the research process while also acknowledging the rationality of my own views as a researcher. Specifically, the funding project in which the research was situated in, DESIRA, as well as the regular meetings with supervisors (who, naturally, also bring in their own experiences and values), created a framework in which the work was continuously and iteratively reflected upon and reinforced in methodological procedures. Qualitative research requires researchers to uphold informed consent, confidentiality, privacy, and practice honesty and integrity (Eungoo & Hwang, 2021; Richards & Schwartz, 2002). To meet these ethical standards for qualitative research and those enforced by KIT and Hohenheim for data privacy, I provided informed consent to each stakeholder for the purpose of the interviews, who in return signed an agreement allowing the use of their anonymized responses. I explicitly stated my position as a researcher at KIT and in the DESIRA project to each stakeholder in the immediate stages of contact and again during the interviews.

4.4 Methodological limitations

A number of factors limited the methodology of this dissertation. Although each relevant limitation has been described in the papers, they are critical considerations when interpreting the results; thus, I will additionally provide a summary of them in this section.

The case study research approach itself is limiting, in that the specific regional, demographical, and sectoral context must be considered when looking at the results of the study. Arguably, the case study region and the interviewed stakeholders provided rich contextual information with which I could answer the research questions. However, the sample size is notably small and cannot be statistically representative of the fruit growing sector. The applied stakeholder selection methodology was appropriately adjusted to reach as many stakeholders as possible in the case study region. Given the known factors regarding technology adoption and knowledge (as discussed in Chapter 2) in agriculture, I sought to interview stakeholders who represented an even range of the demographic characteristics gender, farm size, and age among stakeholders. Reaching an even distribution of these characteristics sometimes proved challenging; for instance, in regards to gender, a number of times that I contacted farming families as stakeholders, I would speak to a female-identifying member of the family, and she would directly hand the phone to her husband once I mentioned the topic as digitalization in agriculture. Although some other stakeholder groups had a more even gender distribution than the farmer group, stakeholders within the groups ‘cultivation consultants’ and ‘researchers’ all identified as male. Of the total 34 stakeholders, 21% of stakeholders identified as female and 79% identified as male. This aspect is touched upon again in Chapter 9. I observed that while most the interviewed stakeholders were keen to discuss this emerging field of digitalization in fruit production, some stakeholders, including some who declined an interview, were tired of simply discussing this and other topics with researchers such as myself, as is the case in such empirical descriptive-analytical sustainability science. Instead, more interactive participation could be an avenue for more transformative sustainability research with stakeholders in this region. This topic is discussed further in Chapter 9. Overall, the selection procedure was exhaustive of the relevant stakeholders in the region at the time of the interviews.

Stakeholders were asked to self-report on their own levels of digital knowledge based on a Likert scale from low to high. A wide range of responses were provided, as can be seen in the publications and in the table of stakeholder characteristics provided in the synopsis Appendix. The role that farm size and tradition plays in this aspect is worth consideration. Small- to medium- sized family farms, such as those found in this case study region, have been observed to lack digitalization (Regan et al., 2018) and be less inclined to adopt digital technologies than larger farms (Kernecker et al., 2020; Linsner et al., 2021). Furthermore, family-run farms in Germany have been found to prefer well-established technical solutions over new innovations (Cravotta & Grottke, 2019). It should also be noted that in this study, the terms ‘small’ and ‘large’ were not given exact units, but rather depended on the relative understanding of each stakeholder. This relativity is commonly found in studies on differences between small and large farms (e.g. Ebel 2020)

The temporal aspect of the interviews is also critical for the consideration of the results. The work for this dissertation began in 2020 and the stakeholder interviews were conducted between February 2020 and April 2021. First recognized at the end of 2019, the SARS-CoV-2 virus, commonly referred to as COVID-19, became a global pandemic within just a few months and lead to multiple “pandemic waves” between 2020 and 2023 (Robert Koch Institut, 2024). The first two waves were most prominent in Germany between the beginning of 2020 until the beginning of 2021 (Robert Koch Institut, 2024). During this time, social distancing measures were heavily enforced at various spatial scales and varying intensity. Fear, uncertainty, and confusion were common during this time, coupled with the necessity to continue livelihoods and professions under new, or at least altered, circumstances. To accommodate for social distancing regulations and preferences of the stakeholders, I offered digital and in-person interviews during the interview series. Although I cannot say with certainty if I would have reached a wider or different stakeholder demographic under different conditions, I do believe that the circumstances may have limited the reach of this methodology.

The COVID-19 pandemic and the government-mandated safety measures created extreme tensions in the German agricultural landscape. For one, the travel bans reduced the availability of seasonal migrant labourers, leading to the threat of a potential national and international food shortage (Bogoeski, 2022). To mitigate this challenge, a political exception for seasonal farmworkers from parts of Europe was issued, allowing thousands of seasonal farmworkers into Germany for the harvest season (German Federal Ministry for Food and Agriculture, 2020; Industriegewerkschaft Bauen-Agrar-Umwelt Bundesvorstand & Institut für nachhaltige Regionalentwicklung in Europa (PECO-Institut e.V.), 2020). However, intensive media coverage of the shared accommodation facilities and transportation of these seasonal migrant workers, which did not always adhere to the social-distancing measures that the majority of the population were enforcing to reduce the spread of the COVID-19 virus, raised ethical concerns and societal awareness surrounding the living conditions of migrant agricultural labourers (Bogoeski, 2022). The conditions were not necessarily a result of the ‘state of exceptionalism created by the pandemic’ (Bogoeski, 2022), but rather highlighted the inequitable living and working conditions of the migrant agricultural laborers (Reid et al., 2021). Thus, tensions at the farm level (regarding for instance worker availability) but also between farmers and society were particularly high at the time of the interview series for this dissertation. It is likely that the expressed frustrations towards the social challenges of labour availability and migrant labourers were influenced by this temporal aspect. Just as the interview results would be different if they were conducted today due to different political and societal circumstances, regardless of the global pandemic, the temporal aspect is critical to consider in research results.

5. Results overview

The results of this cumulative dissertation are represented by the three scientific articles presented in the following chapters. This section provides detailed summaries of each article and their publication status (Table 4). All three articles share the same team of authors: myself, as lead author; my supervisor and colleauge at KIT as well as my external mentor for my PhD, Dr. Christine Rösch; and my PhD supervisor at the University of Hohenheim, Prof. Dr. Claudia Bieling. My co-authors provided extensive and valuable support throughout the conceptualization, methods, result analysis, and framework development to create professional and cohesive narratives through which the research goals of this dissertation could be met.

Table 4: Overview of scientific articles for the dissertation

Article #	**Dissertation chapter #**	**Paper title**	**Journal**	**Status of publication**
1	6	Digital transformation of fruit farming in Germany: digital tool development, stakeholder perceptions, adoption, and barriers	NJAS: Impact in Agricultural and Life Sciences (T and F Online)	Published in NJAS
2	7	Exploring the impact of digitalization on sustainability challenges in German fruit production from the perspectives of stakeholders	Discover Sustainability (Springer)	Published in Discover Sustainability
3	8	The impact of digitalization on the public opinion of fruit farming: stakeholder perspectives in Germany	NJAS: Impact in Agricultural and Life Sciences (T and F Online)	Published in NJAS

5.1 Summary of article 1: Digital transformation of fruit farming in Germany: digital tool development, stakeholder perceptions, adoption, and barriers

The agriculture industry is undergoing a digital transformation, which aims to provide technical solutions for current and future challenges. However, it cannot be assumed that these solutions will automatically lead to the implementation of technologies, nor that they will meet user expectations. To address this issue, the authors combined the two research methods of the dissertation (digital tool review and interview series) to comprehensively analyze whether the available digital tools for fruit production meet the expectations of interviewed stakeholders. A conceptual background on existing state-of-the-art reviews on digital technologies in agriculture, as well as on technology adoption, at the beginning of the paper established a foundation for the rest of the article. This background section additionally highlighted the importance of participatory research on technology adoption and for technology reviews based on on-farm tasks to bridge the gap between theory and reality, particularly in fruit cultivation. The authors reviewed over 200 digital tools based on a novel characterization, focusing on on-farm tasks for better usability of the results. The assessed tools adhered to specific selection criteria and fell within the defined boundaries of the fruit value chain for the study. Fourteen inductive or deductive categories were used to organize the review, some of which were used to code the stakeholder descriptions of digital fruit production. This paper considered only the four stakeholder groups that were most likely the end-users or the developers of the technologies (fruit farmers, cultivation consultants, fruit wholesalers or marketers, and technology developers), resulting in 23 total stakeholder interviews. Authors conducted a cross-analysis of the available tool characteristics, stakeholder expectations, and adopted digital tools by using descriptive statistics as grounds for identifying commonalities and discrepancies. Upon consideration of the commonalities, discrepancies, and the reported barriers to adoption, the authors identified opportunities for more suitable technological development. These include reducing the investment cost barrier by focusing development efforts on tools with multifunctionalities (perform multiple on-farm tasks), tools that have independent usability (does not require the purchase of additional technologies to function), and tools that do not require purchasing, but can rather be hired based on short-term requirements. Additionally, few of the reviewed tools were available with German language technical support. This functional barrier could be a cause of the slow technology uptake in the German fruit cultivation sector. However, an uneven distribution of knowledge on digitalization in this sector was evident among stakeholders due to misinformed marketing and insufficient information, which could additionally influence the adoption rates. Therefore, the dissemination of knowledge and the marketing of digitalized technologies for fruit production should be improved in order for potential users to be able to make informed decisions for or against adoption. The lack of appropriate tools in this sector of German farming indicates evidence of a technology-push development without adequate consideration of user needs. The cooperation between users and developers in the fruit value chain is recommended to understand the causes behind the discrepancies and amend the existing gap between expectations and reality, thus improving usability of digital technologies in fruit cultivation.

5.2 Summary of article 2: Exploring the impact of digitalization on sustainability challenges in German fruit production from the perspectives of stakeholders

Despite facing unique sustainability challenges, the fruit sector has been considered less often than other sectors during the research and development of digital technologies. If this continues, the fruit sector is at risk of being left behind in the ongoing digital transformation of agriculture. At the same time, qualitative research to assess the impact of digitalization on sustainability in fruit cultivation are limited. To fill the knowledge gap, authors analysed semi-structured interviews with stakeholders along the fruit value chain in the case study region of Lake Constance, Germany. Six stakeholder groups were identified as relevant for the focus of this article - fruit farmers; technology developers; cultivation consultants; researchers; nature, agriculture, and consumer associations; and fruit wholesalers or marketers – from which 34 interviews were conducted. Interviewees were asked to describe the most important environmental, social, and socio-economic challenges for fruit cultivation in the Lake Constance region. Stakeholders named the societal acceptance and understanding of fruit cultivation practices, restricted plant protection product (PPP) use, labour availability, and biodiversity support to be key challenges in fruit production. Stakeholders were overwhelmingly optimistic that digital technologies could effectively address the reported environmental challenges in fruit production, particularly through perceived potential for increased efficiency via digital technology implementation. Stakeholders were less confident that the socio-economic challenges could be mitigated through digital technologies. Stakeholders described a missing connection between digital technologies and the described socio-economic challenges, implying either a lack of suitable technologies, or inadequate dissemination of information on the existing technologies to the relevant stakeholders. Differences in challenges and potential for mitigation emerged based on production system and farm size. The majority of stakeholders believed there were differences in challenges based on production system, particularly in regards to those related to PPP and fertilizer use and societal acceptance. While less than half of interviewed stakeholders believed environmental challenges differed based on farm size, over 80% of stakeholders believed farm size does imply a difference in socio-economic challenges. For instance, farm organization and management was reported to be easier for larger farms, and they would be more likely to benefit from economies of scale.

In light of the stakeholder responses and regional context, digitalization should be considered as a tool that offers opportunities to mitigate current sustainability challenges in the Lake Constance fruit production sector, with some considerations. Despite their abundance and complexity, socio-economic challenges are not currently supported by agricultural policy and funding schemes; thus, authors implore that equal attention is given to these challenges and those related to the environment. Furthermore, support and design of technical solutions for fruit farming must be inclusive of small fruit farms and cater specifically to their reported needs, including non-exclusive market policies and cost-effective technical solutions. Finally, dissemination of information on digital technologies in fruit production must be improved to support informed adoption choices for intended users and to enable the public to formulate informed opinions on the sustainability of fruit cultivation practices.

5.3 Summary of article 3: The impact of digitalization on the public opinion of fruit farming: Stakeholder perspectives in Germany

Societal criticisms of agricultural production are creating tensions between the public and farmers and challenging the future of farming. Digitalization in fruit production may create significant social and environmental impacts through increased on-farm efficiency and transparency along the fruit value chain, yet it remains unclear how the public image of fruit production could change through digitalization. Using a qualitative, open, and exploratory case study approach, this study investigated the perceived impacts of digitalization on the public attitude towards fruit production. Specifically, authors sought to understand how stakeholders perceived the public opinion of fruit farming, how stakeholders believed that the use of digitalized technologies in fruit farming (general, meaning regardless of production system, and organic) would influence public opinion of the products and production methods, and how they believed that different technologies could create an impact. To this end, the authors analysed 33 of the stakeholder interviews conducted for this dissertation from the six stakeholder groups. The interviews were transcribed and subsequently analysed using qualitative content analysis (Mayring, 2000), supported by MaxQDA 2020 software. A two-part inductive coding process, as outlined by Saldaña (2013), was chosen as the most appropriate coding type for the aims of this study; first, structural coding broke the information into clear sections, then pattern coding was used to iteratively group and re-group codes to identify emerging patterns in the content per question. Overall, 73% of stakeholders believed that digitalization could change the public opinion of fruit production, and 48% believed that the production system (e.g. organic or IP) matters in the impact that digitalization could have. Positive impacts were anticipated more frequently than negative impacts. Cultivation consultants and fruit farmers were particularly optimistic in this regard, while representatives from nature, agriculture, and consumer associations anticipated negative impacts more than any other stakeholder group. Additionally, two clear pathways emerged through which these positive or negative impacts could occur: 1) through the use of on-farm digital tools, or 2) through increased transparency along the value chain enabled through digitalization. For instance, improved trust of farmers and/or farming practices was anticipated through the use of digital tools for increased transparency, but at the same time, transparency was reported to risk changing the existing perception of agricultural practices in a negative way, such as through de-romanticization among consumers with inaccurate understandings of current fruit cultivation methods. Similarly, although on-farm usage of digital tools could positively impact public image through the reduction of agricultural inputs, the use of these tools may not fit to the ‘natural’ organic image, and therefore negatively influence public perception. Stakeholders frequently expressed concerns that the basis of knowledge about agricultural practices in society is too low. Some stakeholders credited the media and marketing strategies for this perceived deficit, which could challenge the potential benefits that digitalization could have on public opinion. Still, results demonstrate that the impact that digitalization could have on the public opinion of fruit farming may be contingent upon the narrative surrounding the use of digital technologies and their impacts, rather than the use of the tools alone. Authors conclude that prioritizing honest communication about fruit production and building trust towards farmers, such as digital technologies that could enable two-way communication between consumers and farmers, should be central goals of digitalization.

6. Digital transformation of fruit farming in Germany: digital tool development, stakeholder perceptions, adoption, and barriers

Published in NJAS: Impact in Agricultural and Life Sciences
(https://www.tandfonline.com/journals/tjls20)

Full reference: Gaber, K., Rösch, C., & Bieling, C. (2024). Digital transformation of fruit farming in Germany: Digital tool development, stakeholder perceptions, adoption, and barriers. *NJAS: Impact in Agricultural and Life Sciences*, *96*(1). https://doi.org/10.1080/27685241.2024.2349544

6.1 Abstract

The digital transformation of agriculture promises technical solutions for present and future challenges. However, it cannot be assumed that such promises will automatically lead to implementation of the technologies, nor if the technologies meet the user expectations. To this end, the authors conducted a novel review and characterization of over 200 digital tools for fruit cultivation by on-farm functions and 23 interviews with stakeholders related to fruit cultivation in the case-study region of Lake Constance, Germany. Results indicate strengths and weaknesses in the development of digital tools. A cross-analysis of the available tools, stakeholder expectations, and implemented tools indicates commonalities and discrepancies. Tool characteristics that meet stakeholder expectations and adoption by farmers are identified, as well as those that may be impacted greatest by the reported barriers. An uneven distribution of knowledge on digitalization in this sector was evident among stakeholders. The authors identify opportunities for technological development and recommendations to support a user-oriented transformation. Unsuitable tool development and an uneven distribution of digital knowledge in the fruit production industry could lead to a consequential sectoral, regional, and/or national digital divide between those with access to cutting-edge technologies and those without. To further improve the sustainability and resilience of food production, technological development must take into account the needs of stakeholders and support a more user-orientated strategy to support the transformation. Further research on stakeholders' perspectives on digital innovations is needed to investigate if the findings match to other fruit growing regions in Germany and abroad.

Article History: Received 12 October 2023; Revised 20 March 2024; Accepted 25 April 2024

Keywords: Digital technologies, Biodiversity, Agricultural inputs, Labour availability, Societal acceptance, Lake Constance

6.2 Introduction

Agriculture 4.0, in which physical and virtual objects, or digital tools, are controlled and connected through smart networks along the agricultural value chain, can improve the efficiency and transparency of production, storage, transport, and sales of agricultural goods (Arvanitis & Symeonaki, 2020; Deichmann et al., 2016; Madushanki et al., 2019; Talavera et al., 2017; Zambon et al., 2019). Digital tools can improve production efficiency by minimizing the use of water, fuel, and fertilizer through increased precision techniques and by promoting the use of renewable energy (Haarlem, 2020; Miranda et al., 2019). Digital tools are defined by Bacco et al. (2020a) as a "physical and/or virtual instance relying on digital technologies (or on a set of those, as in a digital paradigm) having a given function as defined in its design phase". Digital technologies, therefore, are a combination of hardware and software to make use of digital data (Bacco et al., 2020b).

There is high hope that digitalization can support the transformation of the agriculture and food sector to become both more efficient and more sustainable. Consequently, environmental impacts and social concerns are to be mitigated. Though agriculture has been attributed as having a leading role in German digitalization (Bitkom et al., 2020), the digitalization of the fruit sector is lagging behind (Ossevoort et al., 2016). A wide range of digitalized tools for fruit farming exists, yet little is known about how or if these meet the needs and expectations of technology users.

The models of digital technology development govern the distribution and availability of technologies across agricultural sectors, geographical regions, farming systems, and farm sizes. Digitalization may be driven by the technology-push (TP) model, fostered by advances in science and technology (e.g. Global Navigation Satellite Systems, sensors, web platforms and app applications on mobile phones), or the demand-pull (DP) model, for which technology development emerges as a response to the perceived market potential (Rothwell & Zegveld, 1985). TP and DP are interdependent because R&D objectives may be demand-selected and market needs may arise in response to innovation (Saviotti & Pyka, 2013).

According to the core assumption of the social construction of technology (SCOT), technology includes the physical hardware as well as the required knowledge and associations to implement the technology (Bijker & Pinch, 1987; Vik et al., 2021). The social construction involves a complex interaction between different social groups, each of which sees future technology as a solution to a problem. These groups have their own unique interests, which are reflected in their varying opinions about the emerging technologies. Whether or not digitalization actually solves the problem of agriculture, and in this case study of fruit production, is not a question of technical rationality but depends significantly on whether the affected stakeholders believe that the technical innovation can solve their problems. Therefore, understanding if the digital tools available match the expectations of digital technology consumers, such as farmers and other agricultural actors like advisors, marketers, and developers, is critical for the diffusion of innovations. Beyond that, technology use by individual farmers determines their participation in the transformation and the speed of its progression.

Farmers require technological support to tackle the present and future techno-economic, environmental and social challenges of fruit production. The fruit sector in particular is highly unpredictable with workability restraints such as labour shortages (Marinoudi et al., 2021). Other challenges include dependency on laborers for hand-labour such as tree thinning, the political demands on the use of production resources (e.g. pesticides, fertilizers), increasing crop failure due to higher frost rates and water requirements from climate change, and increasing consumer pressure for sustainable, high-quality, and low-cost fruit.

Against this background, the aims of this study are as follows:

- To provide a comprehensive review of available digital innovations in fruit farming based on on-farm tasks
- Investigate expectations for digitalization in fruit production, barriers, and adoption from stakeholders in case study region
- identify commonalities and discrepancies between characteristics of digital tools for fruit production with the expectations of stakeholders and adopted tools

We hypothesize that in times of strong policy support in a technological field, such as digitalization, businesses will focus on providing technical tools and competing in the fast-growing market rather than on the market's needs, therefore following technology-push policies rather than demand-pull.

The digital tool review fills the research gap surrounding characteristics of digital tools in fruit production and serves as a status-quo marker for the timeframe of the analysis. The qualitative interview assessment and the comparative results highlight the extent to which interviewed stakeholder needs are being met, potential for further tool development, and knowledge gaps of stakeholders on abilities of digital tools. This study provides valuable information to future users of the reviewed technologies, tool developers, and policymakers at a critical moment in time, as the transition towards the fourth agricultural revolution is still underway, and deficiencies in digital tool development could create inequalities across agricultural sectors and geographical regions.

The rest of this article is structured as follows. Section 2 introduces a background on previous state of the art (SOTA) studies for digital agricultural tools and technology adoption. Section 3 details the methodologies used for the digital tool review and the stakeholder assessment, interview series, interview content analysis, and cross-analysis. Section 4 contains the results of this article and thus describes the outcomes of the digital tool review, qualitatively assesses technology adoption and barriers among farmers in the case study region, and compares the perceived characteristics of digitalized technologies in fruit production with the characteristics of adopted tools and of those found in the tool review. Section 5 discusses the study limitations, the derived implications from the cross-analysis, the intricacies of the farmer interviews, and identifies opportunities for digital tool development. Finally, Section 6 concludes this paper.

6.3 Background

6.3.1 State of the art studies for digital agricultural tools

Terminology, depth of digitalization (e.g. systems perspective versus individual technology categories), and agricultural sector of study differ amongst previously published SOTA studies on digital agricultural tools (see Appendix). For instance, while some studies use the term “precision agriculture technologies” (e.g. Bhakta et al., 2019; Bucci et al., 2018; Lowenberg-Deboer & Erickson, 2019), others have synonymously used “smart farming technologies” (SFTs) (e.g. Balafoutis et al., 2017; Noack, 2019) or “technological enablers” (e.g. Aceto et al., 2019). The complex nature of digitalization in agriculture may be perpetuated through the interchangeable use of synonymous terms. A clear definition of technologies included in precision agriculture (PA) does not exist (Lowenberg-Deboer & Erickson, 2019).

While some research provides a broad spectrum of technologies within smart farming (e.g. Karunathilake et al., 2023; Navarro et al., 2020), others have focused on reviewing technology sub-categories, such as apps (e.g. Inwood & Dale, 2019), Unmanned Aerial Vehicles (UAVs) (e.g. Lan et al., 2017), or robotics (e.g. Aravind et al., 2017; Roldán et al., 2017; Thomasson et al., 2019). Reviews of sub-categories within artificial intelligence (AI) for agriculture such as Big Data, computer vision, digital twins, deep learning, and machine learning (e.g. Bhat & Huang, 2021; Coulibaly et al., 2022; Liakos et al., 2018; Patrício & Rieder, 2018; Popa, 2011; Purcell & Neubauer, 2023) add to existing literature on digital agricultural tools. At the same time, other studies consider the complexity of systems rather than an independent aspect of digital agriculture. Bacco et al. (2020a) conducted a taxonomy and inventory of “Digital Game Changers” (DGC), which are considered based on their ability to change aspects and actors of social and economic life. Similarly, Arvanitis & Symeonaki (2020) used the category “agricultural cyber-physical systems” (ACPSs) in their review of Agricultural 4.0 technologies to describe interactions within agricultural systems, and Benyam et al. (2021) employed a systems perspective to their review of digital agricultural technologies food loss and waste prevention.

Other SOTAs assessed Internet of Things (IoT) systems of particular sectors or types of agriculture (e.g. Shi et al., 2019; Talavera et al., 2017; Villa-Henriksen et al., 2020). As previously mentioned, the digitalization of the fruit sector lags behind other sectors, and thus fewer SOTAs exist for digital fruit production. Digital agriculture reviews for fruit farming have focused on specific technology solutions such as Unmanned Aerial Vehicles (UAV)s and robotics in orchards (e.g. Adarsch et al., 2018; Stefas et al., 2016; Zhang et al., 2021; Zhang et al., 2019), AI in viticulture and horticulture (e.g. Miranda et al., 2023; Tardaguila et al., 2021), or highlighted current projects and development (e.g. Köhler, 2018; Zoth, 2018).

The most common approach among the reviewed SOTAs was to group and then assess the technologies or tools based on their technology categories, e.g. web-based technologies and cloud-based computing. While SOTAs for digital agricultural tools are numerous, few studies consider tools outside of published research articles, such as on-market apps (see e.g. Inwood & Dale, 2019) and rather reference research articles with experimental data. Furthermore, these systematic reviews have focused primarily on technical specifications of the tools rather than on-farm functions. Exceptions include the studies by Zhang et al. (2019) and Haarlem (2020), which reviewed literature on technology applications on fruit farms based on on-farm functions performed by agricultural robots and by digital technologies applicable in the Netherlands, respectively. The present study compliments these outcomes by expanding the review of digital agricultural tools based on on-farm tasks, which increases the practicality of the results and applicability for digitalization’s intended end-users, such as farmers.

While it is purposeful to assess the available or researched technologies per technology category or other unique categorization methods, it can be impractical for users and developers of the technologies, as the categorization is not based on the on-farm functions. Therefore, it is unclear what technologies are available per field task and if these technologies can be used across multiple on-farm activities. The studies that categorize based on on-farm activity do not include post-harvest, marketing, or communication opportunities for the farmer. Farmer-to-farmer communication has been named one of the most important sources of information in a cross-country farmer survey (Knierim et al., 2018). Additionally, the lack of on-farm information about the adoption of these tools and expectations of farmers creates a gap between the theoretical versus reality.

6.3.2 Technology adoption in agriculture

Technology adoption in agriculture, particularly regarding PA techniques, has been researched considerably, though often only a few aspects or farm characteristics have been investigated (Busse et al., 2014; Pathak et al., 2019; Paustian & Theuvsen, 2017). The way in which digital technologies can be used at the farm-level to improve sustainability appears to be inadequately assessed and communicated (Coteur et al., 2016; Knierim et al., 2018). Lowenberg-Deboer and Erickson (2019) argue that data collection methods on PA adoption also vary from country to country, which challenges comparisons among existing studies. The previously mentioned issue of synonymous, interchangeable terminology in this field and lack of a clear definition of tools further complicates comparability.

An approach focused on the perception of potential users and the connection to intended or unintended use of new technology is the Technology Acceptance Model (TAM) methodology (Davis, 1989). This model is widely used to understand new technology adoption (King & He, 2006; Pierpaoli, 2013) and is derived from the Theory of Planned Behavior (Ajzen, 1991; Fishbein & Azjen, 1975), which tests the influencing factors to a potential user’s decision regarding when and how new technology is used

(Pierpaoli, 2013). Other technology adoption models have a more economic focus, such as the induced innovation theory (Hicks, 1932), the diffusion model by Griliches (1957), or the Net Present Value analysis, the most basic method for investment decisions (Gallardo & Sauer, 2018). However, these econo-centric models include limitations: in general, the theories do not consider human aspects of technology adoption, such as uncertainties in the investment decision or decision-maker. This is where empirical studies, including the present study, are advantageous.

Empirical approaches are common among studies on technology adoption in agriculture. Similar to available state-of-the-art reviews, most studies on technology adoption in agriculture focus on industrial cropping systems (Pathak et al., 2019). Several large-scale surveys have been conducted among farmers across Europe (e.g. Barnes et al., 2019; Blasch et al., 2020; Groher et al., 2020; Knierim et al., 2018). Generally, these studies found that adoption rates varied across branches of agriculture and technology type (Groher et al., 2020) and systems, leading to inequalities in technology access (Barnes et al., 2019).

Determining technology adoption factors appear to be demographic factors such as age (Barnes et al., 2019). In Germany, technology adoption has previously been determined by demographic factors including age, education, and farm size (Michels, et al., 2019). Paustian and Theuvsen (2017) found that German farmers owning farms smaller than 100 ha were less likely to adopt precision technologies. Younger farmers were considered to have positive attitudes towards cloud technologies in their fields (Jithin Das et al., 2019). Still, other studies show that farmer demographics were not as important as perceptions and attitudes regarding the farm and technology at hand (e.g. Kernecker et al., 2016; Tey & Brindal, 2012). Jithin Das et al. (2019) surveyed 32 Irish farmers with mixed methods (interviews and surveys) and found cost to be the most significant factor influencing SFT adoption, including unavailability of lower-cost technologies for small farms. Similar to Knierim et al., (2018) and Blasch et al. (2020), however using a mixed-methods approach with a survey, interviews, and a workshop, Busse et al. (2014) concluded that German farmers and their communication networks play a significant role in the acceptance and generation of innovations.

Factors that are often studied in other industries are underrepresented among agricultural studies on technology adoption and the complex nature of adoption is poorly explained (Pathak et al., 2019). Research on technology adoption rates and empirical research on the reasons behind the farmers' decisions to adopt must be conducted in all agricultural sectors and regions to avoid inequality in the development and uptake of promising technologies.

6.4 Methods

6.4.1 Digital tool review

In order to assess the characteristics of tools in fruit production, a review of available tools was analyzed. Selection criteria for these tools were defined. First, the tools must fit the definition of digital technologies by Birner et al. (2021) as technologies that use binary, or machine-readable, data which embody a physical product (such as an automatic harvester) or technologies to provide disembodied services (such as apps or farm management programs). Secondly, the tool must be usable in fruit production, either marketed for or compatible for use in fruit production systems. The boundaries of fruit production for this study are defined in Figure 1. These boundaries consider that most fruit grown in Germany is sold and consumed as table fruit and therefore not processed into other products such as alcohol (Bundesministerium für Ernährung und Landwirtschaft, 2019b). Furthermore, the fruits of interest for this study are those grown commonly in Germany, in particular tree fruits such as apple, pear, cherry, plum, apricot, and peach. Other relevant fruits are wine grapes, currants, raspberries, blueberries, and strawberries (Bundesministerium für Ernährung und Landwirtschaft, 2019a). Finally, the tools should be considered in the prototype or on-market phase of development. As the development of this industry is rapid, this tool review should be considered as a snapshot into the available tools in and until the spring of 2021, and it is likely that the tools considered at this point to be 'prototypes' could quickly be available on-market after the review was conducted.

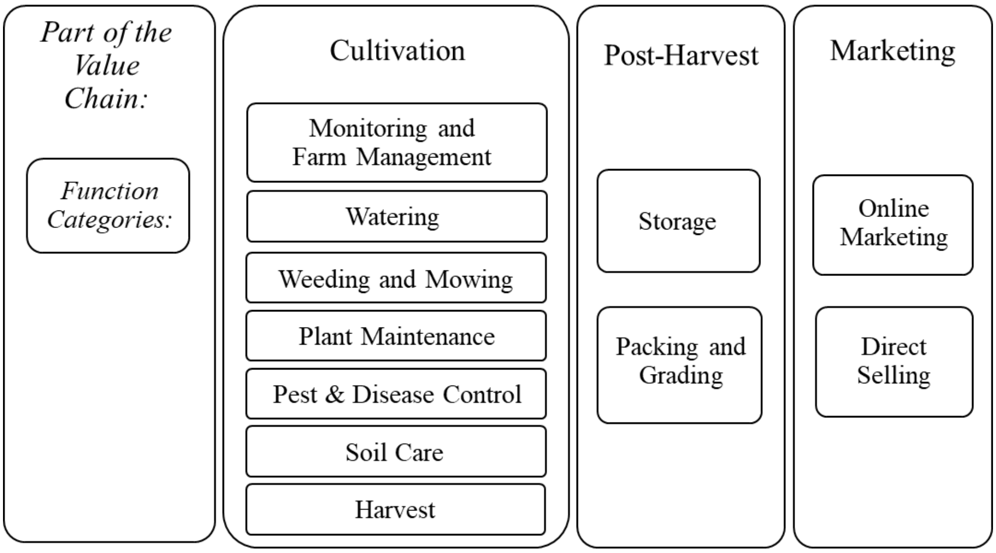

Figure 1: Characteristics of the fruit value chain considered within this study

Considering these selection criteria, a comprehensive literature and media review was conducted to collect the tool review using the standalone literature review method (Templier & Paré, 2015). The standalone review attempts to interpret the body of existing literature. This review was then further compared against interview responses form stakeholders. Between January and April of 2021, reports on on-going research projects (running during the year 2021), marketed products and their company websites, conferences and trade fairs, and news articles were searched for in relation to fruit production. These sources are dated until April 2021. Additionally, an internet search was conducted per listed function in the fruit production system boundary (e.g., "digitalized fruit storage") to find sources such as news articles, company websites to ensure that all value chain sections were searched for (Figure 2). The information for the tools that met the previously listed criteria were collected into a spreadsheet (provided as an additional file) for analysis.

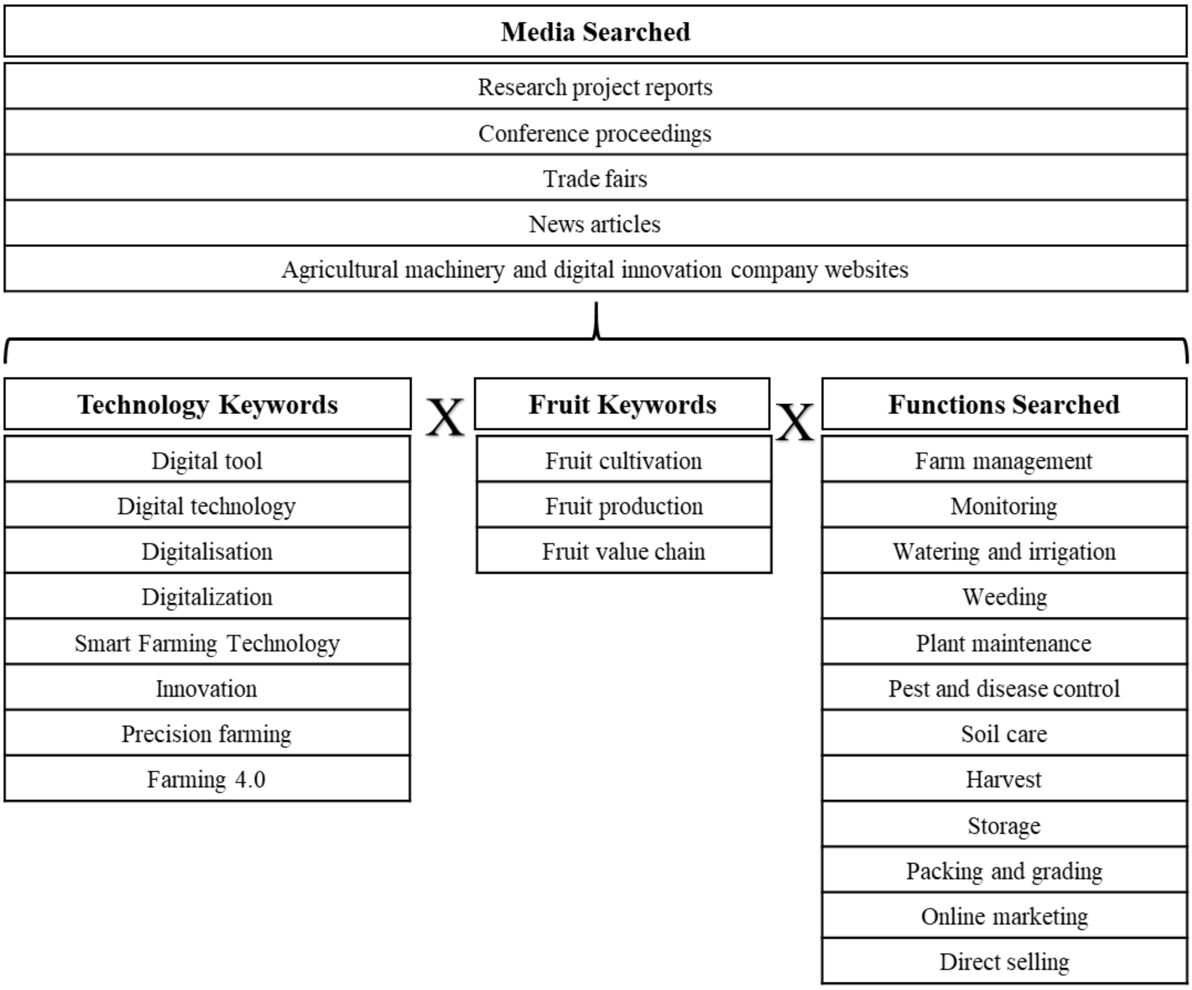

Figure 2: Overview of searched media and keywords for digital tool review

6.4.2 Digital tool review categorization

The tool review was systematically organized to assess specific characteristics of the tools. A total of fourteen inductive or deductive categories were used to categorize the tools (see Appendix). The deductive categories were determined prior to the review of the tools based on information of value for the interested users, developers, and policy makers regarding digital technologies in fruit production. These categories include stage of development (prototype or on-market), technology type (embodied or disembodied (Sunding & Zilberman, 2001)), part of the value chain (cultivation, post-harvest, and marketing), sector of agriculture (horticulture: fruit, horticulture: vegetables, viticulture, and arable farming), usability (stand alone or dependent), form of connectivity (one-to-one, one-to-many, or many-to-many (Porter & Heppelmann, 2014)), and capability (monitoring, control, or autonomous capabilities (Porter & Heppelmann, 2014)).

Some categories required only a binary coding decision of yes or no: German customer/technical support, service, and multifunctionality. Characteristics within inductive categories were established as the tools were assessed: the location of the company, technology category, function, and function category.

6.4.3 Interviews

Region of study

The region of the study was the Lake Constance region in southern Germany. This region is the second-largest fruit cultivation region in Germany with 1,017 fruit farms in the counties of Konstanz, Bodensee-Kreis, Ravensburg, and Lindau (Bundesministerium für Ernährung und Landwirtschaft, 2016). The climatic characteristics of the area, such as mild temperatures and annual precipitation of 900 mm, are advantageous to the fruit growing sector (Landkreis Konstanz & Landratsamt Bodenseekreis, 2017). Apples, pears, plums, and cherries are the most commonly grown fruits and are produced in orchards for fresh consumption (Bundesminsterium für Ernährung und Landwirtschaft, 2020). Around 8,500 ha of agricultural land in the region are organically farmed, accounting for about 12 % of the area compared to the national average of 9.6% (Grimminger et al., 2018). The average sizes of fruit farms in Germany and within the state of Baden-Württemberg at 7 ha and 4.6 ha, respectively (LEL Schwäbisch Gmünd, 2017; Statistisches Bundesamt 2017) are smaller than farms in other sectors.

Stakeholder mapping and selection

Stakeholders were selected for their relevance to the fruit value chain in the Lake Constance region. Using purposive sampling (Bryman, 2012), potential participants were strategically collected in relation to the research question: stakeholders who are the intended users of the technologies and the developers of the technologies were approached for their interest in an interview. Additionally, experts were consulted and asked to define relevant stakeholder groups in the regional value chain. The stakeholder groups are fruit farmers, fruit cultivation and plant protection products (PPP) advisors, fruit wholesalers or marketers, and agricultural machinery and digital innovation developers (Table 1). When divided into interests or stakes in digital tools for fruit production, the former three groups are considered the intended users of the tools, while the latter group is considered the developer group. Of the intended users, farmers are the most targeted users for agricultural technologies. For this reason, more farmers than other stakeholders were sought to take part in the interviews and were reached through snowball sampling (Goodman, 1961): the authors contacted a regional fruit cultivation advisor and a leader of an agricultural organization with the request to provide contact information of farmers who might be interested in participating. Of these farmers, eight were interviewed for the study: five organic farmers and three integrated production (IP) farmers. This group is not representative of the region, but their participation provided useful insights for the purpose of this study.

Table 1: Stakeholder group descriptions (n=4)

Type of interest/stake	Stakeholder group	Description	#	%
Users	Fruit farmers	Farmers predominantly engaged in fruit production on their agricultural land, employing either Integrated Production (IP) or organic principles[1].	8	34.7%
	Fruit cultivation and plant protection product (PPP) advisors	Individuals, whether privately or publicly employed, advise farmers on on-farm activities and/or the purchase and application of agricultural inputs, such as Plant Protection Products (PPPs) and fertilizers.	5	21.7%
	Fruit wholesalers or marketers	Individuals serving as employees or leaders within fruit wholesale organizations or companies or individuals in similar roles within farm shops that offer local delivery services.	5	21.7%
Developers	Agricultural machinery and digital innovation developers	Individuals working as employees or leaders in agricultural machinery or technology companies, ranging from start-ups to international corporations.	5	21.7%

Interview process

A semi-structured interview guideline was developed for the interview series to answer the research questions (see synopsis Appendix). This guideline was developed by the authors and tested with two expert interviews in early 2020. The guideline was used for a series of interviews as part of the DESIRA project (Digitization: Economic and Social Impacts in Rural areas (DESIRA, 2019b) and therefore covers more topics than are relevant for the present study. The interview questions of most relevance for this study were questions 15, 20, and 25 regarding the use of digitalized tools, what the stakeholders perceive or expect to be digitalization in fruit farming, and the barriers to the adoption/use of digital innovations in fruit farming. In total, 23 stakeholders across the four stakeholder groups participated in 1-hour interviews between October 2020 and March 2021. More farmers identifying as men than women participated in the interviews. The dominant age group was from 30-50 and all participants had completed a form of post-secondary education or training. Seven of the eight farmers had farm sizes of 50 ha or smaller, and all farmers produced pomaceous and stone fruit as their main products, with some farms additionally producing secondary products such as berries, cereals, or providing a communal service such as a rental apartment for seasonal workers or tourists. Further demographic details on the participants per stakeholder can be found in the Appendix.

Interview analysis

The audio recordings of each interview were anonymized and transcribed into text documents, which were subsequently analyzed using Qualitative Content Analysis (Mayring, 2000) in MaxQDA 2020 software. The categories used to code the text are the same as those in the digital tool review (see

[1] German horticulture is comprised of two production systems: integrated production (IP) and organic. The choice of PPP and the holistic nature of the production system differentiate the two systems (Das Grüne Lexikon Hortipendium, 2021; Landwirtschaftliches Technologiezentrum Augustenberg, 2023).

Appendix), as the purpose of the content analysis was to be able to compare with the digital farming tool review. The characteristics that were inductively established during the digital tool assessment therefore became deductive categories (Mayring, 2000) for the interview text (Table 2). The tool review's deductive categories *part of value chain* and *technology type* were also able to be coded within stakeholder descriptions and farmer responses to adopted tools, and were therefore included. Other deductive categories - stage of development, agricultural sector, usability, connectivity, and capability - were not described by stakeholders and therefore excluded from the deductive categories for the interview analysis.

Table 2: Deductive Categories for the interview result assessment

Technology Categories		Block chain
		Blower
		Camera
		Computer
		Dosing System
		Drone
		Insect Trap
		Production Line
		Program/App
		QR Code
		Robot
		Satellite Imagery
		Sensor
		Sprayer
		Transmitter
		Web Platform
Functions within Function Categories	*Monitoring and Farm Management*	Field management
		Mapping
		Surveillance
		Climate/weather control
		Employee administration
		Coordination of robots
	Watering	Irrigation management
	Weeding and Mowing	Mowing
		Weeding
		Slashing
	Harvesting	Harvesting
		Transportation
	Plant Maintenance	Pruning
		Thinning
		Defoliation
	Pest and Disease Control	Pest control
		Substance application
		Plant analysis
		Fertilization

		Soil analysis
	Storage	Storage
		Ripening
	Packing and Grading	Sorting/grading
		Packing
		Supply chain management
	Post-harvest quality control	Plant analysis
		Sorting
	Marketing	B2B Marketing
		Online selling
	Other	Cooperation among producers
Part of the Value Chain		Cultivation
		Post-Harvest
		Marketing
Technology Type		Embodied
		Disembodied

6.4.4 Cross-analysis

A quantitative approach was used as grounds for qualitative cross-analysis between the results of the digital tool review and interview responses. Specifically, the frequencies of available tools characterized by the deductive categories in Table 2 were collected into an excel spreadsheet. The frequencies of stakeholder descriptions and farmer descriptions of their tool adoption containing these categories were subsequently added to the spreadsheet. In this way, the frequencies of the categories across all data sets could be observed. To conduct an organized comparison across the data sets of varying sizes, authors used quartiles to group the data within each data set. Commonalities and discrepancies across datasets are visualized in Table 3 and defined as follows: Characteristics that were Q3 or above (i.e. the top 25% of the data set) in all three datasets were considered commonalities. Commonalities are characteristics have thus far experienced a suitable development, as they are expected by stakeholders, available for use, and implemented by interviewed farmers without facing significant barriers. Discrepancies highlight mismatches in expectations, supply, and adoption for this case-study. Characteristics that were in Q3 or above for two of the three datasets were considered partial commonalities. Characteristics that were Q3 or above in one dataset and less than Q3 in the other two were considered discrepancies. Characteristics in which all groups had frequencies of Q1 experienced a lack of both commonalities and discrepancies, implying the characteristic was not relevant for digital tools, stakeholders, nor adopted by farmers.

Table 3: definitions of commonalities, partial commonalities, and discrepancies based on comparisons across dataset quartile groupings

Cross-analysis of characteristic	dataset 1: digital tool review	dataset 2: stakeholder expectations	dataset 3: tool adoption
commonality	>Q3	>Q3	>Q3
partial commonality	>Q3	>Q3	<Q3
	>Q3	<Q3	>Q3
	<Q3	>Q3	>Q3
discrepancy	>Q3	<Q3	<Q3
	<Q3	>Q3	<Q3
	<Q3	<Q3	>Q3
neither commonality nor discrepancy	<Q1	<Q1	<Q1

6.5 Results

6.5.1 Digital tool review results

Characteristics of the reviewed tools have been layered to present the results in a practical format in the following section. Digital tools from the review within their parts of the value chain were assessed for their stage of development (Table 4). As the searched media for the review included research project reports and conference proceedings along with trade fairs and developer websites, both on-market and prototype stages of development were found. Within cultivation, the majority (86%) of tools were found to be on the market, while 90% of post-harvest tools and 94% of marketing tools were on the market. Few tools per value chain section were in the prototype stage, such as in an ongoing research project, with the highest ratio found in cultivation at 13%. Tools regarded as ‘undetermined’ did not disclose adequate information to determine a stage of development.

Table 4: Stages of development per part of the value chain

Part of value chain	Stage of Development	# per value chain	% of tools per value chain
Cultivation	on-the-market	144	86%
	prototype	21	13%
	undetermined	2	1%
Post-harvest	on-the-market	26	90%
	prototype	2	7%
	undetermined	1	3%
Marketing	on-the-market	15	94%
	prototype	1	6%
	undetermined	0	0%

Digital tools from the review within their value chain parts and functions were further reviewed for hirable services (Table 5). Of all the tools reviewed, only tools within cultivation were found to be hirable, and these tools represent just 5% (n=10) of all tools within cultivation. These tools were distributed relatively evenly across the function categories of monitoring and farm management, harvesting, and pest and disease, with just one tool in the plant maintenance function category.

Table 5: Tools that are hirable services per part of the value chain, function category, and function (n=10)

Part of value chain	# of service tools	% of tools in part of value chain	function category	# of service tools	% of tools in function category	function	# of service tools	% of tools in function
cultivation	10	5%	monitoring and farm management	3	1%	field management	1	1%
						mapping	1	1%
						surveillance	1	1%
			harvesting	3	1%	harvesting	3	1%
			plant maintenance	1	1%	thinning	1	1%
			pest and disease control	3	1%	substance application	2	1%
						plant analysis	1	1%

The intended agricultural sector of use was assessed among the reviewed digital tools (Table 6). The information provided about the tools was, in most cases, very clear as to which agricultural sector the tool was designed for or marketed for; however, in 26% of the reviewed tools, this information was not disclosed and therefore the tools were categorized as undetermined. Some tools were marketed as suitable for multiple sectors. Of the reviewed tools, the greatest number of tools were marketed as suitable for the horticulture: fruit (43%), followed by arable farming (24%), vegetables (18%), viticulture (11%) and all sectors (3%).

Table 6: Intended agricultural sector of use (n=214)

Agricultural Sector of use	# of tools per sector	% of total tools
All	6	3%
Horticulture: fruit	91	43%
Viticulture	24	11%
Horticulture: vegetables	39	18%
Arable Farming	52	24%
Undetermined	56	26%

The multifunctionality of the reviewed tools was also assessed per value chain section, meaning that tools are designed to have multiple functions and, therefore, a possible investment advantage. Thirteen among the 214 reviewed tools were found to have multifunctional abilities, of which most were found in cultivation (4%) and the rest were found in post-harvest (2%). No tools with multifunctionality were found in marketing.

The usability of tools, if the tools can be used stand-alone or if they are dependent and require the purchase or rental of at least one other tool, was assessed (Table 7). The greatest number of stand-alone tools was found in marketing as 100% of the tools in this value chain part, followed by 85% and 77% of the tools in cultivation and post-harvest, respectively. The greatest number of dependent tools were found in cultivation as 14% of the tools, followed by 22% of post-harvest tools. Of the two reviewed tools that do not fit adequately into a value chain part and are deemed as 'other', the stand-alone and dependent usability characteristics are split evenly across the two tools.

Table 7: Usability of tools per part of the value chain (n=214)

Part of value chain	**Usability**	**# per value chain**	**% of tools in part of value chain**
Cultivation	stand alone	123	85%
	dependent	21	14%
Post-harvest	stand alone	21	77%
	dependent	6	22%
Marketing	stand alone	16	100%
	dependent	0	0%
Other	stand alone	1	50%
	dependent	1	50%

The embedded digital tools within the review were categorized based on their form of connectivity: one-to-one, one-to-many, and many-to-many (Porter & Heppelmann, 2014) (Table 8). Among the determinable tools, the most common form of connectivity was found to be one-to-one in cultivation (56% of the cultivation tools), followed by one-to-one connectivity in post-harvest tools (56% of the post-harvest tools). It was common that the form of connectivity could not be determined (13% and 44% of cultivation and post-harvest tools, respectively). This is due to inadequate information on the tool websites regarding connectivity.

Table 8: Form of Connectivity of tools per part of the value chain (n=127)

Part of value chain	Form of Connectivity[1]	# per value chain	% of tools per value chain
cultivation	one-to-one	61	56%
	one-to-many	20	19%
	many-to-many	13	12%
	undetermined	14	13%
post-harvest	one-to-one	10	56%
	one-to-many	0	0%
	many-to-many	0	0%
	undetermined	8	44%
other	one-to-one	0	0%
	one-to-many	1	11%
	many-to-many	0	0%
	undetermined	0	0%

[1](Porter & Heppelmann, 2014)

The capabilities of the embedded tools as defined by Porter and Heppelmann (2014) were also categories within the digital tool review assessment (Table 9). The capabilities - monitoring, control, and autonomy - were easily defined based on information provided for each tool, and only 6% of the tools were unable to be determined. The majority of the tools are considered to have autonomy capabilities, meaning that these tools also conduct all other capabilities. The monitoring capability was second-most common at 24% of tools, meaning these tools are only able to monitor the product's condition, operation, and external environment. Control was the least common of the three capabilities at just 9% of the reviewed tools.

Table 9: Capabilities of tools (n=127)

Capabilities[1]	# of capable tools	Percentage of total tools
Autonomy	78	61%
Monitoring	24	24%
Control	12	9%
Undetermined	7	6%

[1](Porter & Heppelmann, 2014)

Finally, the reviewed digital tools were assessed for their technical support in the German language (Table 10). The greatest number of tools with German technical support was in cultivation at 20% of the cultivation tools. The function with most tools available in German was found to be field management (n=7) followed by climate/weather control (n=6). Of the reviewed post-harvest tools, just 7% are available with German technical support, of which sorting and plant analysis functions make up 5%. One function within marketing contained tools that offer German technical support, namely online selling.

Table 10: Tools available in the German language per part of the value chain and per function (n=69)

Part of value chain	# available in German	% of tools in part of value chain	Function	# available in German	% of tools per function
Cultivation	42	20%	climate/weather control	6	3%
			field management	7	3 %
			irrigation management	5	2 %
			mapping	3	1 %
			surveillance	4	2%
			irrigation management	5	2%
			mowing	2	1%
			weeding	2	1%
			harvesting	2	1%
			transportation	1	1%
			defoliation	1	1%
			pruning	0	0 %
			thinning	1	1%
			pest control	1	1%
			substance application	2	1%
			plant analysis	5	2 %
Post-harvest	15	7%	surveillance	1	1%
			sorting	7	3%
			supply chain management	3	1 %
			transportation	1	1%
			plant analysis	4	2%
Marketing	12	6%	online selling	12	6%

6.5.2 Qualitative assessment of adoption in German fruit farming among interviewed fruit farmers

This results section focuses on these interviewed farmers' qualitative responses on barriers to adoption or use of technologies and innovations in fruit production. Eight farmers were interviewed for this part of the study, of which five were organic and three were integrated production (IP) farmers. This small group cannot represent the fruit farmers in the Lake Constance region; nonetheless, their participation provided insights into the actual use and perceived barriers of digital tool adoption.

Adoption of digital tools by farmers

The actual use of digital tools varied widely among the interviewed farmers. When asked if they currently use digital tools or technologies on their farm, all farmers answered yes. However, the explanations of the digital tools or technologies used indicate a variety of knowledge levels. For instance, farmer 24 responded with, *"I use a computer, of course. I use my mobile phone, of course. I use geodata, if available and possible… I have a plant protection product app where we more or less do the plant protection product documentation partly through it.", w*hile farmer 21 responded with, *"Digital? So a photovoltaic system is not going to be a digitalized tool here, is it?"* and farmer 27 with, *"yes… email, exactly".* Farmers 24, 21, and 27 identify as IP farmers. In contrast, organic farmers tended to have a broader knowledge and 'toolbox' of digital tools and technologies. Farmer 26, an organic fruit farmer, responded in detail: *"Yes, well, of course, many machines are now equipped with spraying computers, etc., or something like that. So we already use that… the whole CA storage is of course, completely computer-controlled… The woodchip heating system, for example, is connected via the Internet. So there are also one or two remote maintenance systems… of course, in the administration. Yes. I wouldn't know how to do without it."*

Two other organic farmers mentioned using farm management or administration systems. Farmer 20 used digital tools for crop protection with an automation capability: *"When it detects that the tree is coming here, it switches the fan on or off automatically. Then these data are automatically uploaded right away. So I can follow it almost live on the PC afterwards, (to see) whether it works or not."* Farmer 28 believed organic farmers are faster to uptake digital tools and attributed this to overall greater interest in on-farm technologies: *"in organic farming… there are more farms that are tech-savvy and willing to move in new directions. That's why I could imagine that we are faster in this area in organic farming"*.

Farmers 28, 25, and 14 used crop management tools via on-board computers with automatic recording through GPS, often referred to as digital field indexes. Tools beyond cultivation, such as post-harvest or marketing, appear to be used less often. Farmer 26 mentioned digitalized CA storage, and farmer 28 reported using a digital merchandise management system for their direct sales.

Barriers to adoption: farmer experience

When asked about barriers to their own technology adoption, interviewed farmers were less detailed in their responses in comparison to their responses to question 25 on the general barriers. Two farmers mentioned their personal choice as the reasons for the lack of uptake of specific technologies. For instance, farmer 24, an IP farmer, mentioned they do not use digitalized technologies in their tractors. They mentioned they are interested, *"as long as the price is right and the technology is right. At the moment, geodata is still quite expensive. And the ones that are freely available are no good."* Farmer 27, also an IP farmer, did not see the need in certain technologies such as post-harvest sorting and grading machinery because *"that's manual work with us".* However, organic farmer 28 mentioned infrastructure as the reason they do not use digitalized machinery in their vineyards: *"it's very difficult because (of) these small cells and small plots (of land) to digitize and even then with GPS accuracy, it's all still too inaccurate."*

Barriers to adoption: farmers report on general barriers

Farmers were also asked about general barriers, not necessarily related to their personal decision to adopt. The most commonly named barrier was the cost of investment. Farmer 14 mentioned, *"One obstacle will certainly be the cost of the machine. Because for me, digitalization often means, as far as production is concerned, something with autonomously working things that will be very expensive."*

Farmer 26 mentioned that the "*technology is only supportive*", and therefore the investment costs for the digital tools or technologies are not the only costs to consider. Regarding post-harvest technologies, farmer 27 noted the extreme costs of the currently available digital machinery: "*We give everything away for sorting, because that is the problem, that the sorting machines are extremely expensive… We used to have sorting machines. But now it's exactly a matter of percentages of color, whether the apple has 60% or 75% color. And you can't do that with a normal machine anymore. You really have to have a machine that can measure the color exactly by percentage… We don't have that."*

The handling of the technology was named second most often as a barrier to adoption. The interviewed farmers described knowledge and the learning curve when adopting new technologies as a significant barrier. Furthermore, the older generation of farmers was described to associate fear through their lack of knowledge in handling new technologies: *"Especially among the older generation. And the associated fear of having to get involved with this technology… Because some people didn't grow up with computers, even just plain computers, they lack the basics. Or they lack the normal basic knowledge that makes it much easier for our younger generation to grow with technology. That is definitely one of the major obstacles*." (Farmer 26).

Cost, usability, and reliability were concerns for Farmer 20: *"You can have the best technology, a machine that costs 250,000 euros, and still it produces crooked rows. So you have to be able to use the technology or use it correctly."* Half of the interviewed farmers mentioned lack of reliability as a barrier. Farmer 14 described the early stages of digitalization in fruit production: *"Digitalization is already a bit in its infancy. At least for us in fruit growing… digitalization can mean loss of work, for example, if my farm is only managed with autonomous tractors and the technology fails, I am at a great disadvantage… with digitalization, at some point the technology is so complex that you can't fix it in a hurry".*

Other barriers were mentioned to be acceptance and trust from the farmers, as well as lack of proper infrastructure. The personal choice of the farmer is a deciding factor, according to farmer 14 "*Never change a running system. If apple harvesting has always worked this way or fruit production has always worked this way, why should we rush into something new?*"

Barriers to adoption: regional infrastructure, production system, farm size

Specific to the Lake Constance region, the poor broadband network in the rural areas where farmers work was a barrier to adoption. When asked if there are different barriers to adoption between organic and IP fruit farming, four (two organic and two IP) of the interviewed farmers said no. However, the two farmers who believe there is a difference were both organic farmers. Farmer 26 thought farmers with organic production systems have to be more careful of the entire system: *"We have to pay more attention to nature... And then, of course, the importance of any prognosis model decreases."* Five of the interviewed farmers believed farm size influences the barriers to adoption. Specifically, these farmers believed larger farms could afford the investment costs compared to smaller farms. While the farm sizes are relative, farmer 26 mentioned as an example, *"Someone with twenty hectares can't cope. And the other one has it with sixty."* Still, some of the interviewed farmers believed the farm size does not make a difference in the adoption of digital technologies. Farmer 14 believed it lays more on the personal choice of the farmer than the size of their farm: *"It doesn't matter whether the farm operates 100 hectares or one. There will be no difference. And in my view, it is only up to the farm manager whether he has a certain affinity for using such technology or not."*

6.5.3 Cross-analysis: stakeholder perceptions, tool development, and tool adoption by interviewed farmers

The results of the digital tool review and stakeholder interviews were cross-analyzed in order to deduce commonalities and discrepancies across the datasets. Figure 3 visualizes these results and Table 13 in the Appendix provides a more detailed quantitative analysis.

Commonalities and partial commonalities

The commonalities are found in the overlays of the Venn diagram (Figure 3). ***Suitable tools in action:*** The commonalities between all three datasets are represented at the core of the diagram. These common characteristics include tools that belong to the cultivation part of the value chain, tools within the technology categories of programs/apps, robots, and sensors, and tools with the functions of field management, irrigation management, and substance application. ***Suitable tools:*** commonalities between stakeholder descriptions and the available digital tools, implying supplied characteristics that meet stakeholder expectations, include embodied digital tools, and tools with the functions of climate/weather control, plant analysis, online selling. ***Implementation matches development:*** commonalities between adopted tools and available tools are limited to the function of mapping. ***Expectations match implementation:*** commonalities between stakeholder expectations and adopted tools are limited to the function of pest control.

Discrepancies

Discrepancies were considered to be characteristics with high frequencies per category in one dataset, but lower in the other two, suggesting these characteristics were only relevant for one dataset. ***Expectations for tools and their characteristics***: the technology categories QR Code and camera, as well as the function of supply chain management, were expected by relatively high rates of interviewed stakeholders but were supplied or implemented at lower frequencies. ***Available tools and their characteristics:*** the technology category web platform and the function sorting were provided at higher frequencies than expected or implemented. ***Actual implementation:*** disembodied technologies were implemented by the greatest number of farmers, such as farm management systems or apps, but embodied technologies were more common within the tool review and among stakeholder descriptions. The technology categories blower and satellite imagery, as well as the functions transportation and storage, were implemented at higher frequencies than were found in the tool review and among stakeholder descriptions.

Characteristics that were found to have the lowest frequencies within their category for all datasets were numerous. These include all functions in related to plant maintenance (pruning, thinning, and defoliation), as well as the functions of slashing, coordination of robots and fertilization. Additionally, the technologies categories of block chain, computer, and transmitter were insignificant in all datasets. Marketing tools were the least frequently found or reported among the parts of the value chain category in all datasets. These characteristics are therefore neither supplied by the reviewed digital tools, demanded by interviewed stakeholders, nor adopted by farmers, questioning their relevance in this agricultural sector.

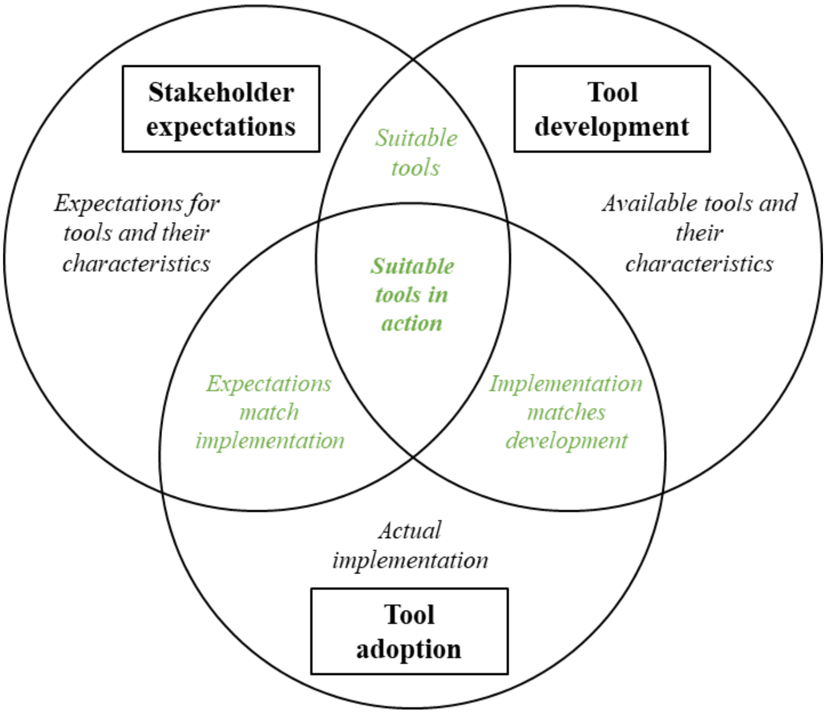

Figure 3: Implications of commonalities and discrepancies between stakeholder expectations, tool development, and tool adoption

6.6 Discussion

6.6.1 Study limitations

Several factors limited the digital tool review. To begin, the review only assessed single tools and technical solutions, not entire systems. Photovoltaic systems, for instance, were considered to be system-level tools and therefore excluded from the review. Furthermore, the post-harvest section of the value chain did not include off-farm transport and logistics, but rather only direct marketing and online marketing, as the farmers themselves can conduct these. Off-farm transport and logistics were considered outside of the ‘boundaries’ of this paper, as visualized in the methodology section. Finally, many digital tools were missing critical information on their websites, which were then described in the analysis as ‘undetermined’. As the review was so large, information was taken only from the publicly available information (websites, technical reports, etc.), and further information was not requested from individual companies.

Stakeholders were not provided with a definition of digitalization in fruit farming prior to the interviews, nor were they informed on the deductive categories from the digital tool review that were used to code their responses. While this allowed for an empirical lens on the stakeholders' perspectives, it may have limited the quantitative grounds for the cross-analysis: as many characteristics were not mentioned by stakeholders, the zero-frequencies in those characteristics resulted in a skewed quartile distribution. Still, the quartiles serve only a basis for comparison and the quantitative data should be understood with reservations, considering the small sample sizes of stakeholders and farmers with adopted tools. The nuances found in the qualitative analysis are of greater value for the aims of this study.

The stakeholder mapping and selection process exhausted the limited number of relevant actors in the Lake Constance region. Due to constraining factors of the funding project, the sample size could not be expanded to represent a more diverse sample. This sample size may lead to criticism within the scientific community. Nonetheless, the interviews provide a valuable snapshot into the perspectives of stakeholders in this region at a critical moment in the digital transformation of agriculture. Furthermore, as research on this transformation continues, the methodology can be used in other regions of Germany, for instance. The detailed characterization of technologies in the tool review (provided as supplementary material) can be used as a blueprint for future studies and to continue as an inventory for digital technologies in fruit production in the ongoing transformation towards Agriculture 4.0. Similarly, the cross-analysis provides a valuable lens through which the sustainability of digital transformation can be assessed at a broader scale or in different sectors.

6.6.2 Cross-analysis implications

Consideration of the interface between expectations of stakeholders, available technology characteristics, and tool adoption is critical for assessing the sustainability of a technological transformation. Commonalities could point to where development of digital tools for fruit production thus far meets the expectations of interviewed stakeholders and adoption by interviewed farmers, and where barriers have not impeded implementation. Meanwhile, discrepancies emphasize mismatches in expectations, supply, and adoption in the boundaries of this case study. Discrepancies could suggest that the technology-push (TP) model without adequate consideration of user interests has driven development, but they may also suggest low stakeholder knowledge on digitalization, which would require better information diffusion on digitalization in fruit production.

At the core of the cross-analysis (*suitable tools in action* in Figure 3), commonalities were identified, including programs/apps, robots, and sensors, and tools with the functions of field management and substance application. The common characteristics of digital tools can be understood as having met stakeholder expectations and were able to be implemented without significant barriers for the interviewed stakeholders.

Beyond the commonalities, the other findings from the cross-analysis can be grouped into two categories based on their implications. First, the characteristics in the discrepancies *expectations for tools and their characteristics* and *actual implementation*, as well as in the partial commonality *expectations match implementation*, were less frequent in the review than in stakeholder descriptions and/or adopted by farmers. This implies that these characteristics are of interest for stakeholders and farmers and, if adopted, can be implemented without significant barriers. For instance, disembodied tools were implemented more frequently than embodied, yet embodied tools were expected and available more frequently than embodied (*actual implementation*). This suggests that disembodied tools could face fewer barriers to adoption than embodied. While characteristics frequently mentioned by stakeholders may equate to a need, they may also be expectations influenced by external factors, such as marketing schemes for tool characteristics or the existence of technologies in their farming communities.

Second, the characteristics in the discrepancy *available tools and their characteristics* and the partial commonalities *suitable tools* and *implementation matches development* were found more frequently in the developed tools than were described by stakeholders and/or adopted by farmers. These differences could be caused by lack of need, interest, or knowledge by stakeholders and, if not adopted, significant barriers that hinder implementation. For example, web platforms and sorting were provided at higher frequencies than expected or implemented (*available tools and their characteristics)*. If stakeholders are unaware of these technologies and functions, they cannot expect them to exist within digitalized fruit production, nor could farmers adopt them. A similar outcome is likely if stakeholders and farmers do not have an interest or requirement for these characteristics. On the other hand, characteristics that were expected and available at high frequencies, yet seldom implemented (*suitable tools*), such as embodied digital tools and tools with the functions of climate/weather control, could be inhibited by significant barriers to adoption. Ultimately, authors cannot determine the causes behind differences in tool development, stakeholder expectation, and adoption within the boundaries of this study. Further participatory research is encouraged to study these phenomena in order to amend the differences and enable a more sustainable digital transition.

6.6.3 Farmer interviews

Uneven distribution of knowledge and barriers to adoption

The open approach used to collect stakeholder perceptions on digitalized fruit production allowed for free responses from stakeholders, influenced by stakeholders' current knowledge levels and without suggestive phrasing or categorization. For this reason, definitions of digital technologies in fruit production varied greatly, from computers and email to automated sprayers and irrigation systems. This finding suggests an uneven distribution of experience and knowledge across interviewed stakeholders. Similar to the findings in the cross-analysis, this could be due to a variety of reasons, including inadequate knowledge transfer and marketing strategies of the technologies or stakeholder interest. In this study's group of interviewed farmers, the IP farmers presented lower knowledge on digital technologies in fruit production than organic farmers. While the IP farmers did not believe that production systems do not face different barriers to adoption, two of the three IP farmers reported personal choice as their reasoning behind lack of adoption. It is likely that this knowledge difference influenced the adoption rates between production systems. The reported barriers of acceptance and trust could perhaps be overcome, or at least put into an appropriate, educated context, if user knowledge on digitalization in fruit production increased. Further research should be conducted on a larger scale among fruit farmers and relevant stakeholders to gain insight on the distribution of digital technology knowledge from a representative sample.

Interviewed farmers mentioned the ageing farmer population to be a barrier in the adoption of technologies, similar to the results found by Barnes et al. (2019), Michels et al. (2020), Paustian and Theuvsen (2017), Rijswijk et al. (2020), and Knierim et al. (2019). Barriers mentioned by German farmers in the Knierim et al. study and by European farmers in the study by Kernecker et al. (2020) mirror those mentioned most by the farmers in this study as cost and compatibility. Access in relation to cost was also found to be the largest barrier in a study on European farmers by Kernecker et al. (2016). Other dimensions involved in the adoption decision process, such as social needs and cultural aspects, require a specific approach by rural development policies (Bacco et al. 2020b). In the study by Ferrari et al. (2022), the authors also found barriers which hinder digitalization to be socio-cultural (such as fear, competence, and complexity), technical (such as connectivity and dependability), and economic. These authors found another category of barriers that were not mentioned by the farmers in the present study, namely regulatory-institutional barriers like data management and regulations. Regarding the reasons for adoption of digital technologies, the study by Kernecker et al. (2020) found similar results to those in this study: improved ease and quality of work through automation or digital administration.

6.6.4 Opportunities for digital tool development

Based on the findings in the digital tool review, stakeholder interviews, and cross-analysis, authors have identified opportunities for future digital tool development for fruit production. The results of the digital tool review demonstrate the great variety of characteristics among the reviewed technologies. Tools fit for use in fruit cultivation (based on the criteria defined in this study) were frequently marketed as usable for arable farming (24%) or vegetable farming (18%); while this could be advantageous for farmers whose farms are not single-sector, as the majority of fruit farms in the region *are* single-sector, this could be disadvantageous and risk being overseen.

Considering that investment cost is described as the main barrier to adoption by the interviewed farmers in this study, as well as the studies by Jithin Das et al., (2019), Knierim et al., (2018), and

Schleicher and Gandorfer (2018), tool characteristics assessed in this study, such as usability, multifunctionality, or being a hirable service could be opportunities to reduce the investment cost barrier. In the case of usability, the majority of tools in cultivation (85%), post-harvest (78%), and marketing (100%) were found to be stand-alone tools, meaning they would function without requiring the purchase of one or more other tools. These results are positive regarding cost investment for farmers. However, few tools were found to have multifunctional abilities, which leads to the assumption that tools are often purchased for single tasks, resulting in high investment costs for a farm with numerous functional requirements. Similarly, tools that are hirable services, which could have a smaller initial cost investment, comprised just 5% of the reviewed tools. These were limited to the cultivation section of the value chain for the functions of monitoring and farm management, harvesting, plant maintenance, and pest and disease control.

Very few digital tools from the review offer German language technical support: 20% of cultivation, 7% of post-harvest, and 6% of marketing tools reviewed offered the German language in addition to English. It cannot be ruled out that German farmers would not be willing to use tools that only provide English technical support. However, it can be assumed that German farmers would prefer tools with technical support in their language. When combined, just one of the hirable service tools and three of the multifunctional tools offer German technical support. Furthermore, only 30 of the 42 tools available with German technical support are marketed for fruit production, while the other 12 are marketed only for arable farming, yet could be functional for fruit cultivation. This is a small collection of available tools for German farmers. The lack of appropriate tools in this sector of German farming indicates evidence of a technology-push development. The failure to meet needs of farmers could lead to a digital divide (Hilbert, 2011), in which fruit farmers would be disadvantaged compared to those in other sectors.

6.7 Conclusion

Upon consideration of the named barriers to adoption, the characteristics of existing tools in the tool review, and the results of the cross-analysis, the current development of tools is not suitable for the needs and abilities of the stakeholders in the case study. Uneven distribution of knowledge on digitalization and a lack of tools that can overcome the named barriers to adoption may perpetuate the lag in digitalization of the German fruit sector. The limited commonalities and various discrepancies among developed tools and stakeholder expectations and implementation leads to the assumption that the current development of digital tools for fruit production has been from a technology-push and not a demand-pull. Reported barriers to adoption are numerous and were found in similar studies in other regions, suggesting greater consideration of stakeholder perceptions and technology adoption strategies is required at a wider geographical and sectoral scale.

Authors recommend actions for a more sustainable and just digital transformation of the fruit sector. First, tools with multifunctionalities and hirable services offer chances to overcome the barrier of cost:

technology developers are encouraged to focus on further development of tools with these characteristics to increase inclusion opportunities for technology users. Government policies must provide financial support at the development level as well as support for investment from users to reduce inequalities in development and adoption. This support must consider the reported differences in barriers according to production system and farm size, and should therefore specifically target small farms and share efforts equally across organic and IP production systems. Second, marketing of tools and the diffusion of knowledge regarding digitalized technologies for fruit production must be improved; misguided marketing and inadequate information could be the cause of slow uptake in the fruit sector. Finally, to support the German fruit farming sector, technical support must be available in the national language to allow for equal opportunities for inclusion in the digital transformation. Cooperation between users and developers in the fruit value chain is recommended to understand the causes behind the discrepancies and amend the existing gap between expectations and reality, thus improving usability and technology adoption. All sectors must be equally considered and developed in this fourth agricultural revolution, otherwise the sustainability of this transition is at risk.

6.8 References

Aceto, G., Persico, V., Pescapé, A., & Member, S. (2019). A survey on information and communication technologies for industry 4.0: State-of-the-art, taxonomies, perspectives, and challenges. *IEEE Communications Surveys & Tutorials, 21*(4), 3467– 3501.

Adarsch, A., Pranav, P. M., Manjunath, C. R., & Soumya, K. N. (2018). Fruit farm surveillance using drones. *International Journal of Trend in Scientific Research and Development, 2*(4), 351–357. https://doi.org/10.31142/ijtsrd12973

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Aravind, K. R., Raja, P., & Pérez-Ruiz, M. (2017). Task-based agricultural mobile robots in arable farming: A review. *Spanish Journal of Agricultural Research, 15*, e02R01. *15*(1). https://doi.org/10.5424/sjar/2017151-9573

Arvanitis, K. G., & Symeonaki, E. G. (2020). Agriculture 4.0: The role of innovative smart technologies towards sustainable farm management. *The Open Agriculture Journal*, *14*(1), 130–135. https://doi.org/10.2174/1874331502014010130

Bacco, M., Brunori, G., Ferrari, A., Koltsida, P., & Toli, E. (2020a). IoT as a digital game changer in rural areas: The DESIRA conceptual approach. *GIoTS 2020 - Global Internet of Things Summit, Proceedings* (pp. 0–5). https://doi.org/10.1109/ GIOTS49054.2020.9119674

Bacco, M., Paolo, B., Brunori, G., Debruyne, L., Ferrari, A., Gotta, A., Panagiota, K., Lepore, F., Orsini, A., Rolandi, S., Ivano, S., & Toli, E. (2020b). *Deliverable 1.3: Synthesis report on the taxonomy and inventory of digital game changers.* https:// desira2020.eu/wp-content/uploads/2020/11/D1.3-Taxonomy-inventory-Digital- Game-Changers.pdf

Balafoutis, A. T., Beck, B., Fountas, S., Tsiropoulos, Z., Vangeyte, J., van der Wal, T., Soto-Embodas, I., & Gómez-Barbero Manuel Pedersen, S. M. (2017). Smart farming technologies – description, taxonomy and economic impact. In S. M. Pedersen & K. M. Lind (Eds.), *Progress in precision agriculture* (pp. 21–77). Springer.

Barnes, A., De Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T., & Gómez-Barbero, M. (2019). Influencing factors and incentives on the intention to adopt precision agricultural technologies within arable farming systems. *Environmental Science* *and Policy, 93*(January), 66–74. https://doi.org/10.1016/j.envsci.2018.12.014

Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sanchez, B., Vangeyte, J., Fountas, S., van der Wal, T., & Gomez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. *Land Use Policy, 80*, 163–174. https://doi.org/10.1016/j.landusepol.2018.10.004

Benyam, A. A., Soma, T., & Fraser, E. (2021). Digital agricultural technologies for food loss and waste prevention and reduction: Global trends, adoption opportunities and barriers. *Journal of Cleaner Production, 323*(September), 129099. https://doi.org/ 10.1016/j.jclepro.2021.129099

Bhakta, I., Phadikar, S., & Majumder, K. (2019). State-of-the-art technologies in precision agriculture: A systematic review. *Journal of the Science of Food and Agriculture, 99,* 4878–4888. https://doi.org/10.1002/jsfa.9693

Bhat, S. A., & Huang, N. F. (2021). Big data and AI revolution in precision agriculture: Survey and challenges. *IEEE Access, 9*, 110209–110222. https://doi.org/10.1109/ ACCESS.2021.3102227

Bijker, W. E., & Pinch, T. J. (1987). The social construction of facts and artefacts: Or how the sociology of science and the sociology of Technology might benefit each other. *Social Studies of Science, 14*(3). https://doi.org/10.1177/030631284014003004

Birner, R., Daum, T., & Pray, C. (2021b). Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Applied Economic Perspectives and Policy, 43*(4), 1260–1285. https://doi.org/10.1002/aepp.13145

Bitkom, D. B., & Rentenbank. (2020). *Schon 8 von 10 Landwirten Setzen Auf Digitale Technologien.* https://www.bitkom.org/Presse/Presseinformation/Schon-8-von-10- Landwirten-setzen-auf-digitale-Technologien

Blasch, J., van der Kroon, B., van Beukering, P., Munster, R., Fabiani, S., Nino, P., & Vanino, S. (2020). Farmer preferences for adopting precision farming technologies: A case study from Italy. *European Review of Agricultural Economics, 49*(1), 33–81. https://doi.org/10.1093/erae/jbaa031

BMEL), B. für E. und L. (2020). *Glossar zur Erklärung wesentlicher Begriffe der Digitalisierung.* https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/han dreichung-digitalisierung.html

Bryman, A. (2012). *Social research methods* (Vol. 4). Oxford University Press.

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

Bundesministerium für Ernährung und Landwirtschaft (BMEL). (2016). *Der Gartenbau in Deutschland: Auswertung des Gartenbaumoduls der Agrarstrukturerhebung 2016. Der Gartenbau in Deutschland.* https://www.bmel.de/SharedDocs/Downloads/ Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile

Busse, M., Doernberg, A., Siebert, R., Kuntosch, A., Schwerdtner, W., König, B., & Bokelmann, W. (2014). Innovation mechanisms in German precision farming. *Precision Agriculture, 15*(4), 403–426. https://doi.org/10.1007/s11119-013-9337-2

Coteur, I., Marchand, F., Debruyne, L., Dalemans, F., & Lauwers, L. (2016). A framework for guiding sustainability assessment and on-farm strategic decision making. *Environmental Impact Assessment Review, 60,* 16–23. https://doi.org/10.1016/j.eiar. 2016.04.003

Coulibaly, S., Kamsu-Foguem, B., Kamissoko, D., & Traore, D. (2022). Deep learning for precision agriculture: A bibliometric analysis. *Intelligent Systems with Applications, 16*(April), 200102. https://doi.org/10.1016/j.iswa.2022.200102

Das Grüne Lexikon Hortipendium. (2021). *Gemüseanbau: Bio oder Konventionell.* https://hortipendium.de/Gemüseanbau:_Bio_oder_Konventionell

Das, V. J., Sharma, S., & Kaushik, A. (2019). Views of Irish farmers on smart farming technologies:

An observational study. *AgriEngineering, 1*(2), 164–187. https://doi. org/10.3390/agriengineering1020013

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly: Management Information Systems, 13*(3), 319–339. https://doi.org/10.2307/249008

DESIRA. (2019). *The project: About DESIRA.* https://desira2020.eu/the-project/

Ferrari, A., Bacco, M., Gaber, K., Jedlitschka, A., Hess, S., Kaipainen, J., Koltsida, P., Toli, E., & Brunori, G. (2022). Rethinking sustainability requirements: Drivers, barriers and impacts of digitalisation in rural areas from the viewpoint of experts. *Information and Software Technology, 145,* 145.

Fishbein, M., & Azjen, I. (1975). *Belief, attitude, intention, and behaviour: An introduction to theory and research* (pp. 578). Addison-Wesley Publishing Company.

Gallardo, R. K., & Sauer, J. (2018). Adoption of labor-saving technologies in agriculture. *Annual Review of Resource Economics, 10,* 185–206. https://doi.org/10.1146/ annurev-resource-100517-023018

Goodman, L. A. (1961). Snowball sampling. *The Annals of Mathematical Statistics, 32*(1), 148–170. https://doi.org/10.1214/aoms/1177705148

Griliches, Z. (1957). Hybrid corn: An exploration in the economics of technological change. *Econometrica, 25*(4), 501–522.

Grimminger, R., Krawutschke, M., & Berger, S. (2018). *Mehr Bio vom Bodensee durch Tradition und Innovation.* https://www.bodenseekreis.de/fileadmin/03_umwelt_ landnutzung/landwirtschaft/downloads/bio-musterregion/fb_musterregion_bod ensee.pdf .

Groher, T., Heitkämper, K., & Umstätter, C. (2020). Nutzung digitaler technologien in der schweizer landwirtschaft. *Agrarforschung Schweiz,* 11(6), 59–67. https://doi.org/ 10.34776/afs11-59

Hicks, J. (1932). *The theory of wages.* Macmillan.

Hilbert, M. (2011). The end justifies the definition: The manifold outlooks on the digital divide and their practical usefulness for policy making. *Telecommunications Policy, 35,* 715–736. https://doi.org/10.1016/j.telpol.2011.06.012

Inwood, S. E. E., & Dale, V. H. (2019). State of apps targeting management for sustain- ability of agricultural landscapes: A review. *Agronomy for Sustainable Development, 39*(8), 15.

Karunathilake, E. M. B. M., Le, A. T., Heo, S., Chung, Y. S., & Mansoor, S. (2023). The path to smart farming: Innovations and opportunities in precision agriculture. *Agriculture (Switzerland), 13*(8), 1–26. https://doi.org/10.3390/agriculture13081593

Kernecker, M., Knierim, A., & Wurbs, A. (2016). *Report on farmers' needs, innovative ideas and interests*. https://www.smart-akis.com/wp-content/uploads/2017/02/D2.2.- Report-on-farmers-needs.pdf

Kernecker, M., Knierim, A., Wurbs, A., Kraus, T., & Borges, F. (2020). Experience versus expectation: Farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precision Agriculture, 21*(1), 34–50. https://doi.org/10.1007/ s11119-019-09651-z

King, W. R., & He, J. (2006). A meta-analysis of the technology acceptance model. *Information and Management, 43*(6), 740–755. https://doi.org/10.1016/j.im.2006. 05.003

Knierim, A., Borges, F., Lee Kernecker, M., Kraus, T., & Wurbs, A. (2018, July 14). What drives adoption of smart farming technologies? Evidence from a cross-country study. *European IFSA Symposium.* http://www.smart-akis.eu

Knierim, A., Kernecker, M., Erdle, K., Kraus, T., Borges, F., & Wurbs, A. (2019). Smart farming technology innovations – insights and reflections from the German smart- AKIS hub. *NJAS - Wageningen Journal of Life Sciences,* 90-91, 1–10. https://doi.org/10. 1016/j.njas.2019.100314

Köhler, D. H. (2018). Digitalisierung im Obstbau – Anwendungen und Aussichten. *Rheinhessischer Obstbautag*, 1–3. https://www.gb-profi.de/fileadmin/user_upload/ GBP/Obstbautag_Rheinhessen_2018.pdf

Lan, Y., De Bin Chen, S., & Fritz, B. K. (2017). Current status and future trends of precision agricultural aviation technologies. *International Journal of Agricultural and Biological Engineering, 10*(3), 1–17. https://doi.org/10.3965/j.ijabe.20171003. 3088

Landkreis Konstanz, & Landratsamt Bodenseekreis. (2017). *Bewerbung als "Bio- Musterregion Bodensee" beim Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg.* https://www.biomusterregionen-bw.de/,Lde/Startseite/Bio- Musterregion+Bodensee

Landwirtschaftliches Technologiezentrum Augustenberg (LTZ). (2023). Integrierter Pflanzenschutz 2023: Erwerbsobstbau. 104.

LEL Schwäbisch Gmünd. (2017). *Obstanbau*. https://lel.landwirtschaft-bw.de/pb/,Lde/ Startseite/Unsere+Themen/Obstanbau

Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors (Switzerland), 18*(8), 1–29. https://doi.org/10.3390/ s18082674

Lowenberg-Deboer, J., & Erickson, B. (2019). Setting the record straight on precision agriculture adoption. *Agronomy Journal, 111*(4), 1552–1569. https://doi.org/10. 2134/agronj2018.12.0779

Madushanki, A. A. R., Halgamuge, M. N., Wirasagoda, W. A. H. S., & Syed, A. (2019). Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: A review. *International Journal of Advanced Computer Science and Applications, 10*(4), 11–28. https://doi.org/10.14569/ijacsa.2019.0100402

Marinoudi, V., Lampridi, M., Kateris, D., Pearson, S., Sørensen, C. G., & Bochtis, D. (2021). The future of agricultural jobs in view of robotization. *Sustainability, 13*(21), 12109. https://doi.org/10.3390/su132112109

Mayring, P. (2000). Qualitative content analysis. *Forum: Qualitative Social Research, 1*(2), 10. http://file:///C:/Users/nn2120/Downloads/1089-3455-2-PB.pdf

Michels, M., Fecke, W., Feil, J. H., Mußhoff, O., Pigisch, J., & Krone, S. (2019). An empirical study of internet use intensity in German agriculture. *German Journal of Agricultural Economics, 68*(1), 1–14. https://doi.org/10.22004/ag.econ.319804

Michels, M., Fecke, W., Feil, J. H., Musshoff, O., Pigisch, J., & Krone, S. (2020). Smartphone adoption and use in agriculture: Empirical evidence from Germany. *Precision Agriculture, 21*(2), 403–425. https://doi.org/10.1007/s11119-019-09675-5

Miranda, J. C., Gené-Mola, J., Zude Sasse, M., Tsoulias, N., Escolà, A., Arnó, J., Rosell- Polo, J. R., Sanz-Cortiella, R., Martínez-Casasnovas, J. A., & Gregorio, E. (2023). Fruit sizing using AI: A review of methods and challenges. *Postharvest Biology and Technology, 206*(September), 112587. https://doi.org/10.1016/j.postharvbio.2023. 112587

Miranda, J., Ponce, P., Molina, A., & Wright, P. (2019). Sensing, smart and sustainable technologies for agri-food 4.0. *Computers in Industry, 108*, 21–36. https://doi.org/10. 1016/j.compind.2019.02.002

Navarro, E., Costa, N., & Pereira, A. (2020). A systematic review of iot solutions for smart farming. *Sensors, 20*(4231), 1–29. https://doi.org/10.3390/s20154231

Noack, P. (2019). Digitalisierung und Smart Farming: Bedeutung und Nutzen für die heutige Landwirtschaft. *Getreidemagazin, 6*, 8–11.

Ossevoort, Robert, Cor, Verdouw, Peter Frans De Jong, Wil Hennen En, and Robbert Robbemond (2016). *Fruit 4.0: De Vruchten van Meer Technologie Technologie- Roadmap.* http://library.wur.nl/WebQuery/wurpubs/fulltext/385030

Pathak, H. S., Brown, P., & Best, T. (2019). A systematic literature review of the factors affecting the precision agriculture adoption process. *Precision Agriculture, 20*(6), 1292–1316.

https://doi.org/10.1007/s11119-019-09653-x

Patrício, D. I., & Rieder, R. (2018). Computer vision and artificial intelligence in precision agriculture for grain crops: A systematic review. *Computers and Electronics in Agriculture, 153*(June), 69–81. https://doi.org/10.1016/j.compag.2018.08.001

Paustian, M., & Theuvsen, L. (2017). Adoption of precision agriculture technologies by German crop farmers. *Precision Agriculture, 18*(5), 701–716. https://doi.org/10.1007/ s11119-016-9482-5

Philadelphia Orchard Project. (2021). *Summary of orchard care.* Philadelpha Orchard Project: Resources. https://www.phillyorchards.org/wp-content/uploads/2015/07/ orchard_care.pdf

Pierpaoli, E. (2013). *Scienze e Tecnologie Agrarie, Ambientali e Alimentar*i. http://amsdot torato.unibo.it/6623/1/Pierpaoli_Emauele_Tesi.pdf

POPA, C. (2011). Adoption of artificial intelligence in agriculture. *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca Agriculture, 68*(1), 284–293. https://doi.org/10.15835/buasvmcn-agr:6454

Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are trans- forming competition. *Harvard Business Review,* November 2014.

Purcell, W., & Neubauer, T. (2023). Digital twins in agriculture: A state-of-the-art review. *Smart Agricultural Technology, 3*(January 2022), 100094. https://doi.org/10.1016/j. atech.2022.100094

Rijswijk, K., Bulten, E., Klerkx, L., Dessein, J., Debruyne, L., Brunori, G., Scotta, I., Bacco, M., Currie, M., Bartolini, F., van der Velden, D., Rolandi, S., & Metta, M. (2020). Digital transformation of agriculture, forestry and rural areas: developing a futureproof socio-cyber-physical system. *1*(1).

Roldán, J. J., Del Cerro, J., Garzón-Ramos, David Garcia-Aunon, P., Garzón, M., de León, & Jorge Barrientos, A. (2017). Robots in agriculture: State of art and practical experiences. In *Service robots* (pp. 67–90). InTechOpen. http://www.asociatiamhc. ro/wp-content/uploads/2013/11/Guide-to-Hydropower.pdf

Rothwell, R., & Zegveld, W. (1985). *Reindustrialization and technology.* M.E. Sharp.

Saviotti, P. P., & Pyka, A. (2013). The co-evolution of innovation, demand and growth. *Economics of Innovation & New Technology, 22*(5), 461–482. https://doi.org/10.1080/ 10438599.2013.768492

Schleicher, S., & Gandorfer, M. (2018). Digitalisierung in der Landwirtschaft: Eine Analyse der Akzeptanzhemmnisse. In *Digitale Marktplätze und Plattformen* (pp. 203–206). Gesellschaft für Informatik. https://dl.gi.de/handle/20.500.12116/23158

Shi, X., An, X., Zhao, Q., Liu, H., Xia, L., Sun, X., & Guo, Y. (2019). State-of-the-art internet of things in protected agriculture. *Sensors*, 19(1833), 24. https://doi.org/10.3390/ s19081833

Statistisches Bundesamt. (2019a). *69. Anbau, Ertrag und Ernte von Obst*. Statistisches Bundesamt (BMEL).

Statistisches Bundesamt. (2019b). *Verwendung der Obsternte.* Statistisches Bundesamt (BMEL).

Statistisches Bundesamt (DESTATIS). (2017). *Landwirtschaftliche Bodennutzung - Baumobstflächen.* https://www.statistik-bw.de/Landwirtschaft/Agrarstruktur/ Betriebe-LFGK.jsp

Stefas, N., Bayram, H., & Isler, V. (2016). Vision-based UAV navigation in orchards. *International Federation of Automatic Control (IFAC)- Papers Online, 49*(16), 10–15. https://doi.org/10.1016/j.ifacol.2016.10.003

Sunding, D., & Zilberman, D. (2001). Chapter 4 the agricultural innovation process: Research and technology adoption in a changing agricultural sector. *Handbook of Agricultural Economics, 1*(PART A), 207–261. https://doi.org/10.1016/S1574-0072(01) 10007-1

Talavera, J. M., Tobón, L. E., Gómez, J. A., Culman, M. A., Aranda, J. M., Parra, D. T., Quiroz, L. A., Hoyos, A., & Garreta, L. E. (2017). Review of IoT applications in agro-industrial and environmental fields. *Computers and Electronics in Agriculture, 142*(118), 283–297.

https://doi.org/10.1016/j.compag.2017.09.015

Tardaguila, J., Stoll, M., Gutiérrez, S., Proffitt, T., & Diago, M. P. (2021). Smart applications and digital technologies in viticulture: A review. *Smart Agricultural Technology, 1*(July), 100005. https://doi.org/10.1016/j.atech.2021.100005

Templier, M., & Paré, G. (2015). A framework for guiding and evaluating literature reviews. *Communications of the Association for Information Systems, 37,* 112–137. https://doi.org/10.17705/1cais.03706

Tey, Y. S., & Brindal, M. (2012). Factors influencing the adoption of precision agricultural technologies: A review for policy implications. *Precision Agriculture, 13*(6), 713– 730. https://doi.org/10.1007/s11119-012-9273-6

Thomasson, J. A., Baillie, C. P., Antille, D. L., Lobsey, C. R., & Mccarthy, C. L. (2019). Autonomous Technologies in agricultural equipment: A review of the state of the art. *ASABE Distinguished Lecture Series, Tractor Design No, 40,* 1–17. https://doi.org/ 10.13031/913

Uwe, D., Aparajita, G., & Mishr, D. (2016). *Will digital technologies transform agriculture in developing countries?* https://hvtc.edu.vn/Portals/0/files/636104758652860273WillDigitalTechnologiesTransformAgricultureinDevelopingCountries.pdf

Van Haarlem, L. (2020). *The future of fruit farming.* [Waginengen University & Research]. https://edepot.wur.nl/531601

Vik, J., Melås, A. M., Stræte, E. P., & Søraa, R. A. (2021). Balanced readiness level assessment (BRLa): A tool for exploring new and emerging technologies. *Technological Forecasting & Social Change, 169*(November 2020). https://doi.org/ 10.1016/j.techfore.2021.120854

Villa-Henriksen, A., Edwards, G. T. C., Pesonen, L. A., Green, O., & Sørensen, C. A. G. (2020). Internet of things in arable farming: Implementation, applications, challenges and potential. *Biosystems Engineering, 191*, 60–84. https://doi.org/10.1016/j. biosystemseng.2019.12.013

Zambon, I., Cecchini, M., Egidi, G., Saporito, M. G., & Colantoni, A. (2019). Revolution 4.0: Industry vs. agriculture in a future development for SMEs. *Processes, 7*(1), 1–16. https://doi.org/10.3390/pr7010036

Zhang, Q., Karkee, M., & Tabb, A. (2019). The use of agricultural robots in orchard management. In J. Billingsley (Ed.), *Robotics and automation for improving agriculture* (pp. 187–214). Burleigh Dodds Science Publishing. https://doi.org/10.19103/as. 2019.0056.14

Zhang, C., Valente, J., Kooistra, L., Guo, L., & Wang, W. (2021). Orchard management with small unmanned aerial vehicles: A survey of sensing and analysis approaches. In *Precision agriculture.* Springer US. https://doi.org/10.1007/s11119-021-09813-y

Zoth, M. (2018). *Technische Entwicklungen im Obstanbau und Perspektiven: am Beispiel DARWIN-SmaArt, BigApple, u.a. BIOLAND Seminar 2018- Nals/Südtirol, 75.*

6.9 Appendix

List of abbreviations

TP	Technology-Push Model
DP	Demand-Pull Model
SOTA	State of the Art
SFT	Smart Farming Technology
PA	Precision Agriculture

DGC	Digital Game Changer
ACPS	Agricultural Cyber-Physical Systems
IOT	Internet of Things
UAV	Unmanned Aerial Vehicle
TAM	Technology Acceptance Model
PU	Perceived Usage
PEU	Perceived Ease of Use
PPP	Plant Protection Product
IP	Integrated Production
CA	Controlled Atmosphere

Acknowledgements

This study is conducted under the European Commission Horizon 2020 project DESIRA (Digitization: Economic and Social Impacts in Rural areas), which aims to improve the capacities of society and political bodies to respond to the challenges that digitalization generates in agriculture, forestry, and the rural regions (DESIRA, 2019). The authors wish to thank Tom Huhnke for his valuable contributions to the digital tool review.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the DESIRA Project, funded by the European Commission under Grant Agreement No. [818194].

ORCID

Kirsten Gaber http://orcid.org/0000-0002-6768-9047

Christine Rösch http://orcid.org/0000-0003-3908-1218

Claudia Bieling http://orcid.org/0000-0001-5001-4150

Consent for publication

Informed consent was obtained from all individual participants interviewed for the study.

State of the Art studies

Table 11: Selected state-of-the-art studies on digital technologies in agriculture

Category within digitalized agriculture	**Term for digital tool**	**Citation**	**Topic**
SOTA: digital game changers	Digital game changer (DGC)	(Bacco et al., 2020a)	Taxonomy and inventory of DGCs in agriculture, forestry, and rural areas
SOTA: Digital agricultural technologies	Digital agricultural technologies	(Benyam et al., 2021)	Review of digital agricultural technologies along the food supply chain from harvest to retail
	Smart farming technologies	(Arvanitis & Symeonaki, 2020)	Review of key technologies toward Agriculture 4.0
	Innovations in smart farming and precision agriculture	(Karunathilake et al., 2023)	State of the art of innovations in smart farming and precision agriculture
SOTA: Precision Agriculture	Smart farming technology (SFT)	(Noack, 2019)	Categorization of SFTs into two in-practice categories: automatic steering systems and automatic section control
	SFT	(Balafoutis et al., 2017)	Taxonomy of SFTs into 3 categories to cover cyclic system of precision agriculture
	Technological Enabler	(Aceto et al., 2019)	State of the art and taxonomy of 10 technological enablers
	Precision agriculture technologies	(Bucci et al., 2018)	Precision agriculture and sustainable farming systems
	Precision agriculture technologies	(Bhakta et al., 2019)	Systematic review of SOTA technologies in precision agriculture
	Precision agriculture technologies	(Lowenberg-Deboer & Erickson, 2019)	Review of available data on precision agriculture
SOTA: autonomy and robotics	Autonomous technologies	(Thomasson et al., 2019)	Autonomous technologies in agricultural equipment
	Precision agricultural aviation technologies	(Lan et al., 2017)	Agricultural aviation technology
	Task-based agricultural robots	(Aravind et al., 2017)	Task-based agricultural mobile robots within arable farming
	Agricultural robots	(Roldán et al., 2017)	Aerial and ground robots
SOTA: Internet of Things	IoT technology	(Shi et al., 2019)	IOT in protected agriculture: real-world deployments and published papers
	IoT solutions	(Navarro et al., 2020)	Systematic review: IoT Solutions for smart farming

	IoT technologies	(Villa-Henriksen et al., 2020)	Review of IoT in arable farming, categorized by applications of monitoring, documentation, forecasting and controlling
	IoT solutions	(Talavera et al., 2017)	Systematic review of IoT applications in agro-industrial and environmental fields, based on application domains monitoring, control, logistics, and prediction
	Agricultural apps	(Inwood & Dale, 2019)	Apps for sustainable agricultural landscape management
SOTA: Artificial Intelligence (AI)	AI in agriculture	(Popa, 2011)	Review of adoption and development of AI in agriculture
	Computer vision and AI	(Patrício & Rieder, 2018)	Systematic review of computer vision in precision agriculture for select grain crops
	Digital twins in agriculture	(Purcell & Neubauer, 2023)	Systematic literature review of digital twins in agriculture
	Big Data and AI	(Bhat & Huang, 2021)	Review of Big Data and AI applications in smart agriculture
	Deep learning	(Coulibaly et al., 2022)	Bibliometric study on research in deep learning for agriculture
	Machine learning	(Liakos et al., 2018)	Review of research on machine learning in agriculture
General Fruit SOTA	Digitalized fruit production	(Köhler, 2018)	Digitalization in fruit production, currently-applied technologies
	Technological developments in fruit production	(Zoth, 2018)	Technical (not necessarily digital) development in fruit production
	Smart applications and digital technologies	(Tardaguila et al., 2021)	Review of smart applications and digital technologies in viticulture
Fruit SOTA: AI	AI methods	(Miranda et al., 2023)	Review of AI for fruit sizing
UAVs in Orchards	Drones	(Adarsch et al., 2018)	Fruit farm surveillance using drones
	UAV	(Stefas et al., 2016)	Vision-based UAV Navigation in orchards
	UAV	(Zhang et al., 2021)	Orchard management with small unmanned aerial vehicles
Fruit SOTA based on farm activity	New technological applications	(Haarlem, 2020)	Tech applications in fruit farming based on farm activity, impact of work on Dutch top fruit farms
	Agricultural robots	(Zhang et al., 2019)	Agricultural robots in orchard management

Digital tool review categories

1. *Location of Company*: the location of the development company or the leading research institution.

2. *German customer/technical support:* A yes/no classification was collected upon determining if the company provided customer and/or technical support in German. All companies provide a minimum of English.
3. *Stage of development:* tools were considered on the market or in a prototype phase of development.
4. *Technology type:* Two technology types, embodied and disembodied (Sunding & Zilberman, 2001), are evaluated in this category. The former type considers tools or innovations to embody technologies, such as tractors and sensors, while the latter is non-physical or disembodiment, such as management schemes and apps.
5. *Service:* if the tools are a hirable service, such as a fleet of robots or farm management software service that does not require the user to purchase the complete tool.
6. *Technology Category:* descriptions of the tools were used to assign a technology category.
7. *Function*: functions were inductively derived from the descriptions of the tools.
8. *Function Category:* functions categories were determined as inclusion criteria (Figure 1) within the fruit value chain prior to the review collection. These functions are based on the basic activities involved in fruit tree maintenance (e.g. Philadelphia Orchard Project 2021) and post-harvest.
9. *Multifunctionality:* binary coding decision (yes/no) was used to assess the tools' multifunctionality, or rather if the tool has multiple functions. This is interesting from the perspective of users and developers regarding cost-benefit; multifunctional tools can offer more solutions to farm functions than tools with singular functionalities.
10. *Part of Value Chain:* similar to the function categories, the value chain was pre-determined as the value chain boundaries of the study (Figure 1) to consider tools that fall within the categories of cultivation, post-harvest, and marketing.
11. *Sector of Agriculture:* the sectors of horticulture: fruit, horticulture: vegetables, arable farming, viticulture, and 'all sectors' were categorized based on the sector of agriculture that the tools were marketed or developed for. Although the focus of this study is fruit cultivation, tools could be developed for other sectors but still be suitable for use in fruit cultivation.
12. *Usability:* tools were classified as 'stand alone' or 'dependent' in order to understand if multiple tools needed to be purchased (or rented in the case of hirable service tools) for the tool to function or if the tool could function alone.
13. *Form of Connectivity:* this categorization considers whether the tool connects to one tool (one-to-one), many tools (one-to-many), or is a system of many tools connecting to many other tools (many-to-many) (Porter & Heppelmann, 2014). This classification is only considered for embodied tools, as disembodied tools such as web platforms or apps inherently connect as one-to-many.

14. *Capability:* adapted from (Porter & Heppelmann, 2014), tools are considered to have monitoring, control, or autonomous capabilities: Monitoring considers that the tool is able to provide monitoring of the targeted product's condition, surrounding environment, and/or operation and usage; control considers that the tool contains software or has cloud software that enables it to control functions and personalize the user experience; and autonomy considers that the tool has combined monitoring and control capabilities as well as having the ability to autonomous product operation, self-coordinate its operation with other products and systems, and provide self-diagnosis and service. Similar to the form of connectivity category, this classification is only considered for embodied tools with a physical and software component.

Interviewed stakeholder characteristics

Table 12: Characteristics of interviewed stakeholders (n=23)

	Stakeholder group			
Age	**Fruit farmers (n=8)**	**Fruit cultivation and PPP advisors (n=5)**	**Fruit wholesalers or marketers (n=5)**	**Agricultural machinery and digital innovation developers (n=5)**
30-40	3	1	1	4
41-50	3	2	2	1
51-60	2	1	1	0
61-70	0	1	1	0
Gender				
Female	2	0	2	0
Male	6	5	3	4
Diverse	0	0	0	0
Highest level of education				
Elementary school	0	0	0	0
Secondary school diploma and/or technical training	2	0	0	0
University degree (Diplom, Magister, Bachelor, Master, Doctorate)	4	5	5	5
Other	0	0	0	0
Size of farm (ha)				
0-10	1			
011-20	2			
21-30	1			
31-40	2			
41-50	1			
51-60	0			
61-70	0			
71-80	1			
Main product of farm				
Pomaceous and stone fruit	8			
Berries	3			
Other fruit	0			
Cereals	2			
Other plant crops	0			
Eggs	1			
Milk	0			
Other animal products	0			
Bed and breakfast	0			
Holiday apartment	3			
Care work for the community	0			
Other service	3			

Comparative analysis: digital tool review and stakeholder interviews

Table 13: Comparative analysis of selected categories assessed within the digital tool review and the stakeholder interviews

	Tools from digital tool sample		**Stakeholders who described these categories as digitalization in fruit production**		**Tools used by farmers**	
Categories of analysis	**#**	**Quartile**	**#**	**Quartile**	**# (of farmers)**	**Quartile**
Part of value chain						
Cultivation	167	>Q3	16	>Q3	7	>Q3
Post-harvest	29	Q2	9	Q2	1	Q2
Marketing	16	<Q1	4	<Q1	1	<Q1
minimum	*16*		*4*		*1*	
Q1	*23*		*6*		*1*	
Q2	*29*		*9*		*1*	
Q3	*98*		*13*		*4*	
maximum	*167*		*16*		*7*	
Technology type						
Disembodied	86	<Q1	9	<Q1	6	>Q3
Embodied	126	>Q3	19	>Q3	3	<Q1
minimum	*86*		*9*		*3*	
Q1	*96*		*12*		*4*	
Q2	*106*		*14*		*5*	
Q3	*116*		*17*		*5*	
maximum	*126*		*19*		*6*	
Technology category						
Block chain	1	Q1	0	Q1	0	Q1
Blower	2	Q1-Q2	0	Q1	1	Q3
Camera	7	Q2-Q3	9	>Q3	0	Q1
Computer	1	Q1	0	Q1	0	Q1
Dosing system	3	Q2	0	Q1	0	Q1
Drone	8	Q2-Q3	3	Q2-Q3	0	Q1
Insect trap	3	Q2	0	Q1	0	Q1
Production line	3	Q2	2	Q2	0	Q1
Program/app	53	>Q3	10	>Q3	5	>Q3
QR code	1	Q1	6	>Q3	0	Q1
Robot	53	>Q3	12	>Q3	2	>Q3
Satellite imagery	1	Q1	2	Q2	3	>Q3
Sensor	30	>Q3	4	Q2-Q3	1	Q3
Sprayer	13	Q2-Q3	2	Q2	1	Q3
Transmitter	1	Q1	0	Q1	0	Q1
Web platform	29	>Q3	3	Q2-Q3	0	Q1
minimum	*1*		*0*		*0*	
Q1	*1*		*0*		*0*	
Q2	*3*		*2*		*0*	
Q3	*17*		*4*		*1*	

maximum	*53*		*12*		*5*	
Function						
Climate/weather control	16	Q3	4	Q3	0	Q1
Field management	23	>Q3	5	>Q3	6	>Q3
Mapping	14	Q3	2	Q2	4	>Q3
Surveillance	13	Q2-Q3	1	Q1-Q2	0	Q1
Employee administration	2	Q1-Q2	3	Q2-Q3	0	Q1
Irrigation management	14	Q3	4	Q3	1	>Q3
Mowing	4	Q1-Q2	1	Q1-Q2	0	Q1
Slashing	1	<Q1	0	Q1	0	Q1
Weeding	13	Q2-Q3	0	Q1	0	Q1
Harvesting	11	Q2-Q3	3	Q2-Q3	0	Q1
Transportation	5	Q2	0	Q1	2	>Q3
Defoliation	1	<Q1	0	Q1	0	Q1
Pruning	1	<Q1	0	Q1	0	Q1
Thinning	2	Q1-Q2	0	Q1	0	Q1
Pest control	5	Q2	7	>Q3	2	>Q3
Substance application	19	>Q3	12	>Q3	5	>Q3
Plant analysis	24	>Q3	10	>Q3	0	Q1
Fertilization	1	<Q1	0	Q1	0	Q1
Soil analysis	4	Q1-Q2	2	Q2	0	Q1
Storage	1	<Q1	3	Q2-Q3	1	>Q3
Surveillance	2	Q1-Q2	1	Q1-Q2	0	Q1
Sorting	14	Q3	3	Q2-Q3	0	Q1
Supply chain management	8	Q2-Q3	5	>Q3	0	Q1
Post-harvest quality control	7	Q2-Q3	0	Q1	0	Q1
B2B marketing	1	<Q1	3	Q2-Q3	0	Q1
Online selling	15	Q3	4	Q3	0	Q1
Coordination of robots	1	<Q1	0	Q1	0	Q1
minimum	*1*		*0*		*0*	
Q1	*1,5*		*0*		*0*	
Q2	*5*		*2*		*0*	
Q3	*14*		*4*		*0,5*	
maximum	*24*		*12*		*6*	

7. Exploring the impact of digitalization on sustainability challenges in German fruit production from the perspectives of stakeholders

Published in Discover Sustainability (https://link.springer.com/journal/43621)

Full reference: Gaber, K., Rösch, C. and Bieling, C. (2025). Exploring the impact of digitalization on sustainability challenges in German fruit production from the perspectives of stakeholders. *Discover Sustainability, 6*, 806. https://doi.org/10.1007/s43621-025-01703-x

7.1 Abstract

Unique challenges exist in the fruit cultivation sector and, if not considered in the development and application of technologies, this sector is at risk of being left behind in the ongoing digital transformation of agriculture. While understanding perspectives of stakeholders is critical for technology acceptance, their knowledge and views are underrepresented in analyses on the impact of digitalization on fruit production. This research works to fill this knowledge gap by qualitatively analyzing semi-structured interviews on the impact of digitalization on sustainability challenges in fruit production with 34 stakeholders along the fruit value chain in the case study region of Lake Constance, Germany. Societal acceptance and understanding of fruit cultivation practices, restricted plant protection product use, labour availability, and biodiversity support were the main reported environmental and socio-economic challenges. Nearly all stakeholders (94%) were hopeful that digital technologies could effectively address environmental challenges in fruit production, particularly through increased efficiency, while greater uncertainties were reported for the socio-economic challenges. Perceptions of digitalization’s chances and challenges varied among individuals, fruit production systems, and farm sizes. Authors provide recommendations, including targeted support for small-scale fruit farmers and suggestions for future research activities, and emphasize the importance of factual knowledge dissemination on digitalization in fruit farming to support informed adoption choices for intended users. The results of this study offer critical viewpoints on the current challenges in fruit production and the potential for digitalization to increase sustainability in this sector.

Keywords: Digital technology; stakeholder perceptions; adoption; barriers; Germany; fruit farming

7.2 Introduction

Climate change and weather extremes pose substantial challenges for fruit farmers, disrupting horticultural processes, altering growing conditions, and amplifying pest and disease pressures [1–3]. Early blossoming exposes crops to frost, while dry spring and summer periods reduce water availability, leading to potential yield losses. Societal demands and consumer expectations, emphasizing nature protection and specific concerns, e.g. about bee survival, further complicate the fruit farming landscape. Simultaneously, consumers expect consistently high quality and affordably priced fruits, creating a dual pressure on fruit farming. In response to environmental concerns, the use of pesticides in fruit production is under scrutiny, with the European Commission aiming for a 50% reduction in chemical pesticide use by 2030 [4, 5]. Of all crops grown in Germany, apple cultivation is the most pesticide-intensive, due to the low genetic diversity and susceptibility to fungal infections, as well as the societal demands for visually flawless products [6]. The potential for technologies in digitalized agriculture (and its sub-forms, including precision farming and smart farming) to contribute to increased sustainability in agriculture has been demonstrated [7–12]. Digitalized agriculture is inspired by the paradigm of Industry 4.0 and includes a wide range of technologies and technological advances, from artificial intelligence (AI) and the Internet of Things (IoT) to robots and drones [13]. These technologies hold promises such as a 90% reduction in pesticide use, but simultaneously pose the risk of a rebound-effect, such as increased energy usage through new technologies or the expansion of intensive agricultural production [6]. The history of technology has shown that next to the intended positive effects, unintended negative side-effects, so-called “unseens”, occur [14–16]. Digital technologies' social sustainability impacts receive less attention than their environmental counterparts [17, 18]. A number of ethical issues regarding digital agriculture exist, including invasion of farmers' privacy and lack of accountability for problems resulting from AI tool use [19–21] and potential rural unemployment and amplified inequalities through the use of agricultural robotics (e.g. [22]). The cooperation of humans and robots for the execution of agri-food tasks may be the best strategy to realizing societal goals and responding to modern challenges [23]. Public acceptance of agricultural sustainability may be improved if the positive impact of using digital technologies in food production, such as the reduction of inputs during weed control measures through precise herbicide spraying techniques, is communicated to the public [24].

As digitalization progresses within agricultural sectors, and as urgent environmental and social issues threaten the sustainability of agricultural production, it is critical to understand which positive and negative effects are anticipated. Qualitative research involving stakeholders provides valuable insights on the interests, needs, expectations, and adoption tendencies of the intended users for digital technologies to influence the sustainability of agricultural systems, which can enable a user-oriented digital transformation. Existing studies indicate varying interest levels among farmers towards digitalization, with larger farms showing a greater inclination to adopt these technologies due to their capital-intensive nature [25]. Typically, farmers embrace most agricultural innovations [26]. Reviews on farmer adoption tendencies for agricultural innovations, precision agriculture technologies (e.g. [26–28]) and field robotics and Unmanned Aerial Vehicles (UAVs) (e.g. [29]) highlight commonalities across agricultural sectors and regions, such as the factors of age, farm size, and education level.

In the case of fruit production, development of digital innovations is progressing. Autonomous robots have been developed for fruit harvesting (e.g. [30, 31]) and farm management tasks can be conducted by UAVs and robots (e.g. [32–35]). Efficiency in apple production can be enhanced through smart sensors and modelling (e.g. [36–38]). Artificial intelligence models are additionally altering the fruit production landscape. Deep learning approaches for fruit sizing (e.g. [39]), detection and segmentation (e.g. [40]) have been developed to aid the particularly labour-intensive activity of harvesting fruit, as well as for early recognition of fruit disease like pear and apple scab [41]. Machine learning as a digital assistant for farmers has been developed to achieve a sustainable and competitive fruit and wine production through, for instance, dis- ease prognosis, early pest detection, and suggestions of optimal dates for harvest [42]. Smart traceability systems along the value chain using Industry 4.0 technologies such as blockchain and AI, a concept referred to as Food Traceability 4.0, offer the potential for enhanced traceability, improved safety and product quality, and decreased food waste in the fruit and vegetable sector [43].

Despite the rapid progression of digital technology development, adoption rates in fruit farming lag behind those of arable farming [44]. The reasoning behind this lag is currently unclear, although research specific to the German fruit sector suggests that misguided marketing and inadequate information on digitalization may be the cause [45]. Studies on stakeholder perceptions of digital tools in other agricultural sectors in Germany offer largely positive results with some exceptions. For instance, a representative sample of the German public were positively inclined towards autonomous crop robots, particularly for the goal of reduced agrochemical use in plant production [46]. While Pfeiffer et al. [17] also found overall positive attitudes among the German population towards digitalization in agriculture, great differentiations in attitudes among German citizens were found in the study by Langer and Kühl [47] on robots in dairy farming. German farmers as critical stakeholders in the digital transformation tend to have a neutral to positive view on field robots (e.g. [48, 49]). Another representative survey of German citizens by Wilmes et al. [50] determined digital technologies to have a negative effect on willingness to buy food products produced by farms in Germany; however, this effect turned positive when environmental arguments in favour of digital technologies were introduced. Still, stakeholder perspectives on the benefits and drawbacks of digital technologies, particularly regarding sustainability, remain largely unexplored. Within the limited research on stakeholder perspectives on digitalization in relation to environmental and social sustainability, for instance towards agroforestry [51], water resources in Mediterranean agriculture [52], or large scale German arable farming [53], studies representing stakeholder perspectives and sustainability in fruit cultivation do not yet exist.

The research conducted for this study contributes to filling this literature gap and was completed within the same research framework as articles [45, 54]. The results of this study build on the previous findings, providing a comprehensive understanding of stakeholder perspectives on how digital technologies might contribute towards sustainability in German fruit production. Specifically, this study adds to the existing scientific discourse on stakeholder perceptions of digital tools in German agriculture by first examining the socio-economic and environmental challenges in the sector of fruit production, considering factors such as farm size and production systems. The research then investigates whether digital technologies can effectively address these challenges and contribute to enhanced sustainability and acceptability from the perspectives of farmers and other fruit value chain stakeholders. The study encompasses both small and large-scale farms[1] and includes organic and Integrated Production (IP) systems[2] in its analysis.

7.3 Methods and materials

This study employs a case-study methodology, concentrating on the Lake Constance region in Baden-Württemberg, which is recognized as the second-largest apple-growing region in Germany. Using a qualitative, open, and empirical approach, the research delves into stakeholders' expectations, concerns, and beliefs regarding digitalized fruit production and sustainability. The methodological framework included stakeholder identification, a semi-structured questionnaire, and 34 stakeholder interviews. Following data collection, the information was transcribed, translated, and comprehensively analyzed using MAXQDA 2020 software. This meticulous process aimed to ensure a nuanced understanding of the diverse perspectives within the fruit farming community of the Lake Constance region, offering insights into the intricate dynamics of adopting digital technologies in fruit cultivation.

7.3.1 Description of the case study region

The Lake Constance region, encompassing the counties of Konstanz, Bodensee-Kreis, Ravensburg, and Lindau, stands as a vital hub for fruit farming, boasting over 1,000 fruit farms [59]. Benefiting from mild temperatures and an annual precipitation of 900 mm, the region holds particular significance as the primary fruit-growing zone in Baden-Württemberg, covering more than half of the cultivated tree fruit area at over 9,000 hectares out of a total of 17,640 hectares [60]. Fruit farms in the Lake Constance region are traditionally small-scale and have an average size of 8,8 hectares [61]. Small-scale farms are widely acknowledged for their pivotal role in promoting greater landscape diversity and making significant contributions to biodiversity conservation, as well as environmental and socio-economic benefits (e.g. [62, 63]). Within Baden-Württemberg, the approximately 3,560 orchards have an average size of five hectares. Nearly 400 of these orchards adhere to organic cultivation practices, collectively managing an area of 3,260 hectares. A particularly noteworthy trend

[1] In Germany, where large farms are considered to be over 100 ha, the average farm size is about 65 ha [55]. Nearly half of all German fruit farms are categorized as small, each covering less than 20 hectares [56].
[2] German horticulture is comprised of two production systems: integrated production (IP) and organic. Current “conventional” fruit production is carried out according to IP guidelines. Therefore, IP and organic fruit farming encompass the conventional/organic binary. The choice of PPP and the holistic nature of the production system differentiate the two systems [57, 58].

is the substantial 14% increase in the number of organic fruit growers from 2017 to 2022, standing out amidst the overall decrease in fruit farms by 11% over this same time period [60].

7.2.1.1 Environmental context

One of the key challenges facing fruit production in the study region is the impact of climate change and weather extremes, which include wet periods leading to heightened mildew pressures, adversely affecting fruit production [64]. The study region's proximity to the nation's largest drinking water reservoir, the Lake of Constance, necessitates stringent regulations governing the application of agricultural inputs, such as plant protection products and fertilizers, to mitigate the risks of polluting the drinking water through runoff or leaching into the reservoir [65]. This underscores the need to explore different options for reducing chemical inputs as a proactive response to these challenges, including technological changes in farm management.

7.2.1.2 Socio-economic context

Fruit production in the Lake Constance region is deeply rooted in tradition and is characterized by small- to medium-sized family farms, who take pride in their family farm structures and long tradition of fruit growing. Recent political strategies and societal pressures have increased tensions in the area. Regional actors in the fruit value chain, including farmers, are particularly active in the community regarding current political pressures and social movements related to agriculture. Recent examples include their reactions to the “Save the Bees” referendum by the state of Baden-Württemberg in 2019 and 2020 [66] and silent protests as part of the continued European farmer protests at the internationally-recognized fruit production expo “Fruchtwelt Bodensee” [67]. On a national scale, civil activism to disrupt systems in Germany is well-established, and conflicting interests in current themes has led to protests that gain international attention, a current example being the ongoing farmers protests that began at the end of 2023 (see [68]). Criticism towards agriculture in Germany is a well-known phenomenon (e.g. [17, 69]). At the same time, German citizens place high value on regional products and tend to choose these for environmental purposes [70].

7.3.2 Stakeholder selection and qualitative interviews

This study employed a qualitative and explorative research design based on interviews. Stakeholders were strategically selected following a purposive sampling approach [71], guided by two key criteria:

1. Stakeholders identified as either intended users or developers of digital technologies.
2. Stakeholders engaged in the fruit value chain, spanning farm-level participants, marketing and wholesale representatives, and those viewing the industry from a broader technology or research perspective.

Authors generated a list of stakeholders who met these criteria with the use of an internet search engine, which included websites of technology companies, research groups, and farmer associations. Additionally, initial interviews were conducted with experts in regional farming and digital farming technologies, serving as a foundation to refine stakeholder groups and identify additional relevant stakeholders. This iterative process mirrored elements of snowball sampling [72]. These experts also played a crucial role in shaping the interview guideline, as outlined in the Appendix. The finalized list of stakeholders was categorized into six distinct groups (Table 1), forming the basis for in-depth qualitative exploration in this study.

Table 1 *Stakeholder group categories and their descriptions, adapted from [45, 54]*

Fruit farmers	Farmers, predominantly engaged in fruit production on their agricultural land, employing either Integrated Production (IP) or organic principles
Technology developers	Individuals working as employees or leaders in agricultural machinery or technology companies, ranging from start-ups to international corporations
Cultivation consultants	Individuals, whether privately or publicly employed, advise farmers on on-farm activities and/or the purchase and application of agricultural inputs, such as Plant Protection Products (PPPs) and fertilisers
Researchers	Local or national-based researchers affiliated with public or private institutions possessing knowledge of fruit cultivation, fruit value chain conditions, and/or agricultural technologies
Nature, agriculture and consumer associations	Individuals who are members, employees, or leaders of public or private organisations dedicated to nature preservation, agriculture, or consumer interests. These individuals play a role in representing the interests of groups or communities related to these sectors
Fruit wholesalers or marketers	Individuals serving as employees or leaders within fruit wholesale organisations or companies or individuals in similar roles within farm shops that offer local delivery services

Utilizing the power-interest matrix developed by Johnson et al. [73] and adapted from Mendelow [74], stakeholder groups were evaluated according to their level of interest and power in influencing the sustainability of digitalization in fruit production (Fig. 1). Initially, a target of five to six interviews was set for each stakeholder group. However, recognizing farmers as the primary audience for digital technologies and acknowledging their pivotal role, this group was given a higher target of eight interviews evenly distributed between organic and IP farmers.

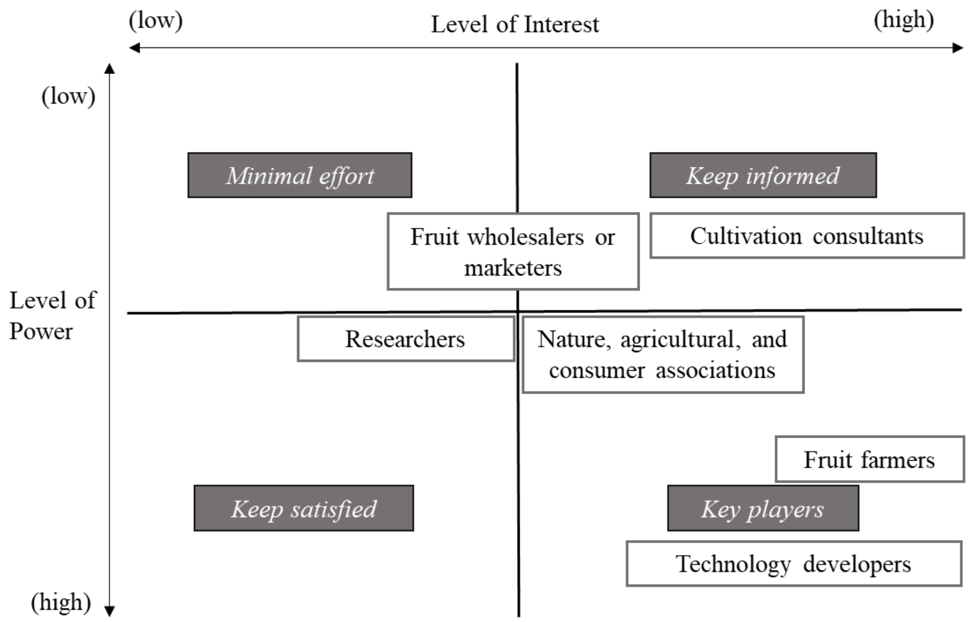

Fig. 1 *In the Power-Interest matrix, as found in [54] and based on Johnson et al. [73] and adapted from Mendelow [74], stakeholder groups are assessed according to their level of interest and power concerning digitalization in fruit production. This matrix helps identify the importance and influence of each stakeholder group in shaping the outcomes and sustainability of digitalization initiatives in the context of fruit farming*

Among the six identified stakeholder groups, two were found to be underrepresented in the region and challenging to engage: (1) technology developers and (2) nature, agricultural, and consumer groups. Recognizing the importance of these groups, proactive efforts were made to actively pursue and include them by expanding the geographical search area to ensure their participation. This approach successfully met the targeted number of interviews for each stakeholder group. While proximity to the Lake Constance region was prioritized, it was not a strict requirement for all stakeholders, especially considering the national and international scales at which digital technologies are developed. Certain groups, such as farmers and consultants, were expected to have regional expertise, allowing for an expanded stakeholder radius.

Between October 2020 and April 2021, 34 stakeholders from six stakeholder groups participated in interviews. 15 interviews were conducted digitally using Zoom-online software, while 19 were conducted in-person. Each interview had an approximate duration of one hour and were one-on-one interviews between the stakeholder and the corresponding author of this article. Characteristics of the interviewed stakeholders (Fig. 2) reveal commonalities. Most stakeholders were male, falling within the age range of 41 to 60. Their professional affiliations were primarily in the private sector and they resided in predominantly rural or mixed regions. All stakeholders had completed post-secondary training or education, contributing to a diverse and knowledgeable participant pool.

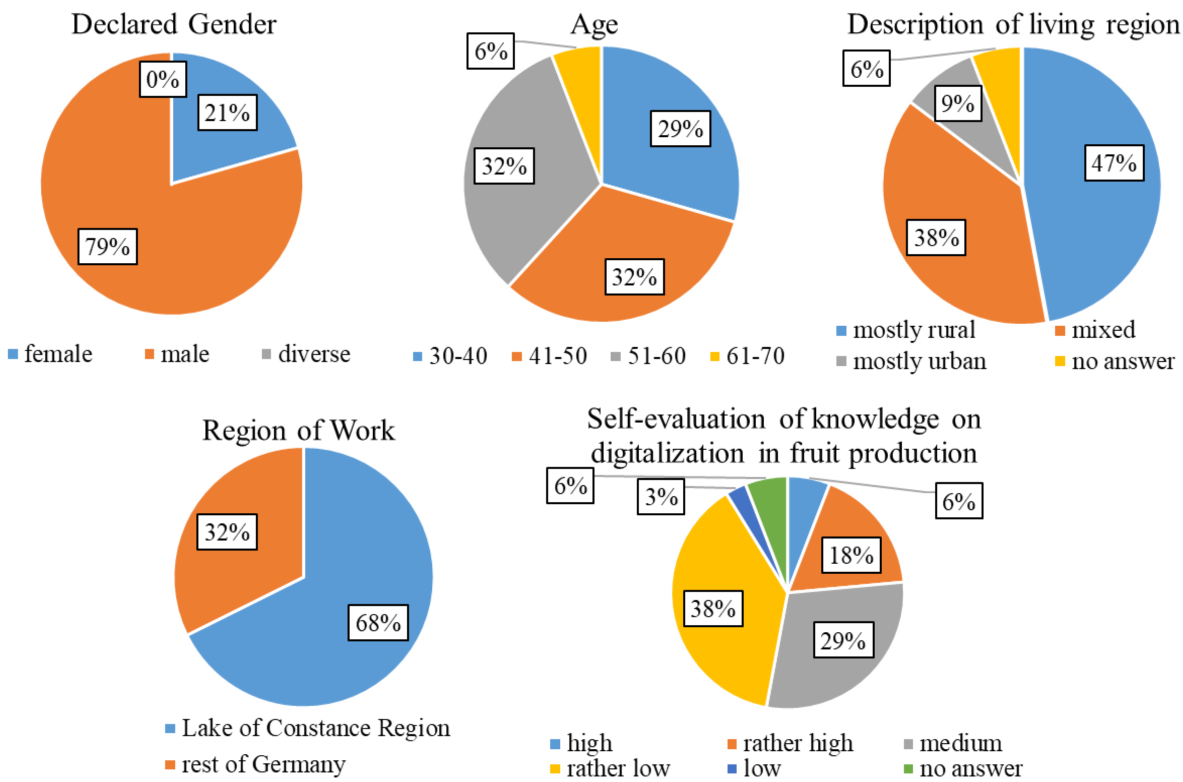

Fig. 2 *The characteristics of the six stakeholder groups (n=34 participants) engaged in the interviews within the study region or online, adapted from [54]*

A number of limitations should be considered during the interpretation of the results. The sample size of 34 stakeholders is small and cannot be considered representative of the fruit growing sector; however, the stakeholder selection methodology exhausted the limited number of relevant and interested stakeholders in the case study region. Due to financing project constraints, it was not possible to increase the sample size to reflect a more diverse sample. In the same way, it was additionally not possible to have enabled a more balanced gender representation among the stakeholders, as the German agricultural sector is largely male-dominated [75]. Although the authors made equal efforts to interview both IP and organic farmers, ultimately, more organic farmers were interested in participating than IP farmers, resulting in five organic and three IP farmers. Finally, the authors recognize that while the data could be considered outdated, the stakeholder interviews in this study provided a valuable snapshot into the perspectives in the region and sector at a critical moment in the ongoing digital transformation. These findings can be used as a basis for comparison with future studies that utilise similar methods to observe changes over time.

The interview guideline (Appendix) was formulated as part of an interview series for the DESIRA project (Digitization: Economic and Social Impacts in Rural Areas [76]) and therefore covers more topics than are relevant for the present study. Only responses from questions 18, 19, 21, and 22 were considered relevant for this study. The guideline consisted of 20 questions, with an expanded set of 27 questions tailored for farmers. Questions 1–17 were demographic-related for analysis purposes and thus formulated to be closed in order to simplify this straightforward phase of the interview. Questions

18–26 were the content-focused questions intended to answer the research questions. These were formulated as open-ended questions to encourage discussion by the participant. Question 27 was a closed question and was included for the purposes of the DESIRA project. The additional seven questions for farmers focused on eliciting information about farm characteristics, encompassing details such as farm size and the types of crops cultivated. The interview guideline underwent a refinement process and finalization, benefiting from feedback obtained through two expert interviews conducted in early 2020. These experts, both of whom are established researchers on digitalisation in German agriculture, were selected based on their prominence in the relevant scientific literature and involvement in research projects on digitalisation in German agricultural contexts. This iterative approach ensured that the questions were comprehensive and effectively aligned with the study's objectives.

Interview questions were not provided to participants in advance, ensuring a consistent and spontaneous response pattern. The participants viewed the questions during the interview- either via the shared screen during the online interview format or with a provided question set during the in-person interviews- to support comprehension of the interview questions. The interviewer intentionally omitted a definition of the term „digitalization “. As the goal of these interview questions was to gather perspectives and inductively code and categorize the responses ex-post, this omission allowed interviewees to respond from the basis of their own understanding of digitalisation in fruit cultivation without strictly framing the discussion around the researcher’s perspective. Consequently, the interview questions in this study reflect the interviewees' interpretations of digitalization. Further information on these stakeholders’ perspectives on the meaning of digitalization in fruit cultivation can be found in previously published work through the same interview series in the DESIRA project by Gaber et al. [45]. The interview process adhered to the principle of free, prior and informed consent from all participants. The interviews were initiated by exploring the primary environmental and socio-economic challenges faced by fruit growers in the Lake Constance region, focusing on potential distinctions between IP and organic fruit growing, as well as variations based on farm size. Subsequently, stakeholders' perspectives on the digitalization of fruit production were examined, exploring the potential of digitalization to address environ- mental, socio-economic, and social challenges.

7.3.3 Interview result analysis

The recorded interview audio files underwent a thorough anonymization process and were transcribed by a third-party transcription company. The ensuing analysis employed Qualitative Content Analysis [77] with MaxQDA 2020 software. Transcripts were systematically organized according to stakeholder groups. In the analytical phase, interview responses were coded using a two-phase inductive coding method proposed by Saldaña [78]. In the first coding phase, one-word or short statement codes that derived directly from the participants' own spoken language (in-vivo) were identified, preserving the authenticity of the original responses. In the second phase, pattern coding was used to identify major themes from the data: the in-vivo codes were re-coded using descriptive codes to group similar codes together, facilitating the emergence of themes. Category titles were then assigned to groups of similar descriptive codes to summarize and structure the analysis (Figs. 3 and 4; Table 2; descriptions in Tables 3 and 4 in the Appendix). The corresponding author conducted the coding. The co-authors worked collaboratively during the iterative coding process to ensure reliability and feasibility of the coding framework. This rigorous analysis ensures a comprehensive exploration of stakeholder perspectives, providing valuable insights into the challenges and opportunities associated with digitalization in fruit production. The excerpts, example coding, and categories presented in this article have been translated to English.

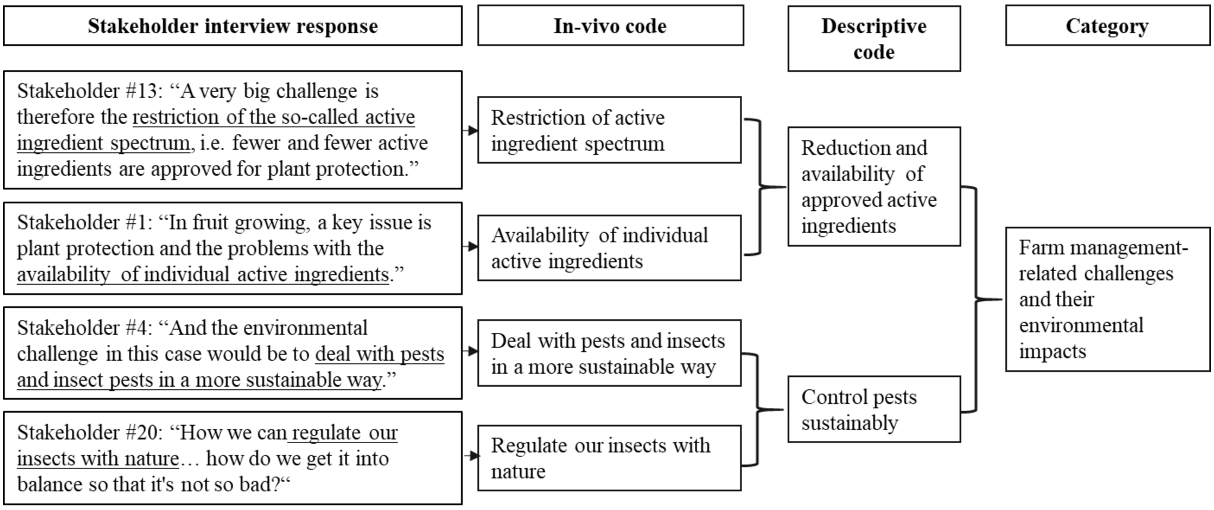

Fig. 3 *Example of coding process of interview excerpts (translated) regarding environmental challenges in fruit production*

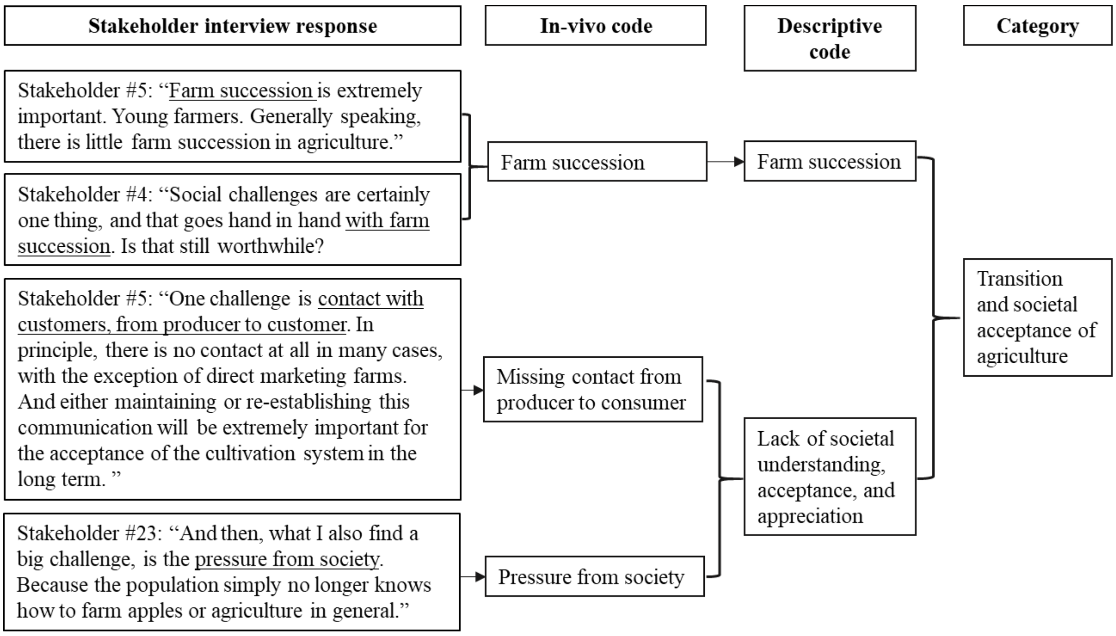

Fig. 4 *Example of coding process of interview excerpts (translated) regarding socio-economic challenges in fruit production*

Table 2 *Environmental and socio-economic categories and coded challenges*

Environmental challenges	
Category	**Descriptive code of challenge**
Farm management-related challenges and their environmental impacts	Reduction and availability of approved active ingredients
	Reduction of use of PPPs
	Untrustworthy active ingredients
	PPP drift and nitrate leaching
	Minimize residues
	Control pests sustainably
	Need-based fertilization
	Maintain high yield and quality with changing regulations
	Support of biodiversity, avoidance of species loss
	Increase resilience
	Soil compaction
	Avoiding resistance
	High fuel consumption
Climate and energy	Climate change
	Weather extremes
	Access to water
	Frost
	Hail and precipitation
Insects, pests, and diseases	Disease
	Intensive permaculture increases pest challenges
	Scab pressure
	Damage from insects
	Pollination
Regional environment	Humidity from lake proximity causes increased apple scab
	Problematic, weak young sites
	Lake largest water reservoir, protected area
	High local precipitation

Socio-economic challenges	
Category	**Descriptive code of challenge**
Challenges related to farm labour and management	Wages and housing standards for farm labourers
	Integration of foreign seasonal workers into the community
	Reliability, work ethic, training of the labourers
	Labour availability
	Dependency on seasonal workers due to shortage of local labourers
	Bureaucracy
Transition and societal acceptance of agriculture	Structural change of farming
	Disturbance to tourism industry by certain agricultural practices
	Creation of valuable, attractive jobs/retention of employees
	Farm succession
	Lack of societal understanding, acceptance, and appreciation
Markets and marketing	Power of monopolies
	Price competition and pressure
	Inadequate marketing methods/channels
	Global competition
Socio-economic-environmental nexus	Crop losses due to weather extremes
	Land use competition
	Food security

7.4 Findings

This results section is structured as follows: first, Sect. 7.4.1 illustrates common themes within the reported environmental challenges, then perceived differences in production system and farm size.

This is followed by an elaboration of the described potential for digitalization to mitigate the reported challenges. The same structure for the socio-economic challenges follows in Sect. 7.4.2. Some challenges naturally relate, cause, or even exacerbate other challenges. Stakeholders also frequently provided multiple responses to interview questions; unless clarified, the responses were considered to have equal value. For these reasons and because of the added value that the nuances found within qualitative analyses can offer over quantitative, the focus of this results section is on the qualitative analysis. Descriptive statistics and graphs are used to emphasize the general frequencies of which categories of responses were reported by stakeholders, but should be understood with reservations, also with consideration of the small sample sizes of stakeholders.

7.4.1 Environmental challenges and digitalization in fruit production

7.4.1.1 Reduction of PPP use and supporting biodiversity

Stakeholder descriptions of environmental challenges in fruit production were grouped into the following categories: farm management- related challenges and their environmental impacts; climate and energy; insects, pests, and diseases; and regional environment (Table 3 and Fig. 7, located in the Appendix). Environmental challenges within the category “farm management- related challenges and their environmental impacts” were most commonly reported by stakeholders. This category related to the interactions between farm-management practices and the environmental impact these interactions created on the surrounding ecosystem. The reduction of PPP use was a critical theme among the reported current environmental challenges for fruit production in the Lake Constance region. This challenge was described to stem from societal, political, economic, and environmental pressures. For instance, a developer: “How can I reduce or minimize spraying agents? It is always interesting from a cost point of view, of course, economically… but also extremely interesting from an ecological point of view”, and an advisor: “Over the next few years, it will be a legal requirement to reduce the proportion of chemical-synthetic products by 40 to 50 percent. In other words, what we have already been doing for years, decades, in integrated production: reducing the pro- portion of chemical-synthetic products has now been enshrined in law as a task”. Many of the response elaborations linked the reduction of PPP use to other challenges, demonstrating the natural interrelation between environmental issues. Representatives from NAC associations named this challenge more than any other group. One representative described this challenge in relation to another, namely sustainably controlling pests: “I believe that, on the one hand, we could simply reduce the use of critical pesticides even further. And the ecological challenge in this case would be to deal with pests and insect pests in a more sustainable way”.

Neither organic nor IP fruit farmers named this challenge of PPP reduction. Instead, farmers were more concerned by challenges related to precipitation and crop management. “The classic challenge, and also here in the region, is disease because we have a lot of precipitation, there is probably [more] scab pressure compared to other regions” reported an organic farmer. Another organic farmer linked precipitation to high fuel consumption and PPP application: “High fuel consumption, I would definitely put it there. Because of the weather. I would not even say climate, but weather. Because quite honestly, yes, when the weather is, let us say, bad for us, we have to make a lot of passes with the crop protection sprayer”.

Biodiversity support and avoidance of species loss was a second critical category of responses. Similar to the challenge of PPP reduction, biodiversity support was often described in relation to political and societal pressures. “And the challenges [of biodiversity support] will be considerable over the next few years, especially as political and public pressure is increasing in this direction, especially now with the Bee Protection Ordinance and so on” reported an organic farmer. One wholesaler described biodiversity itself to not be the issue, but rather the myth surrounding biodiversity issues in farming: “Of course, we have biodiversity, this insect extinction as a keyword. Where I say that this is not really a challenge. We have studies that show that [biodiversity] in fruit production, both conventional and organic, is actually quite good. But in the public perception, it is somehow always bad. And so, yes, we are always challenged to justify ourselves about something that is actually not a problem at all, from my point of view”. This implies that the narrative on fruit cultivation and sustainability in the public is currently inadequate and is allowing misinformation to be spread, leading to both negative public perception of fruit cultivation and increased frustrations of the farmers towards the public.

The majority of stakeholders (over 70%) believed a difference in environmental challenges exists based on production system. Stakeholders who responded with “yes” often elaborated upon their answers, whereas “no” responses did not elicit further elaboration. All organic fruit farmers and nature, agricultural, and consumer group stakeholders believed a difference exists, whereas other groups, such as fruit cultivation consultants, were more critical. Most challenges described to differ based on production systems belonged to the response category “farm management- related challenges and their environmental impacts”. In particular, stakeholders described the PPPs allowed in IP to be more efficient than those in organic farming, and that fewer PPPs are approved for use in organic farming. Stakeholders mentioned that the challenge of biodiversity support and avoidance of species loss differs by production system. IP farming was reported to be more threatened by this challenge, as the organic farming system incorporates the positive potential of insects, for instance through flowering strips, more often than in IP farming. However, this depends largely on the interests of the farmer rather than the certified production system of the fruit farm: “in organic farming, we try to have bio- diversity over the entire area. And we try to get the incredible insect potential into the entire area. In IP or conventional cultivation, we try to keep the insects out of the plants due to approvals of plant protection products… then it is again up to the head of the farmer whether they use the free space sensibly”, reported an organic fruit farmer. Still, other stakeholders said there are no significant differences between production systems because in the end, the regional characteristics and challenges are the same regardless of production method: “For me, this has nothing to do with ecology or anything else. But almost rather with bureaucracy… So these problems in plant protection are pretty much the same between [IP] and organic production", described a fruit wholesaler.

When asked if a difference in environmental challenges exists based on the size of the fruit farm, a wider variety of stakeholder opinions was observed than for differences based on the production system. Less than half of all stakeholders believed a difference exists, and a few chose not to respond to this question for undisclosed reasons. As with the previous question, some stakeholders provided two answers. For instance, most interview partners who believed differences exist based on farm size referred to ecosystem challenges in relation to cost efficiency. A fruit wholesaler described biodiversity mitigation strategies to be easier for larger farms to conduct, depending on the strategy: "depending on how [a farmer manages] biodiversity, larger farms can take part of their land out of production and, yes, perhaps do some hedge planting or extensification measures there. If a small farm does that, it is often a high proportion of its farmland and it cannot afford to give up that area". In contrast, a consultant described smaller farms to be less challenged by issues related to biodiversity, as they have a greater positive impact on species diversity through their small structures, which offer more possibilities for diversification. Still, many respondents saw differences in how farms face environmental challenges to depend on the farmer or organization of the farm, not the farm size: "there are no differences. It is up to what the farmer does", described an organic farmer; "the people who work there are the decisive factor… What knowledge and expertise do they have? What are their goals? What kind of ethical background do they have?" reported a researcher.

7.4.1.2 Digitalization to mitigate environmental challenges through increased efficiency and productivity

Nearly all stakeholders (32 of 34; 94%) believed that digitalization could mitigate the environmental challenges (Fig. 5); all interviewed researchers, consultants, representatives from NAC associations and developers were convinced of this. Increased efficiency and productivity were strong themes among stakeholder responses. One developer mentioned the endurance of digitalized machinery: "people simply do get tired… [the digitalized machinery] can just deliver the same performance over a whole day". Other stakeholders in these groups described digitalization to improve the quality of the products and the productivity of on-farm tasks through automation, leading to overall improved environmental efficiency. A consultant was optimistic that digitalization could address two challenges at once: earlier, more precise application with PPPs that are less effective. "In order to be able to consciously use ecological products in advance that do not have such a high degree of efficiency, but can still regulate an initial population well, these are possibilities, perhaps, that we will be able to master the ecological challenges in the future through digitalization". Another developer provided an example in the case of fungicide application: "A concrete example would be when I can draw conclusions about fungal infestation on the basis of image data information. I can then take much more selective and time-limited measures, i.e., at the optimal time, and no longer have to apply pesticides over large areas as a preventive measure". The precision aspect of digitalization was an additional benefit mentioned by many stakeholders: precise measurements of the soil and plants could reduce the amount of applied PPPs and therefore alleviate the related environmental challenges. Similarly, stakeholders discussed how optimized weather prognoses could allow for more efficient management of the farm and PPP applications.

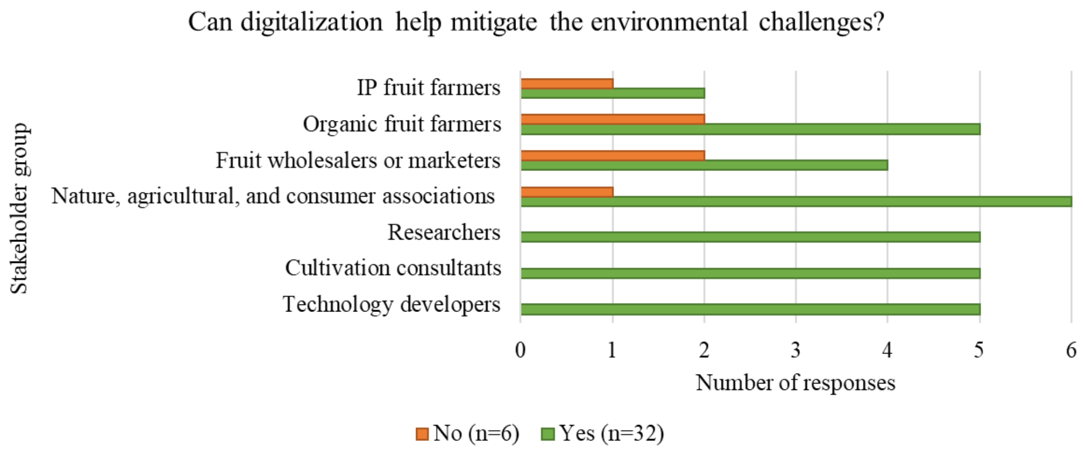

Fig. 5 *Stakeholder group responses to the influence of digitalization on the environmental challenges in fruit production. Stakeholders could provide multiple answers*

Over 80% of the stakeholders in the farmer group and the fruit wholesaler group (seven out of eight farmers, four out of five wholesalers) believed digitalization could mitigate reported environmental challenges, but these groups also included more skeptical opinions than the others. One fruit wholesaler and one IP fruit farmer did not believe that digitalization could mitigate current environmental challenges. Six stakeholders responded with "no" when asked if digitalization could mitigate the described environmental challenges. However, four of these stakeholders also provided "yes" responses in their open-ended interview answers. As previously described, unless otherwise clarified, both responses were considered to have equal value. An organic farmer mentioned that existing digital tools in fruit production do not offer mitigation strategies for the challenge of biodiversity: "there are solutions for the work around it, for biodiversity, for maintenance work in certain areas. But to get more biodiversity, I do not see any digitalization options yet". Either this signifies a lack of digital tools for this issue, or if they do exist, the communication about these tools may be insufficient.

7.4.2 Socio-economic challenges and digitalization in fruit production

7.4.2.1 Societal acceptance and labour availability

Stakeholders were asked to name the most important socio-economic challenges in fruit production in the Lake of Constance region (Table 4 and Fig. 8, located in the Appendix). Socio-economic challenges can be understood as societal and/or economic issues that threaten the activities within and/or the overall existence of fruit production. In- vivo coding of the interview responses and inductive categorization resulted in the following categories: challenges related to farm labour and management; transition and societal acceptance of agriculture; markets and marketing; and socio-economic-environmental nexus. The majority of named challenges were grouped into the category "transition and societal acceptance of agriculture". Overwhelmingly, stakeholders were concerned about societal values around agricultural production: the challenge "lack of societal understanding, acceptance, and appreciation" was reported by over 90% of stakeholders. Increased quality expectations among consumers, demands for low prices, and societal pressures regarding agricultural practices, such as PPP reduction, were described to stem from deficient competencies about farming. "What I also find to be a big challenge is the pressure from the population. Because the population simply no longer knows how to farm apples or agriculture in general", reported a representative from an NAC association. Consultants, researchers, NAC association representatives, and fruit wholesalers/marketers were particularly concerned that, despite the perceived lack of care or understanding from consumers about how fruit is produced, consumers are quick to criticize the need for pesticides or higher prices for organic products.

To combat this disconnect, stakeholders frequently reported that consumers must learn to recognize added value in products, from higher quality standards to regional products. A consultant suggested, "Maintaining or re-establishing communication [between farmers and consumers] will be extremely important for the acceptance of the cultivation system in the long term. That consumers understand why a product looks the way it does in the supermarket. And why it costs what it costs. And, on the other hand, that farmers understand why consumers make the choices they do. And there are now so many intermediate storage, processing and marketing steps in between, all of which want to make a profit". While farmers did not express this concern as frequently as other groups, one IP farmer also hoped for greater appreciation for regional products and less partiality for organic labels by consumers. He also connected the socio-economic challenge of societal acceptance and appreciation to environmental concerns: "I would simply like to see a little more appreciation for our local agriculture and for what we do here. Because the apple that comes from Italy or from somewhere else has seen completely different pesticides than the one here in the Lake Constance region. And then organic is not necessarily better. And we still do not get that across to our customers. So we cannot go on consuming everything just because it says organic on it. We can no longer afford that, I am deeply convinced… I do not think it is the way we can go for the next few years and for the next few generations… Because all this organic stuff that has been carted around the globe does not have a great environmental footprint either".

As with the environmental challenges, socio-economic issues are interrelated. For instance, stakeholders linked labour challenges to societal competence. The lack of appealing, well-paid positions with career prospects, which attract and retain employees, creates a strain on the regional fruit production. "Again, this aspect of appreciation comes into play, how attractive the profession is, who actually wants to do it?" reported a developer. All stakeholder groups except researchers and farmers reported concerns over farm succession. Instead, stakeholders from these groups focused more on the direct challenges related to farm labour and management.

Labour availability was the second-most important challenge according to stakeholders. The concern about attaining domestic and foreign labour is related to a multitude of reported factors, including unappealing physical labour, rising minimum wage, and the lack of regional farm labourers. A researcher mentioned that in fruit production, "you really aim for the cheapest possible labour for unpleasant routine work. And that's a huge challenge. That is not going to work anymore. It already does not work today". In German fruit farming, when imported fruit can be purchased at much lower prices, it is a challenge for German farmers to offer the minimum wage to employees while pricing their products competitively. "You always have to make sure that you are competitive in order to be able to sell the fruit in the country in the end. And that does present challenges", described a developer. The increasing costs required by farmers to employ labourers threaten the economic feasibility of the occupation. While other stakeholder groups reported farmers to deal with intensive bureaucracy, especially when employing foreign seasonal labourers, this challenge was not described by farmers themselves.

Most interviewed stakeholders (62%) believe that differences exist between production systems regarding socio-economic challenges. A common theme among descriptions was that organic agriculture has a better image and therefore is more accepted by society than IP or conventional production methods. An IP farmer reported, "I lost customers [at the farmer's market] because I said very clearly, I am not an organic farmer", implying a disadvantage for non-organic farmers regarding social acceptance and stigma of non-organic production methods. Still, interviewed organic farmers mentioned that consumers have higher expectations for the quality of organic fruit than for non-organic fruit, but simultaneously expect low prices, creating greater social acceptance challenges and market pressures for organic farmers. Some stakeholders reported the requirements for labourer conditions to be higher in organic than in IP fruit farming. An organic farmer conveyed, "The amount of work, manual labour on the organic farm is definitely higher than on an IP farm". Therefore, organic farmers may be more confronted by the described challenges related to domestic and foreign labourers. Stakeholders within the technology developers group described organic farming as having both a price advantage over IP farming, yet they must tackle the challenge of reaching the same yield potential and therefore economic margins as an IP farm.

Similar to the socio-economic challenges for different production systems, most interviewed stakeholders (82%) agreed that there are also differences in these challenges based on farm size. The stakeholders who provided responses in the groups fruit wholesalers or marketers, fruit cultivation consultants, and technology developers all agreed that farm size does imply a difference in challenges. Specifically, developers mentioned that farm organization and management is easier for larger farms, as well as the benefit of the economy of scale. One developer said, “We know that the large companies in particular also benefit from certain economies of scale. Of course, this cannot be generalized, but they also demonstrate a certain professionalism, have lower costs and are simply organized in a completely different way”. Similarly, larger farms benefit from synergy effects, such as the better economic utilization of machinery. However, these stakeholders also mentioned that smaller farms are less challenged in hiring labourers and more often received familial help than large farms with more land area. An organic farmer described small farms to offer better working conditions for their hired workers and that the farm manager has a better overview of their team than a manager of a large farm. Still, other farmers reported that workers on larger farms tend to earn higher salaries. Smaller farms may have more issues finding farm successors and face greater challenges to enter the market with their products, according to a NAC association stakeholder. Regarding societal acceptance, smaller fruit farms may have an advantage. A developer reported that “small farms in particular are somewhat glorified in public, because there is a bit of a prejudice that as soon as a farm is small, it is good, it is what we imagine idyllic about agriculture and everything is good. And as soon as the farm is large, it can no longer be good, because if it is mass production, it cannot be good”. Stakeholders who believed that differences in these challenges do not exist based on farm size did not elaborate on their answers.

7.4.2.2 Digitalization to mitigate socio-economic challenges through increased efficiency and transparency

When asked if digitalization can help mitigate the socio-economic challenges (Fig. 6), perspectives varied within each stakeholder group. Of the stakeholders who believed digitalization could mitigate said challenges (16 of 34 stakeholders; 47%), responses centered largely around two themes: increased efficiency through automation and increased transparency along the value chain for increased acceptance and market advantage. Specifically, the challenge of labour availability and the dependency that farmers were reported to have on labourers- domestic and foreign, permanent and seasonal- could be eased through automated technologies. An IP farmer mentioned that the use of automated machinery could make work more accessible for a wider scope of potential labourers, for instance people with intellectual or physical disabilities, and therefore increase local job opportunities. When discussing what digitalization could replace, a researcher listed “tasks that you no longer want to do, that are unpleasant, exhausting, boring, not challenging, are no longer necessary. And higher, more interesting fields of activity are created, which make the workplace more interesting”. However, the same researcher described the risk of higher wages for labourers and job discrimination associated with this positive aspect of digitalization: “with the higher added value that can then be realized, appropriate payment is also really necessary… whoever cannot fulfil [the higher paying jobs] gets kicked out”.

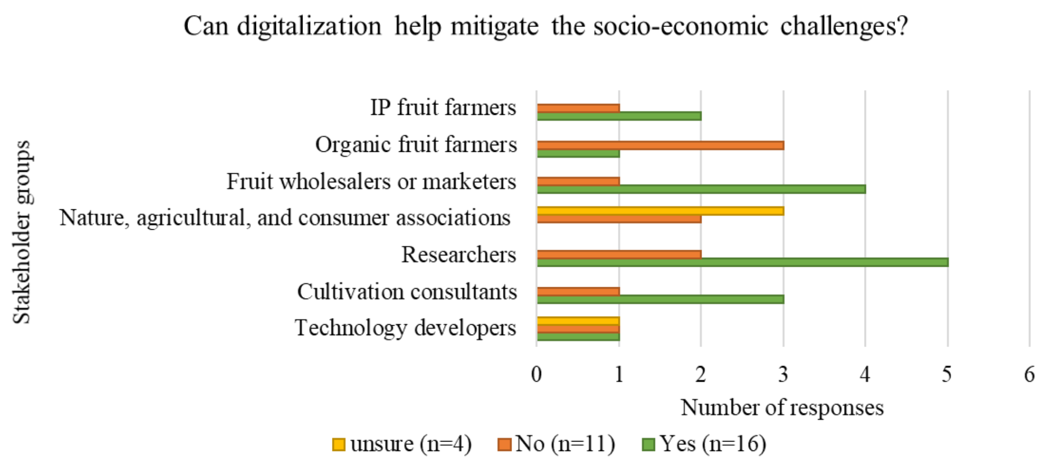

Fig. 6 *Stakeholder group responses to the influence of digitalization on the socio-economic challenges in fruit production. Stakeholders could provide multiple answers*

The second theme of increased transparency for consumers into the production of agricultural products through technologies was described to potentially allow for more public knowledge and social acceptance of fruit cultivation methods, which could in turn lead to a price advantage for local farmers. Consultants and researchers most frequently mentioned this potential. The traceability of products and production conditions may additionally lead to easier, more reliable quality control by wholesalers and certification bodies. Stakeholders also mentioned the marketing advantage: more customers can be reached through online platforms or social media than through non-digitalized forms of marketing.

Of the respondents who were uncertain, stakeholders reported not seeing a direct connection from digital technologies to socio-economic challenges. Additionally, some stakeholders reported that the customer base is already developed and loyal, and because people tend to exhibit habitual behaviours and therefore are not likely to change their buying patterns due to increased transparency of products or different marketing via digitalization. A researcher mentioned that while he has observed new technologies like robotics to improve societal acceptance of arable farming, this may not be the case in all agricultural sectors. He used animal husbandry as an example: “But if we then look into the stalls and look at the topic of ‘animal welfare’, we actually find that these arguments that we put forward, that digitalization in the barn probably leads to animal welfare. In principle, yes, it is seen as positive, but overall we have found that it does not really move us forward in terms of acceptance, because the situation is that if the entire husbandry system is rejected, then, and it seems to be the case in some cases, then yes, minor changes in the system [through digitalization] do not move you forward [towards acceptance]”.

7.5 Discussion

Stakeholder perceptions and interests determine the role they play in the digital transformation of agriculture. The willingness of stakeholders to take part in this transformation depends partially on the extent to which they believe digitalization can influence sustainability. The results of this study indicate that the majority of interviewed stake- holders believe digitalization can positively influence current sustainability challenges in fruit production in the Lake Constance region, particularly through increased efficiency, productivity, and transparency.

This research delves into real-world problems by exploring participants' experiences, perceptions and behaviours, answering “how” and “why” questions rather than “how many” or “how much” in order to understand themes and patterns that are difficult to quantify. Although it presents some numerical data, it is important to keep in mind the limited sample size and to emphasise the importance of context and narrative.

This discussion section is separated into two parts: the first section explores support measures for digitalization to mitigate environmental and socio-economic sustainability challenges based on the findings of this study. Second, the discussion is concluded with a section that examines the role that digitalization could play specifically with the socio- economic sustainability of fruit farming in the Lake Constance region.

7.5.1 Support for digitalization to mitigate environmental and socio-economic sustainability challenges

While the majority of stakeholders believed that digitalization could mitigate both environmental and socio-economic challenges, responses were higher for the former category. Digitalization was believed to be able to mitigate environmental challenges in fruit production through greater endurance of machinery over human labourers, improved environmental efficiency and precision and optimized prognoses. These expectations may not be attainable with the complexities surrounding digitalized fruit cultivation today, including unsuitable tool development and an uneven distribution of digital knowledge in the fruit cultivation industry [45]. Arguably, these themes of efficiency and productivity belong to the growth paradigm that has led to a number of sustainability problems existing today. Digital technologies developed by large agro-food companies are not radically changing how agriculture is conducted, but rather optimising the current production model, and may lock farmers into the current and unsustainable system that uses large-scale machinery and chemical inputs [79–81]. Considering that digitalization of the fruit sector is already underway, the responsible way forward is to ensure that it is focused on mitigating current and future sustainability challenges, with consideration of the unique challenges and regional contexts found within this sector. The digitalization of fruit production requires support in order to continue to function in this same paradigm and not contribute to further degradation of the environment, but rather contribute positively to sustainability.

The environmental challenges described by stakeholders were numerous and primarily concerned reduction and use of PPPs, support of biodiversity and avoidance of species loss, weather extremes, climate change, and sustainable pest control. These reported, perceived challenges match those found in the literature on fruit cultivation (e.g. [82, 83]) and those of concern by political frameworks and current goals around environ- mental sustainability. These include the EU Commission's proposal to cut greenhouse gas emissions by at least 55% by 2030 [5], the Climate Law to be climate neutral by 2050 [84], and the Green Deal's Farm to Fork strategy [85]. Communication on- and sup- port for digitalization at the national government level has typically focused on environmental aspects, such as the strategy to support biodiversity by the federal ministry of food and agriculture [86], and the Rentenbank Investment Program for Agriculture which supports investments in particularly environment- and climate-friendly management practices [87]. The environmental impact of digitalization is more researched and more awareness has been brought to this aspect than potential socio-economic impacts, despite the fundamental changes digitalization could impose across all aspects related to agriculture [18]. This may be the reason why stakeholders were more confident that digitalization could mitigate environmental challenges in comparison to socio-economic. However, as some stakeholders reported not seeing a direct connection from digital technologies to socio-economic challenges, the root of this difference may instead be a lack of digital tools to solve these complex issues, or if they do exist, communication to the intended users about available tools and their functions may be insufficient, as previously found by [45].

Martens and Zscheischler argue that digitalization's contribution to solving sustainability challenges is dependent upon the design of political, legal, and economic frameworks [88]. Numerous socio-economic challenges were described by stakeholders; within the ubiquitous 3-pillar concept of sustainability (e.g. [89]), the pillars are inherently interdependent and thus require equal political attention and support. Yet, challenges listed by stakeholders such as those related to farm management, societal competence, and agricultural transition are seldom described by policy makers in Germany. To the authors' knowledge, national funding programs for digitalization with a focus on the named socio-economic challenges do not exist and research initiatives that employ qualitative, empirical, and/or transdisciplinary methods in fruit production are lacking. As such, the current political framework lacks adequate strategies to support sustainability challenges facing fruit cultivation in the digital agricultural transformation. Considering the accelerated pace of digitalization in agriculture, it is critical that support structures exist for all agricultural sectors, otherwise the risk of sectoral digital divide, or the gap between those able to benefit from the digital age and those who are not [90], may become reality.

7.5.2 Highlight: socio-economic sustainability challenges and digitalization in fruit production

In light of the previously described structural deficits, as well as the frequency and calibre of the socio-economic challenges expressed by stakeholders, the following section highlights the challenges and opportunities for digitalization in the context of socio-economic sustainability and fruit cultivation in the Lake Constance region. Stakeholders were primarily concerned by the low societal acceptance of fruit cultivation and products, and listed numerous challenges related to labour availability. Increased efficiency through automation and increased transparency along the value chain for increased acceptance and market advantage were the main themes that emerged regarding digitalization's potential to mitigate the socio-economic challenges. The results of this study both confirm and contest findings from the limited existing literature on digitalization as a potential mitigation strategy for socio-economic challenges in agriculture, such as the opportunities that agriculture may gain through the digital transformation (see e.g. [11, 91]) including becoming a more attractive activity, offering new jobs, and improving the economic sustainability of agricultural businesses. In particular, stakeholders reported digitalization to potentially ease the frequently named challenges related to dependency on domestic and foreign, permanent and seasonal labourers, while also expressing concerns that digitalized jobs may become discriminatory, exclusive, and require higher wages than farmers can afford. The interviews for the present study began in the fall of 2020, following a particularly challenging harvest season. Due to the COVID-19 pandemic, seasonal labourers, particularly from outside countries, were harder to hire than usual. This timing should be considered when looking at the frequency of manual labour challenges mentioned by stakeholders in the results of this paper. While digital farming technologies may replace manpower as labour shortages continue to challenge the agricultural productivity [53], interviewed stakeholders in the present study did not mention risks or opportunities related to the potential complete replacement of workers. This could be due to the low adoption of completely autonomous robots in German agriculture, as was concluded in the empirical study of digital technologies and German horticultural workers by Prause [18]. However, technologies with semi-autonomy may be enough to influence the sectoral labour force. The use of robotics or semi-autonomous machines might lead to sectoral job losses [80, 92] through, for instance, a shift from highly skilled labour to temporary, migrant labour [93]. These findings contest the previously mentioned economic opportunities found in the literature and the concerns of exclusive, high-wage digitalized jobs as described by the stakeholders. This contradiction highlights the uncertainties that still exist: the impacts of digitalization in fruit cultivation are yet to be fully understood at this stage in the digital transformation, emphasizing the need for continued research and observation to support a sustainable transition.

When asked about differences in challenges based on farm size and production system, the greatest number of stakeholders reported differences in socio-economic challenges based on farm size. Given the research that has shown the correlation between farm size and adaptability to technological innovations [94–96], Martens and Zscheischler [88] have questioned how European governments will protect smallholders from this digital divide. Prause et al. [80] argue that opposition between small-scale agro- ecological farming and large-scale industrial farming will be fortified by digitalization. Smaller farms were perceived by stakeholders in this study to face greater challenges to enter the market with their products. Markets and large-scale buyers may favour larger farms, who tend to punctually deliver large volumes of commodities over smaller farms [97, 98]. Digitalization could further exclude small-scale producers from certain markets, as high-cost digital supply chain technologies are being encouraged for regulatory compliance proofing, which may not be affordable for smallholders [80]. Policy makers recognize the advantage that larger farms have over smaller farms in market access: the Agricultural Ministers Conference in 2020 proposed that an International Digital Council should be developed by the Food and Agriculture Organisation of the United Nations (FAO) to, among others aims, reduce the digital-divide and improve access to digital technologies, including for smallholder farmers [99]. Recognition is a helpful first-step towards support, but actions are required to ensure that smallholder farmers, such as those commonly found in the fruit production sector in the Lake Constance region, do not face greater disadvantages than middle- and large- scale farmers. Targeted support that considers the results of this study, such as specific development of affordable supply chain technologies or policies in markets that favour small farms, would aid in reducing the gap in opportunities and challenges based on farm size in digitalized fruit farming.

Most current socio-economic challenges for fruit production in the Lake Constance region reported by stakeholders relate to transition and societal acceptance of agriculture. As consumers have gradually become further removed from the agricultural industry since the industrialization of agriculture [100], their concerns surrounding agriculture have increased [101]. Potential consequences of deficient agricultural knowledge, such as misplaced public support for political campaigns, mistrust of farmers, and a lack of understanding of price politics threaten the sustainability of farming [102]. Many stakeholders described a general lack of knowledge or interest from consumers regarding fruit production, which they described to harbour unfair criticisms and inappropriate expectations for price and seasonal availability. This gap between high expectations from society and the prices consumers are willing to pay is referred to as the citizen- consumer gap [103]. Farmers reported this mismatch less frequently than the other stakeholder groups. One farmer suggested consumers change their expectations for the price of products in order for the farmers to be able to financially manage the increasing environmental and societal demands on fruit cultivation. Stakeholders were hopeful that increased transparency from farm to fork through digital technologies in fruit cultivation could mitigate the most commonly reported challenge of societal appreciation and understanding of agricultural practices such as changing consumer expectations. The German Agricultural Society (DLG) has echoed this optimism by suggesting that the transparency of production processes and traceability that can be simplified through digitalization will create trust and increase appreciation of agriculture [104]. For instance, blockchain technologies can work with IoT-related technologies (such as sensors and digital tags) to collect and upload data along the value chain, from fruit picking to final consumption, for increased traceability and transparency [105]. Digital media tools that use blockchain platforms to allow consumers to trace the transformation of food along the supply chain through, for instance, the scan of a QR code on their product [106, 107]. Beyond this, open-source digital platforms and apps that enable two-way communication between fruit farmers and consumers, such as digital Community Supported Agriculture (CSA) platforms or direct marketing apps, could build trust between the parties [54]. While the related article by Gaber et al. [54] investigated the *perceived* impact that digitalization, including increased transparency enabled through digital technologies, could have on the public opinion of fruit farming, the true impact of increased transparency in fruit production has yet to be researched. Despite the opportunities offered by technologies towards improved transparency and the optimism described by stakeholders on this aspect, little evidence suggests that increased information on practices can alter societal appreciation for farming [103]. In fact, in the case of animal husbandry, as also described by a researcher within this study, critical attitudes have been observed to grow with improved consumer knowledge [69, 108]. Furthermore, based on the results of a survey conducted by Pfeiffer et al. [17] with respondents across Germany, authors reported that it is unlikely that digitalization benefits can impact public acceptance due to the widespread criticism of agriculture among citizens. Weible et al. [69] argue that critical attitudes may rather be improved through the public communication of efforts taken to improve agricultural systems to meet societal expectations. This could include the implementation of digital technologies focused on improving sustainability challenges. Authors build upon this argument to suggest that the narrative surrounding digitalization in agriculture be accessible to the wide public, considering varying levels of foundational agricultural knowledge, and focus on efforts practitioners in the value chain, with a particular focus on farmers, are taking to meet the current environmental and societal issues.

7.6 Conclusions and recommendations

Current environmental and socio-economic challenges threaten the sustainability of fruit production. This study adds to the limited literature on stakeholder perspectives of digitalization in fruit production. Stakeholders named the reduction of available PPPs, biodiversity support, labour, and societal acceptance of fruit production to be key challenges in fruit production in the Lake Constance region. According to interviewed stakeholders, digitalization can alleviate sustainability challenges in fruit production, particularly regarding environmental challenges, through e.g. increased efficiency, productivity, and transparency. At the same time, stakeholders discussed uncertainties and perceived risks of digitalization, including the impact on the regional and sectoral labour availability and the unseen connection between digitalization and regional socio-economic issues.

It can be questioned if the role of digitalization is indeed to address sustainability challenges. The authors of this study argue that, in light of the urgency of the current sustainability challenges, the progression of digitalization in agriculture, and the opportunities described by stakeholders in this study, digitalization should be considered as a tool to mitigate current sustainability challenges in the Lake Constance fruit production sector, with some considerations. The authors encourage agricultural policy and funding schemes to give equal attention to environmental and socio-economic challenges, as the latter, particularly related to digitalization, are not adequately supported despite their abundance and complexity. The digitalization of the fruit production sector must be supported through intelligent user-oriented technological design and political and financial frameworks. Moreover, this re-focusing of support should include intentional, user-driven technological design, considering the unique challenges faced by stakeholders in this sector and within their regional contexts. Specifically, support and design must be inclusive of small fruit farms, such as those commonly found in the Lake Constance region, and cater specifically to their reported needs, including non-exclusive market policies and cost-effective technical solutions. Further research on the potential for digitalization to bridge the existing gaps in sustainability challenges between small and large farms, as well as organic and IP farming practices, is necessary. These efforts would allow for equal opportunities across farm size, user demographics, and agricultural sectors to fairly benefit from the chances offered by digitalization. Additionally, research activities aimed at understanding how the technologies that offer to improve transparency along the value chain could impact societal acceptance of fruit cultivation and how the use of technologies may influence the challenges associated with labour availability are required. The improvement of information dissemination on digitalization in fruit cultivation could help to increase digital literacy among intended users, in order for them to be able to make informed choices for or against the implementation of digital tools.

7.7 References

1. Stöckle CO, Marsal J, Villar JM. Impact of climate change on irrigated tree fruit production. Acta Hortic. 2011;889:41–52. https://doi.org/10.17660/ActaHortic.2011.889.2.

2. Dierend W. Kulturschutzeinrichtungen im Obstbau. Ulmer. 2009.

3. Krölling C. Optimierung ressourcenschonender Anbaukonzepte zur Qualitätssicherung bei Apfel unter Berücksichtigung des Klimawandels, Freistaat Sachsen, 2021.

4. The European Commission. The European Green Deal: Communcation from the commission to the European parliament, the European Council, the Council, the European economic and social committee and the committee of the regions, Brussels. 2019.

5. The European Commission. The European Green Deal: Annex, Brussels. 2019.

6. Chemnitz C, Wenz K, Haffmans S. Pestizidatlas 2022: Daten und Fakten zu Giften in der Landwirtschaft, Heinrich-Böll- Stiftung. 2022. Available: https://www.boell.de/de/2022/01/04/pestizidatlas.

7. Busse M, et al. Innovation mechanisms in German precision farming. Precis Agric. 2014;15(4):403–26. https://doi.org/10.1007/s11119-013-9337-2.

8. Miranda J, Ponce P, Molina A, Wright P. Sensing, smart and sustainable technologies for agri-food 4.0. Comput Ind. 2019;108:21–36. https://doi.org/10.1016/j.compind.2019.02.002 .

9. Walter A, Finger R, Huber R, Buchmann N. Smart farming is key to developing sustainable agriculture. Proc Natl Acad Sci USA. 2017;114(24):6148–50. https://doi.org/10.1073/pnas.1707462114.

10. Basso B, Antle J. Digital agriculture to design sustainable agricultural systems. Nat Sustain. 2020;3(4):254–6. https://doi.org/10.1038/s41893-020-0510-0.

11. Hrustek L. Sustainability driven by agriculture through digital transformation. Sustain. 2020;12(20):1–18. https://doi.org/10.3390/su12208596.

12. Finger R, Swinton SM, El Benni N, Walter A. Precision farming at the nexus of agricultural production and the environment. Annu Rev Resour Econ. 2019;11:313–35. https://doi.org/10.1146/annurev-resource-100518-093929.

13. Hassoun A, et al. The fourth industrial revolution in the food industry—part I: industry 4.0 technologies. Crit Rev Food Sci Nutr. 2023;63(23):6547–63. https://doi.org/10.1080/10408398.2022.2034735.

14. Zscheischler J, et al. Landwirtschaft, Digitalisierung und digitale Daten. 2024.

15. Scholz RW, Beckedahl M, Albrecht E, Marx D. DiDaT Weißbuch: Verantwortungsvoller Umgang mit digitalen Daten- Orientierungen eines transdisziplinären Prozesses. Nomos Verlagsgesellschaft. 2021.

16. Scholz RW, et al. Unintended side effects of the digital transition: European scientists' messages from a proposition-based expert round table. Sustainability. 2018. https://doi.org/10.3390/su10062001.

17. Pfeiffer J, Gabriel A, Gandorfer M. Understanding the public attitudinal acceptance of digital farming technologies: a nationwide survey in Germany. Agric Hum Values. 2021;38(1):107–28. https://doi.org/10.1007/s10460-020-10145-2.

18. Prause L. Digital agriculture and labor: a few challenges for social sustainability. Sustainability. 2021;13:5980. https://doi.org/10.3390/su13115980.

19. Dara R, Hazrati Fard SM, Kaur J. Recommendations for ethical and responsible use of artificial intelligence in digital agricul- ture. Front Artif Intell. 2022. https://doi.org/10.3389/frai.2022.884192.

20. Gardezi M, et al. Artificial intelligence in farming: challenges and opportunities for building trust. Agron J. 2023. https://doi.org/10.1002/agj2.21353.

21. Ryan M. The social and ethical impacts of artificial intelligence in agriculture: mapping the agricultural AI literature. AI Soc. 2023;38(6):2473–85. https://doi.org/10.1007/s00146-021-01377-9.

22. Ayris K, Jackman A, Mauchline A, Rose DC. Exploring inclusion in UK agricultural robotics development: who, how, and why? Agric Hum Values. 2024. https://doi.org/10.1007/s10460-024-10555-6.

23. van der Burg S, Giesbers E, Bogaardt MJ, Ouweltjes W, Lokhorst K. Ethical aspects of AI robots for agri-food; a relational approach based on four case studies. AI Soc. 2024;39(2):541–55. https://doi.org/10.1007/s00146-022-01429-8.

24. Saleh R, El Benni N, Masson S, Ammann J. Public acceptance and sustainability perceptions of food produced with chemi- cal, digital and mechanical weed control measures. Food Qual Prefer. 2024;113:105079. https://doi.org/10.1016/j.foodqual.2023.105079.

25. Köhler DH. Digitalisierung im Obstbau—Anwendungen und Aussichten. In: Rheinhessischer Obstbautag; 2018, pp. 1–3. Available: https://www.gb-profi.de/fileadmin/user_upload/GBP/Obstbautag_Rheinhessen_2018.pdf.

26. Olum S, Gellynck X, Juvinal J, Ongeng D, De Steur H. Farmers' adoption of agricultural innovations: a systematic review on willingness to pay studies. Outlook Agric. 2020;49(3):187–203. https://doi.org/10.1177/0030727019879453.

27. Feyisa BW. Determinants of agricultural technology adoption in Ethiopia: a meta-analysis. Cogent Food Agric. 2020;6:200. https://doi.org/10.1080/23311932.2020.1855817.

28. Tey YS, Brindal M. Factors influencing the adoption of precision agricultural technologies: a review for policy implications. Precis Agric. 2012;13(6):713–30. https://doi.org/10.1007/s11119-012-9273-6.

29. Degieter M, De Steur H, Tran D, Gellynck X, Schouteten JJ. Farmers' acceptance of robotics and unmanned aerial vehicles: a systematic review. Agron J. 2023;115:2159–73. https://doi.org/10.1002/agj2.21427.

30. Baeten J, Donné K, Boedrij S, Beckers W, Claesen E. Autonomous fruit picking machine: a robotic apple harvester. In: Laugier C, Siegwart R, editors. Field and service robotics: results of the 6th international conference. Berlin: Springer; 2008, pp. 531–539.

31. Zhang J, Kang N, Qu Q, Zhou L, Zhang H. Automatic fruit picking technology: a comprehensive review of research advances, vol. 57. Amsterdam: Springer; 2024.

32. Adarsch A, Pranav PM, Manjunath CR, Soumya KN. Fruit farm surveillance using drones. Int J Trend Sci Res Dev. 2018;2:351–7. https://doi.org/10.31142/ijtsrd12973.

33. Stefas N, Bayram H, Isler V. Vision-based UAV navigation in orchards. IFAC Pap Online. 2016;16:10–5. https://doi.org/10.1016/j.ifacol.2016.10.003.

34. Zhang C, Valente J, Kooistra L, Guo L, Wang W. Orchard management with small unmanned aerial vehicles: a survey of sensing and analysis approaches. New York: Springer; 2021.

35. Zhang Q, Karkee M, Tabb A. The use of agricultural robots in orchard management. In: Billingsley J, editor. Robotics and automation for improving agriculture. Cambridge: Burleigh Dodds Science Publishing; 2019. p. 187–214.

36. Siefen N. Apfel4.NULL: einsatz von sensoren für eine nachhaltige Produktion und Lagerung. Besseres Obst. 2021;16–17.

37. Siefen N, McCormick RJ, Vogel AM, Biegert K. Effects of laser scanner quality and tractor speed to characterise apple tree canopies. Smart Agric Technol. 2023;4:100173. https://doi.org/10.1016/j.atech.2023.100173.

38. Biegert K. Smart Horticulture: application of sensors and modelling to predict fruit growth, quality and storage behaviour of 'Braeburn' apples. 2022.

39. Miranda JC, et al. Fruit sizing using AI: a review of methods and challenges. Postharvest Biol Technol. 2023. https://doi.org/10.1016/j.postharvbio.2023.112587.

40. Barbole DK, Jadhav PM, Patil SB. A review on fruit detection and segmentation techniques in agricultural field BT. In: Second international conference on image processing and capsule networks; 2022, pp. 269–288.

41. Kodors S, Lacis G, Zhukov V, Bartulsons T. Pear and apple recognition using deep learning and mobile. Eng Rural Dev. 2020;19(May):1795–800. https://doi.org/10.22616/ERDev.2020.19.TF476.

42. Nordmark L, et al. Launch of IoT and artificial intelligence to increase the competitiveness in Swedish apple and grapevine production. Acta Hortic. 2021;1314:235–40. https://doi.org/10.17660/ActaHortic.2021.1314.30.

43. Hassoun A, et al. Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: A short update on Traceability 4.0. Food Chem. 2023. https://doi.org/10.1016/j.foodchem.2022.135303.

44. Ossevoort R, Verdouw C, Frans De Jong P, Hennen En W, Robbemond R. Fruit 4.0: De vruchten van meer technologie Technologie-roadmap. 2016. Available: https://edepot.wur.nl/385030.

45. Gaber K, Rösch C, Bieling C. Digital transformation of fruit farming in Germany: digital tool development, stakeholder perceptions, adoption, and barriers. NJAS Impact Agric Life Sci. 2024. https://doi.org/10.1080/27685241.2024.2349544.

46. Spykman O, Emberger-Klein A, Gabriel A, Gandorfer M. Autonomous agriculture in public perception—German consumer segments' view of crop robots. Comput Electron Agric. 2022;202:107385. https://doi.org/10.1016/j.compag.2022.107385.

47. Langer G, Kühl S. Perception and acceptance of robots in dairy farming—a cluster analysis of German citizens. Agric Hum Values. 2024;41(1):249–67. https://doi.org/10.1007/s10460-023-10483-x.

48. von Veltheim FR, Theuvsen L, Heise H. German farmers' intention to use autonomous field robots: a PLS-analysis. Precis Agric. 2022;23:670–97. https://doi.org/10.1007/s11119-021-09854-3.

49. von Veltheim FR, Heise H. German farmers' attitudes on adopting autonomous field robots: an empirical survey. Agriculture. 2021;11:216. https://doi.org/10.3390/AGRICULTURE11030216.

50. Wilmes R, Waldhof G, Breunig P. Can digital farming technologies enhance the willingness to buy products from current farming systems? PLoS ONE. 2022;17:1–20. https://doi.org/10.1371/journal.pone.0277731.

51. Tranchina M, et al. Exploring agroforestry limiting factors and digitalization perspectives: insights from a european multi- actor appraisal. Agrofor Syst. 2024;98(7):2499–515. https://doi.org/10.1007/s10457-024-01047-x.

52. Argente García JE, et al. Digitalising governance processes and water resources management to foster sustainability strategies in the Mediterranean agriculture. Environ Sci Policy. 2014. https://doi.org/10.1016/j.envsci.2024.103805.

53. Knierim A, Kernecker M, Erdle K, Kraus T, Borges F, Wurbs A. Smart farming technology innovations—Insights and reflections from the German Smart-AKIS hub. NJAS Wageningen J Life Sci. 2019. https://doi.org/10.1016/j.njas.2019.100314.

54. Gaber K, Rösch C, Bieling C. The impact of digitalization on the public opinion of fruit farming: stakeholder perspectives in Germany. NJAS Impact Agric Life Sci. 2025. https://doi.org/10.1080/27685241.2025.2508139.

55. Bundesinformationszentrum Landwirtschaft. Wie viele landwirtschaftliche Betriebe gibt es in Deutschland und wie groß sind sie? 2024. Available: https://www.praxis-agrar.de/service/infografiken/landwirtschaftliche-betriebe.

56. Statistische Ämter des Bundes und der Länder. Landwirtschaftliche Betriebe mit Anbauflächen gartenbaulicher Erzeugnisse 2016. 2019. Available: https://www.statistikportal.de/en/node/266.

57. Landwirtschaftliches Technologiezentrum Augustenberg. Integrierter Pflanzenschutz 2023: Erwerbsobstbau. 2023.

58. Das Grüne Lexikon Hortipendium. Gemüseanbau: Bio oder Konventionell. 2021. https://hortipendium.de/Gem%C3%BCseanbau:_Bio_oder_Konventionell.

59. Bundesministerium für Ernährung und Landwirtschaft. Der Gartenbau in Deutschland: Auswertung des Gartenbaumoduls der Agrarstrukturerhebung 2016, Berlin. 2016. https://www.bmel.de/SharedDocs/Downloads/Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile.

60. Statistisches Landesamt Baden-Württemberg. Pressemitteilung 2015/2022: Äpfel dominieren den Obstanbau in Baden- Württemberg. Größtes Anbaugebiet am Bodensee, Stuttgart. 2022.

https://www.statistik-bw.de/presse/pressemitteilungen/pressemitteilung/aepfel-dominieren-den-obstanbau-in-baden-wuerttemberg-1/.

61. Kösler J. Statistisches Monatsheft Baden-Württemberg: Der Baden-Württembergische Baumobstanbau. 2023.

62. Fanzo J. From big to small: the significance of smallholder farms in the global food system. Lancet Planet Health. 2017;1(1):e15–6. https://doi.org/10.1016/S2542-5196(17)30011-6.

63. Grasswitz TR. Integrated pest management (IPM) for small-scale farms in developed economies: challenges and opportunities. Insects. 2019. https://doi.org/10.3390/insects10060179.

64. Bodensee-Stiftung. Zukunftsfähiger Bodensee: Jahresbericht 2013, Radolfzell. 2013. https://www.bodensee-stiftung.org/wp-content/uploads/BoSti_Jahresbericht_13_0.pdf

65. Bodensee-Wasserversorgung. Die Bodensee-Wasserversorgung: Wasser aus dem See-Trinkwasser aus dem Hahn. https://www.bodensee-wasserversorgung.de/startseite.html. Accessed 10 Dec 2023.

66. Bodensee Biene and Obst vom Bodensee. Ja zu Bienen und Artenvielfalt. 2019. https://www.bodenseebiene.de/wp-content/uploads/2019/09/bodenseebiene-flyer.pdf. Accessed 15 May 2024.

67. Moderner Landwirt. Stiller Protest der Landwirte auf der Fruchtwelt Bodensee. 2024. https://moderner-landwirt.de/stiller-protest-der-landwirte-auf-der-fruchtwelt-bodensee/. Accessed 18 May 2024.

68. Matthews A. Farmer protests and the 2024 European parliament elections. Intereconomics. 2024;59(2):83–7. https://doi.org/10.2478/ie-2024-0018.

69. Weible D, Christoph-Schulz I, Salamon P, Zander K. Citizens' perception of modern pig production in Germany: a mixed- method research approach. Br Food J. 2016;118(8):2014–32. https://doi.org/10.1108/BFJ-12-2015-0458.

70. Bundesministerium für Ernährung und Landwirtschaft. Deutschland, wie es isst: Der BMEL-Ernährungsreport 2022. 2022. https://www.bmel.de/SharedDocs/Downloads/Broschueren/Ernaehrungsreport2019.pdf?__blob=publicationFile%0Ahttp://www.bmel.de/SharedDocs/Downloads/Broschueren/Ernaehrungsreport2017.pdf?__blob=publicationFile.

71. Bryman A. Social research methods, vol. 4. New York: Oxford University Press; 2012.

72. Goodman LA. Snowball sampling. Ann Math Stat. 1961;32(1):148–70. https://doi.org/10.1214/aoms/1177705148.

73. Johnson G, Scholes K, Whittington R. Stakeholder mapping: the power/interest matrix. 2008.

74. Mendelow AL. Environmental scanning—the impact of the stakeholder concept. In: Proc. int. conf. inf. syst.; 1981, pp. 407–417.

75. Bundesministerium für Ernährung und Landwirtschaft. Landwirtschaftliche Arbeitskräfte, Landwirtschaft, 2020. https://www.bmel-statistik.de/landwirtschaft/landwirtschaftliche-arbeitskraefte. Accessed 25 Jul 2024.

76. DESIRA. The Project: about DESIRA. 2019. https://desira2020.eu/the-project/.

77. Mayring P. Qualitative content analysis. Forum Qual Soc Res. 2000;1:10.

78. Saldaña J. The coding manual for qualitative researchers. 2013.

79. Bronson K. Looking through a responsible innovation lens at uneven engagements with digital farming. NJAS Wageningen J Life Sci. 2019;90–91:100294. https://doi.org/10.1016/j.njas.2019.03.001.

80. Prause L, Hackfort S, Lindgren M. Digitalization and the third food regime. Agric Human Values. 2021;38(3):641–55. https://doi.org/10.1007/s10460-020-10161-2.

81. Jankowski P, Hoffmann ML, Rohde F, Rehak R. Shaping digital transformation for a sustainable society—Contributions from Bits und Bäume.2023.

82. Granatstein D, Kupferman E. Sustainable horticulture in fruit production. Acta Hortic. 2008;767:295–308. https://doi.org/10.17660/ActaHortic.2008.767.31.

83. Medici M, Canavari M, Toselli M. Interpreting environmental impacts resulting from fruit cultivation in a business innovation perspective. Sustain. 2020;12(23):1–14. https://doi.org/10.3390/su12239793.

84. The European Commission. Proposal for a regulation of the European parliament and of the council: establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law). Brussels. 2020. https://doi.org/10.1017/CBO9781107415324.004.

85. The European Commission. Farm to Fork Strategy. 2020.

86. Bundesministerium für Ernährung und Landwirtschaft. Biodiversity: Protecting bees and insects. Topics >Farming >Species Diversity. 2023. https://www.bmleh.de/EN/topics/farming/species-diversity/biodiversity-protecting-bees-insects.html.

87. Rentenbank. Förderung des BMEL-Investitionsprogramm Landwirtschaft. Landwirtschaft, 2023. https://www.rentenbank.de/zuschussprogramme/landwirtschaft/.

88. Martens K, Zscheischler J. The digital transformation of the agricultural value chain: discourses on opportunities, challenges and controversial perspectives on governance approaches. Sustainability. 2022. https://doi.org/10.3390/su14073905.

89. Purvis B, Mao Y, Robinson D. Three pillars of sustainability: in search of conceptual origins. Sustain Sci. 2019;14(3):681–95. https://doi.org/10.1007/s11625-018-0627-5.

90. Hilbert M. The end justifies the definition: the manifold outlooks on the digital divide and their practical usefulness for policy making. Telecomm Policy. 2011;35:715–36. https://doi.org/10.1016/j.telpol.2011.06.012.

91. Bundesministerium für Ernährung und Landwirtschaft. Ackerbaustrategie 2035; 2019, p. 68.

92. Carolan M. Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture. J Peasant Stud. 2020;47(1):184–207. https://doi.org/10.1080/03066150.2019.1584189.

93. Rotz S, et al. Automated pastures and the digital divide: how agricultural technologies are shaping labour and rural com- munities. J Rural Stud. 2019;68:112–22. https://doi.org/10.1016/j.jrurstud.2019.01.023.

94. Kernecker M, Knierim A, Wurbs A, Kraus T, Borges F. Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. Precis Agric. 2020;21(1):34–50. https://doi.org/10.1007/s11119-019-09651-z.

95. Kutter T, Tiemann S, Siebert R, Fountas S. The role of communication and co-operation in the adoption of precision farming. Precis Agric. 2011;12(1):2–17. https://doi.org/10.1007/s11119-009-9150-0.

96. Daberkow SG, McBride WD. Farm and operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US. Precis Agric. 2003;4(2):163–77. https://doi.org/10.1023/A:1024557205871.

97. Ricciardi V, Mehrabi Z, Wittman H, James D, Ramankutty N. Higher yields and more biodiversity on smaller farms. Nat Sustain. 2021;4(7):651–7. https://doi.org/10.1038/s41893-021-00699-2.

98. Wiggins S, Kirsten J, Llambí L. The future of small farms. World Dev. 2010;38(10):1341–8. https://doi.org/10.1016/j.worlddev.2009.06.013.

99. Bundesministerium für Ernährung und Landwirtschaft. Klöckner: Farmers must be winners in trade Background. Press Release. 2020. https://www.bmleh.de/SharedDocs/Pressemitteilungen/EN/2020/abschluss-gffa-2020.

100. Zimbelman RG, Wilson LL, Bennett MB, Curtis SE. Public image of animal agriculture in the United States. Livest Prod Sci. 1995;43(2):153–9. https://doi.org/10.1016/0301-6226(95)00040-R.

101. Rumble JN, Irani T. Opening the doors to agriculture: the effect of transparent communication on attitude. J Appl Commun. 2016. https://doi.org/10.4148/1051-0834.1030.

102. Igo C, Frick M. A case study assessment of standard benchmarks for implementing food and fiber systems literacy. 1999.

103. Zukunftskommission Landwirtschaft. The Future of Agriculture A common agenda. 2021.

104. Deutsche Landwirtschafts-Gesellschaft. Digitale Landwirtschaft: Ein Positionspapier der DLG. Frankfurt am Main, 2018. https://www.dlg.org/fileadmin/downloads/fachinfos/DLG_Position_Digitalisierung.pdf.

105. Zhang Y, et al. Blockchain: an emerging novel technology to upgrade the current fresh fruit supply chain. Trends Food Sci Technol. 2022;124:1–12. https://doi.org/10.1016/j.tifs.2022.03.030.

106. FAO and WFF. Digital technologies for multidimenstional youth engagement in agrifood systems transformation, Rome. 2024.

107. Matzak F. Eine technologie sorgt für transparenz. In: Ökologie und Landbau; 2021, pp. 28–30.

108. Sonntag WI, Ermann M, Spiller A, von Meyer-Höfer M. Im Streit um die Nutztierhaltung: Gesllschaftsorientierte Kommunikationsstrategien für die Agrar- und Ernährungswirtschaft. Ger J Agric Econ. 2021;10:1–16.

7.8 Appendix

Abbreviations

AI	Artificial Intelligence
CSA	Community Supported Agriculture
FAO	Food and Agriculture Association of the United Nations
IOT	Internet of Things
NAC	Nature, Agriculture and Consumer (associations)
PPPs	Plant Protection Products
IOT	Integrated Production
UAV	Unmanned Aerial Vehicle

Environmental and socio-economic challenges and descriptions

Table 3 *Environmental challenges and descriptions by stakeholders*

Category	Descriptive code of challenge	Description of challenge by stakeholders
Farm management-related challenges and their environmental impacts	Reduction and availability of approved active ingredients	Fewer active ingredients being approved for use as restrictions increase.
	Reduction of use of PPPs	Producers are challenged to greatly reduce or complete adhere from use of PPPs in their farming practices
	Untrustworthy active ingredients	Concern over available active ingredients that reach the market without thorough testing
	PPP drift and nitrate leaching	Laws to control potential drift of PPPs and leaching of nitrate into groundwater add complexity to farming activities
	Minimize residues	Environmental and social pressure to reduce the amount of PPP residues on food products
	Control pests sustainably	Challenge to sustainably control pests in orchards and fields
	Need-based fertilization	Farmers challenged to apply correct amount of fertilizer, without over- or under- fertilizing
	Maintain high yield and quality with changing regulations	Maintaining product yield and quality while adjusting practices to fit new regulations and societal pressures to, e.g., reduce use of PPPs in production
	Support of biodiversity, avoidance of species loss	Biodiversity and avoidance of species loss are not prioritized enough and/or increasingly challenged by environmental and social pressures.
	Increase resilience	Resilience must be increased and systems such as mixed cultures, crop mixes, must be incorporated for this.
	Soil compaction	Soil life is being compromised through the frequent driving of heavy machinery over soils and the associated soil compaction.
	Avoiding resistance	Pests and invasive plants are becoming increasingly resistant to PPPs as the active ingredient spectrum becomes increasingly restricted
	High fuel consumption	Frequent use of fossil fuels for tractor and sprayer use, particularly in organic farming when PPPs are applied more frequently and with the increasing weather extremes
Climate and energy	Climate change	Changing climate is leading to consequential effects in fruit production
	Weather extremes	Weather extremes such as extreme cold temperatures or heat waves are increasing in frequency and can have detrimental affects on fruit production
	Access to water	Water is becoming a limited resource but is critical for agricultural production
	Frost	Fruit production in particular can suffer large harvest losses from frost, therefore intensive frost protection actions at farm-level are required
	Hail and precipitation	Increasing rates of hail storms and heavy precipitation, which cause damage to fruit orchards and farms
Insects, pests, and diseases	Disease	Managing plant diseases and adjusting management practices with increasing PPP restrictions
	Intensive permaculture increases pest challenges	Pests and diseases can thrive better and longer in intensive, permaculture farms such as orchards
	Scab pressure	High rates of fungal disease like apple scab, particularly in the humid regions for fruit growing

	Damage from insects	Managing damage from insects and adjusting management practices with increasing PPP restrictions
	Pollination	Loss of insect populations reduces the pollination rates and therefore success of the agricultural area
Regional environment	Humidity from lake proximity causes increased apple scab	Humidity from Lake of Constance increases rates of apple scab and other fungal diseases
	Problematic, weak young sites	Young farm sites in the region are at greater risk of failure compared to long-established orchards due to pest invasion or failed plant growth
	Lake largest water reservoir, protected area	Lake of Constance, as Germany's largest drinking water reservoir, therefore stricter regulations for PPP use
	High local precipitation	Regional precipitation rates higher than other fruit growing regions, therefore require greater interventions such as hail nets

Table 4 *Socio-economic challenges and descriptions by stakeholders*

Category	**Descriptive code of challenge**	**Description of challenge by stakeholders**
Challenges related to farm labour and management	Wages and housing standards for farm labourers	Paying fair wages for farm workers, considering for instance the rising minimum wage, is a challenge for some farmers. Indirect costs of hired farm workers such as on-farm housing and bureaucracy along with fair wages is not economically feasible for all farms.
	Integration of foreign seasonal workers into the community	Foreign seasonal labourers are often not given opportunities to integrate into the local communities and instead can be viewed to overwhelm the communities when many arrive at the same time of year.
	Reliability, work ethic, training of the labourers	Fruit production is challenged to find and retain reliable labourers with relevant training.
	Labour availability	Local and international workers are increasingly challenging to find. More jobs with better pay and more comfortable working conditions are becoming available in nearby regions.
	Dependency on seasonal workers due to shortage of local labourers	Local labourers are, for some tasks such as intense seasonal harvesting, difficult to find. Farms are dependent upon the influx of international seasonal workers. This dependency creates risks, for instance, when seasonal workers are not allowed into Germany or are offered better pay and/or conditions elsewhere.
	Bureaucracy	Large amounts of bureaucracy and office work for quality control and bookkeeping in addition to field work, including bureaucracy for international seasonal workers like visa arrangements
Transition and societal acceptance of agriculture	Structural change of farming	General challenge of structural change in agriculture is also faced locally, with an aging population of farmers and small farms being taken over by larger farms or enterprises. Farmers have also become more specialized and focus their production on one or few products, which increases their vulnerability to losses from disease or weather extremes.

	Disturbance to tourism industry by certain agricultural practices	The popular tourism industry in the region is affected by unattractive farming practices like hail nets and the spraying of PPPs, and this leads to local conflicts
	Creation of valuable, attractive jobs/retention of employees	Fruit farming is challenged to create and offer attractive jobs with competitive pay in order to find and retain labourers.
	Farm succession	Increasing challenge of farm succession in the region as local cities offer higher paying jobs or more comfortable, reliable working conditions than fruit farming
	Lack of societal understanding, acceptance, and appreciation	Lack of societal understanding, acceptance, and appreciation of agricultural practices leads to misguided pressure from society and politics on farmers and their livelihoods, which in turn challenges the existence of fruit farming.
Markets and marketing	Power of monopolies	Fewer companies operate along the regional fruit value chain than in previous years due to monopolization, which has given more power to these companies over the farmers
	Price competition and pressure	Competing prices with imported fruits as well as fruits of other production methods, such as IP versus organic products, drives profit margins down
	Inadequate marketing methods/channels	Variety of marketing methods creates a paradox of choice and increasing competition pressures the farmers
	Global competition	The globalised market for fruits challenges the prices of local products
Socio-economic-environmental nexus	Crop losses due to weather extremes	Crop losses through increasing weather extremes in the region, such as frost, hail, and drought lead to economic challenges
	Land use competition	Land for fruit production competes with, for instance, recreational area, as fruit production regions require optimal climactic conditions. This can cause regional tensions and competition.
	Food security	Ensuring high quality, local food production to keep a low food footprint and reduce food imports

Environmental challenges

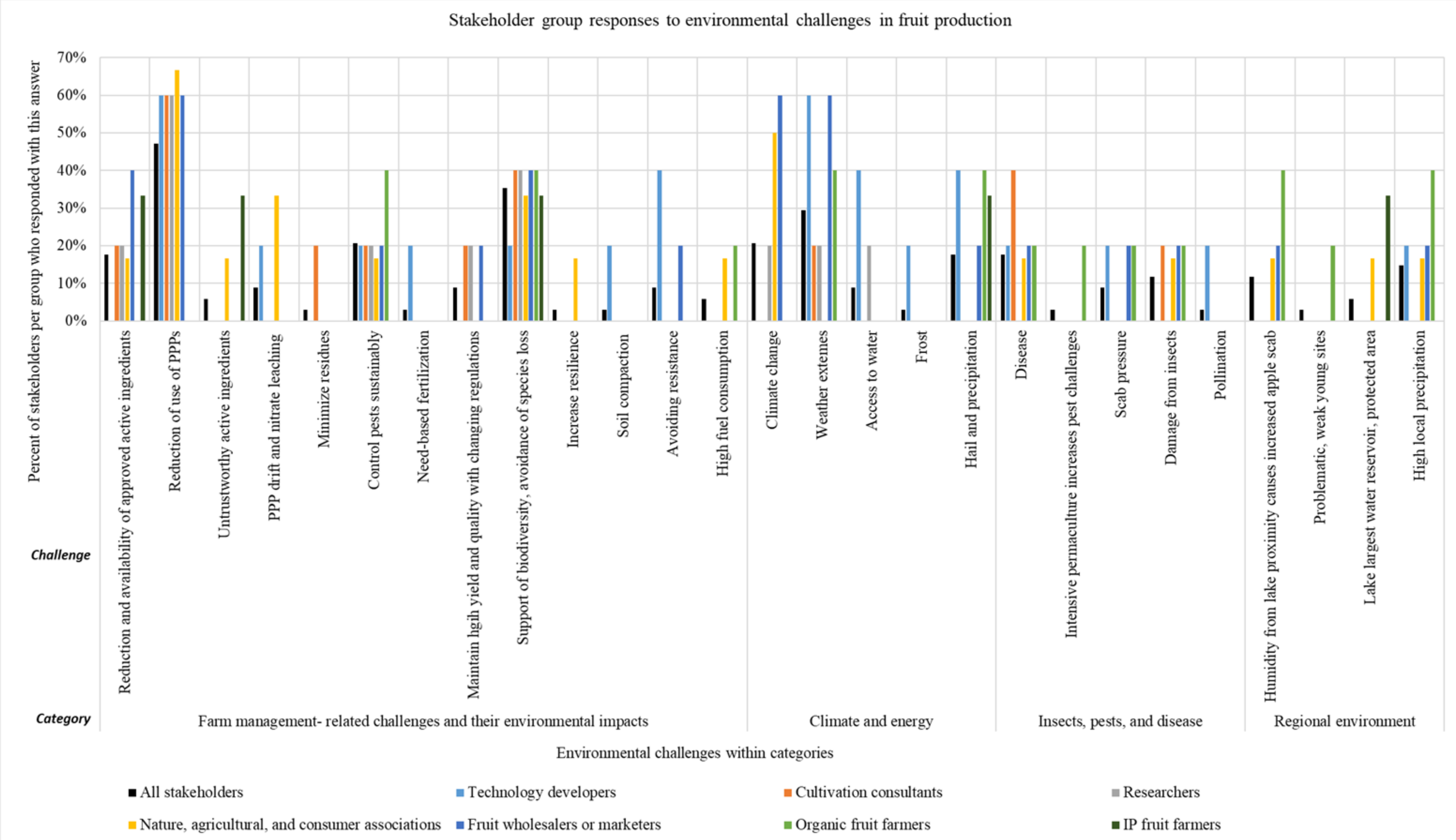

Fig. 7 Reported environmental challenges in fruit production per stakeholder group

Socio-economic challenges

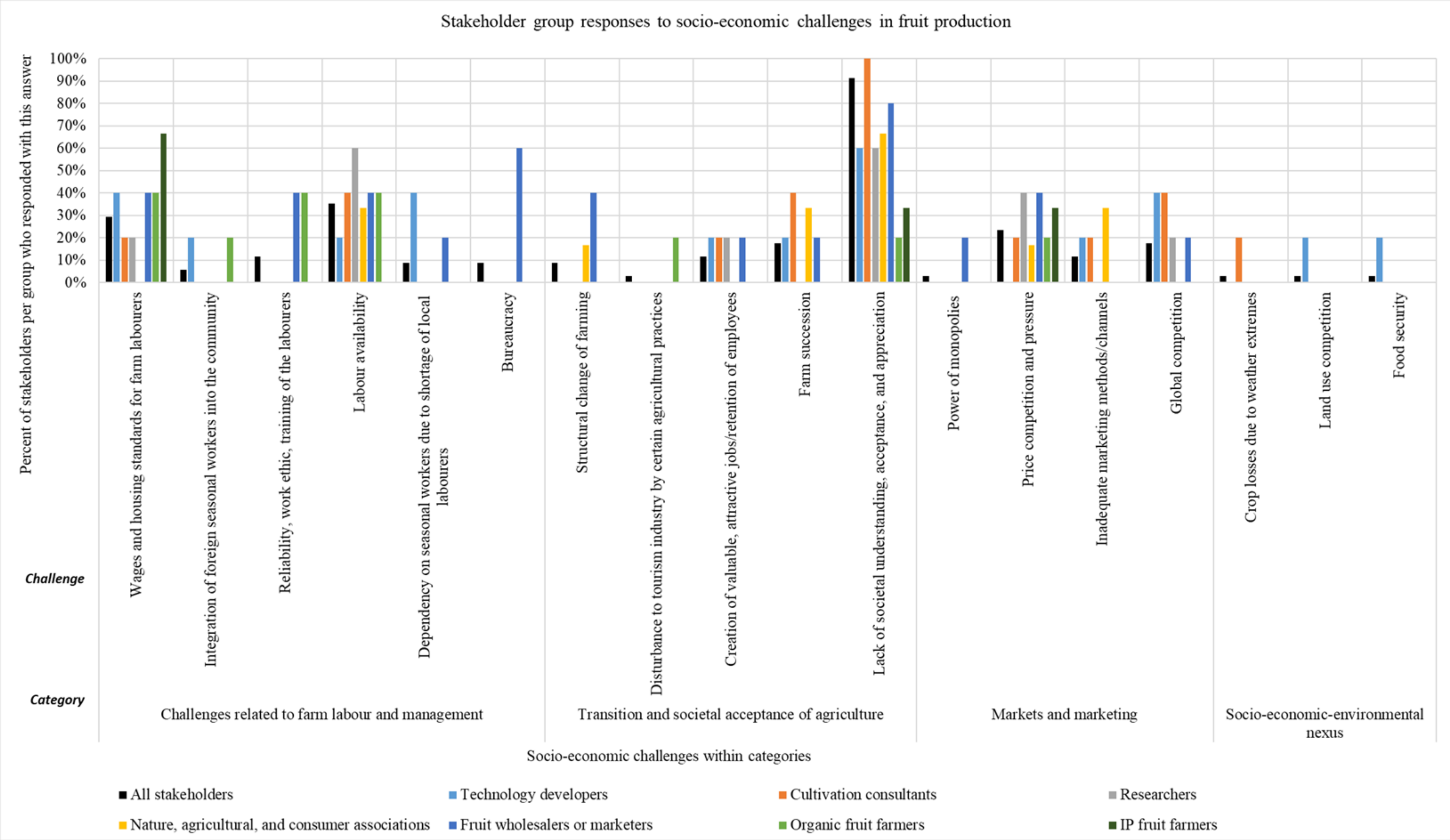

Fig. 8 *Reported socio-economic challenges in fruit production per stakeholder group*

Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by K.G. Material preparation and methodology were led by K.G.; C.R. and C.B. provided guidance and feedback. The first draft of the manuscript was written by K.G.; editing and reviewing were provided by C.R. and C.B. K.G. led the revision; feedback on the revision was provided by C.R. and C.B. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. This work was supported by the DESIRA Project, funded by the European Commission under Grant Agreement No. 818194.

Data availability

The author confirms that all data generated or analysed during this study are presented within the article and/or the appendix.

7.9 Declarations

Ethics approval and consent to participate

This study involved human participants through the use of interviews. The consent form for this study was created through the data protection office of the Karlsruhe Institute of Technology. All participants provided informed consent prior to participation and were assured of confidentiality and the voluntary nature of their involvement. The study design assured protection of study participants and neither included clinical data about participants nor configured itself as a clinical trial. No minors were involved in this study. Participants signed a written informed consent form that confirmed that the recorded and transcribed interviews would be anonymized and used for scientific and teaching purposes. Participants were informed that their participation was voluntary and could be withdrawn at any time.

Consent for publication

Informed consent for publication was obtained from all individual participants interviewed for this study.

Competing interests

The authors declare no competing interests.

Received: 15 November 2024 / Accepted: 27 July 2025

Published online: 12 August 2025

8. The impact of digitalization on the public opinion of fruit farming: Stakeholder perspectives in Germany

Published in NJAS: Impact in Agricultural and Life Sciences
(https://www.tandfonline.com/journals/tjls20)

Full reference: Gaber, Kirsten, Christine Rösch, and Claudia Bieling. 2025. “The impact of digitalization on the public opinion of fruit farming: Stakeholder perspectives in Germany” NJAS: Impact in Agricultural and Life Sciences 97 (1). https://doi.org/10.1080/27685241.2025.2508139

8.1 Abstract

Digitalization in fruit production can create significant social and environmental impacts through on-farm efficiency gains and by enabling transparent communication from farm to fork. As societal criticisms currently challenge the future of agricultural practices, it remains unclear how the public opinion of fruit production will change through digitalization. This study explored the perceived impacts of digitalization on the public attitude towards fruit production by investigating the views of stakeholders along the fruit value chain, using the Lake Constance region in Southern Germany as a case study. Of the 33 inter- viewed stakeholders, 73% believed that digitalization could impact the public opinion of fruit products and production methods. Positive impacts were anticipated more frequently than negative. Two clear pathways through which this change could occur emerged: through (1) on-farm usage of digital tools or (2) increased transparency along the value chain. Nevertheless, stakeholders expressed concerns that the foundational knowledge about agricultural practices in society is currently too low, challenging the potential benefits of digitalization to improve public opinion. The described impact may be contingent upon the narrative surrounding the use of digital technologies and their impacts. Prioritizing honest communication about fruit production and building trust towards farmers should be central goals of digitalization.

Article History: Received 27 September 2024; Revised 15 January 2025; Accepted 15 May 2025

Keywords: Digitalization; fruit production; case study; Germany; public opinion

8.2 Introduction

As the basis of all primary production, agriculture is facing major challenges to meet the increasing demands of a growing world population. The goals of food production and environmental protection can conflict with each other, as agriculture also has a significant responsibility for preserving key environmental assets such as soil, water, climate and biodiversity. Moreover, societal criticisms are challenging agricultural production practices. Concerns primarily surround environmental and labourer- and animal-welfare aspects of today's production methods (Balmann, 2016). A disconnect between consumers and farmers with the continued advancement of industrialized agriculture has been observed (Duncan & Broyles, 2006; Zimbelman et al., 1995) and the resulting deficit in agricultural knowledge or literacy has led to an increase in concerns among consumers (Rumble & Irani, 2016). Deficient understanding about production methods could lead to mistrust, misguided public support for political campaigns, and a lack of understanding of price politics, which together threaten the future of farming (Igo et al., 1999).

Digitalized technologies are anticipated to mitigate both environmental and societal challenges in the agri-food sector (Nesheim et al., 2015; Wolters et al., 2021). Impacts created through the digital transformation of agriculture, such as greater environmental efficiency and increased transparency along the value chain, could alter the public image of agricultural production methods. As improved transparency and communication of agricultural production methods can positively influence consumer attitudes and trust (e.g. Fu et al., 2023; Rumble & Irani, 2016), there is hope that the transparency of production processes and traceability that can be simplified through digitalization will create trust and increase appreciation of agriculture (Deutsche Landwirtschafts-Gesellschaft, 2018). Digitalization can be helpful in the communication between the agricultural sector and the consumer, in the development of direct marketing and cooperation models, and in the recording and presentation of process quality (Bund für Umwelt und Naturschutz Deutschland, 2019). For instance, blockchain-based systems and, more significantly, the labelling of blockchain technology use on products, have been found to have a positive effect on purchase intention via perceived product quality (Treiblmaier & Garaus, 2023). The use of blockchain technologies in agriculture, such as through the framework for securing agriculture-related data as suggested by (Kassanuk & Phasinam, 2022), may enable safer recording of farming data as well as public access to the data, which could function to positively influence public opinion of agricultural products and practices through increased transparency to the consumer (Yap et al., 2023).

Still, critical attitudes towards farmers and farming practices may not equate to an overall lack of societal acceptance, nor do they necessarily stem from a lack of knowledge on agricultural production, as critical attitudes have also been observed to grow with increased societal knowledge (Landwirtschaft, 2021; Sonntag et al., 2021). Consumers have expressed negative attitudes regarding technical progress in the agri-food sector, as they are unfamiliar and therefore uncomfortable with the concept and have often perceived such progress as being unnatural (Mohr & Höhler, 2023; Pfeiffer et al., 2021; Zander et al., 2013). Consumers generally exhibit a preference for "naturalness" regarding farming and food systems (Román et al., 2017), which works in favour of organic farming and products, as they are perceived as more natural when compared to non-organic production methods (Kühl et al., 2023; Lang & Rodrigues, 2022; Zander et al., 2013).

Critical views on agricultural production are widespread among the German population (Pfeiffer et al., 2021; Weible et al., 2016; Zander et al., 2013). German farmers are portrayed as pioneers of digitalization (Bitkom & Bauernverband, 2020) and the agricultural sector has been credited for leading national digitalization (Rentenbank, 2018). The general attitudes of German individuals towards technology (e.g. technophilic or technophobic) strongly determines the acceptance or rejection of farming systems that use digital farming technologies (Wilmes et al., 2022). Overall, German citizens are in favour of the use of digitalized technologies in agriculture (Spykman et al., 2022; von Veltheim & Heise, 2021), particularly as a means to reduce agrochemical use (Spykman et al., 2022). Still, Pfeiffer et al. (2021) speculate that criticism of agriculture in Germany is so widespread that potential benefits from digitalization are unlikely to significantly increase public acceptance of agriculture.

Horticulture as an agricultural sector is not immune to these issues related to public perceptions. This sector faces its own unique environmental and societal challenges (e.g. Chemnitz et al., 2022; Marinoudi et al., 2021). Additionally, societal acceptance has been found to be more favourable for organic fruit than for non-organic (e.g. Cerda et al., 2012; Yue et al., 2009). The development of digital technologies for fruit cultivation is progressing, including autonomous harvesting (e.g. Baeten et al., 2008; Zhang et al., 2024), deep learning and AI for the detection of fruit characteristics (e.g. Barbole et al., 2022; Kodors et al., 2020; Miranda et al., 2023; Nordmark et al., 2021), smart sensors and modelling for improved efficiency in apple production (e.g. Siefen, 2021; Siefen et al., 2023; Biegert, 2022), and unmanned aerial vehicles and robots for fruit farm surveillance and management (e.g. Adarsch et al., 2018; Stefas et al., 2016; Zhang et al., 2021; Zhang et al., 2019). Still, the impact of digitalization on the public perception of fruit production has yet to be studied.

It is evident that different views exist on the relationship between digitalization, agricultural production, and consumers' perceptions and expectations to address sustainability challenges. Considering the various stakes at hand in the digitalization of agriculture, stakeholders along agricultural value chains offer valuable insights from their areas of expertise. To this end, the research questions that guided this study are as follows: (1) how do stakeholders perceive the public opinion of fruit farming? (2) How do stakeholders believe that the use of digitalized technologies in fruit farming (general, meaning regardless of production system, and organic) will impact the public opinion of the products and production methods, and how do they believe that different technologies could create this impact?

8.3 Materials and methods

This study uses a qualitative, open, and exploratory case study approach. The authors conducted semi-structured interviews with stakeholders along the fruit value chain in Southern Germany and sought to understand what stakeholders actually consider when asked about digitalization without guidance from the interviewers. The chosen methodology is best suited to answer the research questions, as it allowed themes to naturally emerge based on the stakeholders' individual perceptions and phrasing. The themes were subsequently identified during the qualitative analysis of the interviews.

8.3.1 Region of study

The region of Lake Constance in southern Germany is the second-largest fruit growing area in the country (Bundesministerium für Ernährung und Landwirtschaft, 2016; Kösler, 2023). The geographical region of Lake Constance includes the counties of Konstanz, Bodenseekreis, and Ravensburg in the state of Baden-Württemberg, as well as the county of Lindau in the state of Bavaria (Genuss Bayern, 2024). Mild temperatures and the proximity to the Lake of Constance have enabled agriculture to thrive for generations. Small- to medium-sized family farms produce cereals, potatoes, corn and specialty crops, such as fruit, vegetables, and wine (Grimminger et al., 2018). Just over 1017 fruit farms can be found across all four counties in the Lake Constance region (Bundesministerium für Ernährung und Landwirtschaft, 2016). Nearly 75% of the regional tree fruit area (10344 ha) is dedicated to apple cultivation (7692 ha) (Baden Württemberg, 2022a, 2022b, 2022c; Bayerisches Landesamt für Statistik, 2018). In the state of Baden-Württemberg, the organic-certified cultivation area for fruit is greater than the average organic-certified cultivation area for total agriculture at 18% and 12%, respectively (Kösler, 2023). While nearly half of all national fruit farms are categorized as small at less than 20 ha hectares (Statistische Ämter des Bundes und der Länder, 2019), fruit farms in the Lake Constance region are even smaller with an average of 8.8 ha (Kösler, 2023). The impact of climate change and weather extremes, such as heightened mildew pressure from extended wet periods which results in a greater need for plant protection products and digital tools to combat diseases (Bodensee, 2013), in addition to changing consumer demands and societal criticisms threaten the future of fruit production in the region.

8.3.2 Stakeholder selection and mapping

Among the numerous identification methods for stakeholder analysis, Freeman's stakeholder definition was selected for this study: "any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 1984). In this study, the "organization" was considered as the fruit production sector and the "objective" was considered as the digitalization of the sector as a potential future scenario. Two key criteria guided the stakeholder selection, which followed a purposive sampling approach (Bryman, 2012): (1) stakeholders identified were either intended users or developers of digital technologies; (2) stakeholders were engaged in the fruit value chain, ranging from the farm- and retail-level to those who viewed the fruit production industry from a wider technology or research lens. As a result of an extensive internet search, which included websites of research projects and groups, farmer associations, and technology development companies, authors compiled a preliminary list of regional stakeholders who met these criteria. An interview was conducted with a German expert in digital farming technologies to improve the draft interview guideline and to find not yet identified stakeholders. Additionally, the authors requested the contact details of farmers who could be interested in participating from a regional advisor on fruit cultivation and a leader of an agricultural group. This iterative process was similar to snowball sampling (Goodman, 1961). The stakeholders were inductively categorized into groups based on their occupation and shared stakes or interests: farmers, cultivation consultants, marketing and wholesale representatives, researchers, technology developers, and representatives of nature, agricultural, and consumer associations.

Authors of the study aimed to conduct five to six interviews for each stakeholder group (Table 1), with the exception of fruit farmers: as they are the intended users of digital technologies in fruit production, have potentially more heterogeneous views, and are most affected by the consumer's perspective, thus have the highest stakes, authors aimed for eight farmer interviews.

Table 1. *Result of the analysis of stakeholder groups in fruit production and their descriptions, adapted from* Gaber et al. (2024)

Stakeholder group	#	Description
Fruit farmers	8	Farmers predominantly engaged in fruit production on their agricultural land, employing either integrated production (IP) or organic principles.
Technology developers	5	Individuals working as employees or leaders in agricultural machinery or technology companies, ranging from start-ups to international corporations.
Cultivation consultants	5	Individuals, whether privately or publicly employed, advise farmers on on-farm activities and/or the purchase and application of agricultural inputs, such as Plant Protection Products (PPPs) and fertilizers.
Researchers	4	Local or national-based researchers affiliated with public or private institutions possessing knowledge of fruit cultivation, fruit value chain conditions, and/or agricultural technologies.
Nature, agriculture and consumer associations	6	Individuals who are members, employees, or leaders of public or private organizations dedicated to nature preservation, agriculture, or consumer interests. These individuals play a role in representing the interests of groups or communities related to these sectors.
Fruit wholesalers or traders	5	Individuals serving as employees or leaders within fruit wholesale organizations or companies or individuals in similar roles within farm shops that offer local delivery services.

Technology developers and nature, agricultural, and consumer associations were limited in the region and were challenging to engage. To better understand how to prioritize activities for engaging stakeholders, the authors used the power-interest matrix developed by Johnson et al. (2008) and adapted from Mendelow (1981) to evaluate the interest and power of stakeholder groups in relation to the influence of digitalization on the public opinion of fruit production (Figure 1). This stakeholder mapping approach identifies stakeholder expectations and power to better understand political priorities, as well as to suggest levels of intervention in the case of engagement challenges (Johnson et al., 2008). Groups with low levels of power and/or interest would not merit extenuating efforts to adjust the methodology to be included, whereas groups with high levels of power and/or interest would. As the authors valued technology developers and nature, agricultural, and consumer associations to both have high interest and high power ("key players") in the study, proactive efforts were required to involve these groups. While the authors previously considered the proximity to the Lake Constance region as a priority in the selection of possible interview partners, the authors re-evaluated its importance for these particular groups, considering the national and international scales at which digital technologies are developed. Ultimately, the authors expanded the geographical focus of the stakeholder selection methodology to meet the goal interview number for these groups.[1]

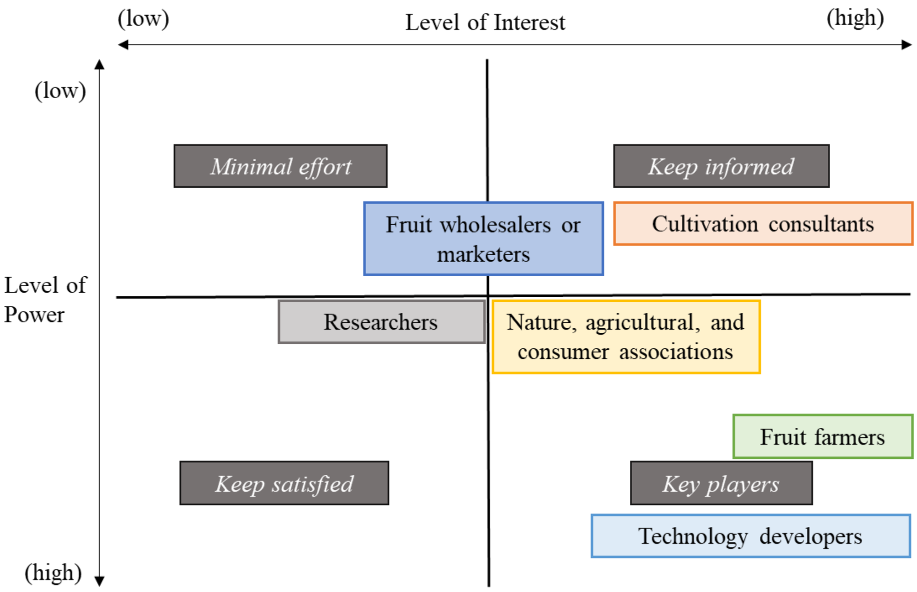

Figure 1. *The Power-Interest Matrix of the identified stakeholders regarding digitalization in fruit production based on* Johnson et al. (2008) *and adapted from* Mendelow (1981)

8.3.3 Stakeholder interviews

In total, 33 stakeholders across the six stakeholder groups participated in 1-hour interviews, which were conducted in German and offered both in- person and online. The interviews were semi-structured with questions based on the research goals. As previously mentioned, an interview guideline (included in the Annex) was developed and improved based on the recommendations provided in the expert interview. The guideline encompasses more subjects than are pertinent to the current study because it was used for an interview series as part of the DESIRA project (DESIRA, 2019). The most relevant interview questions for this investigation were 26 and 26(a). Specifically, stakeholders were asked the following questions: (1) in your opinion, would the use of digitalized technologies in fruit production change public opinion about the products or production methods? (Yes, no and what reasons play a role here). (2) Does your answer differ when we speak about the use

[1] The two production systems used in German horticulture are integrated production (IP) and organic. The two systems are distinguished from one another by the use of PPP and the level of holistic integration in the production system (Augustenberg, 2023; Das Grüne Lexikon Hortipendium, 2021). Of the interviewed farmers, three farmed following IP standards, and five following organic standards.

of digitalized technologies in organic fruit production? (If yes, how and what are the reasons for these differences).

The interviewed stakeholders were predominantly males between 41 and 60 years and most of them lived in mostly rural or mixed regions (Figure 2). All of them had post-secondary training or education. The self-evaluation of knowledge on digitalization in fruit production showed a wide range, with most responses falling in the rather low (39%), medium (30%), and rather high (18%) knowledge categories.

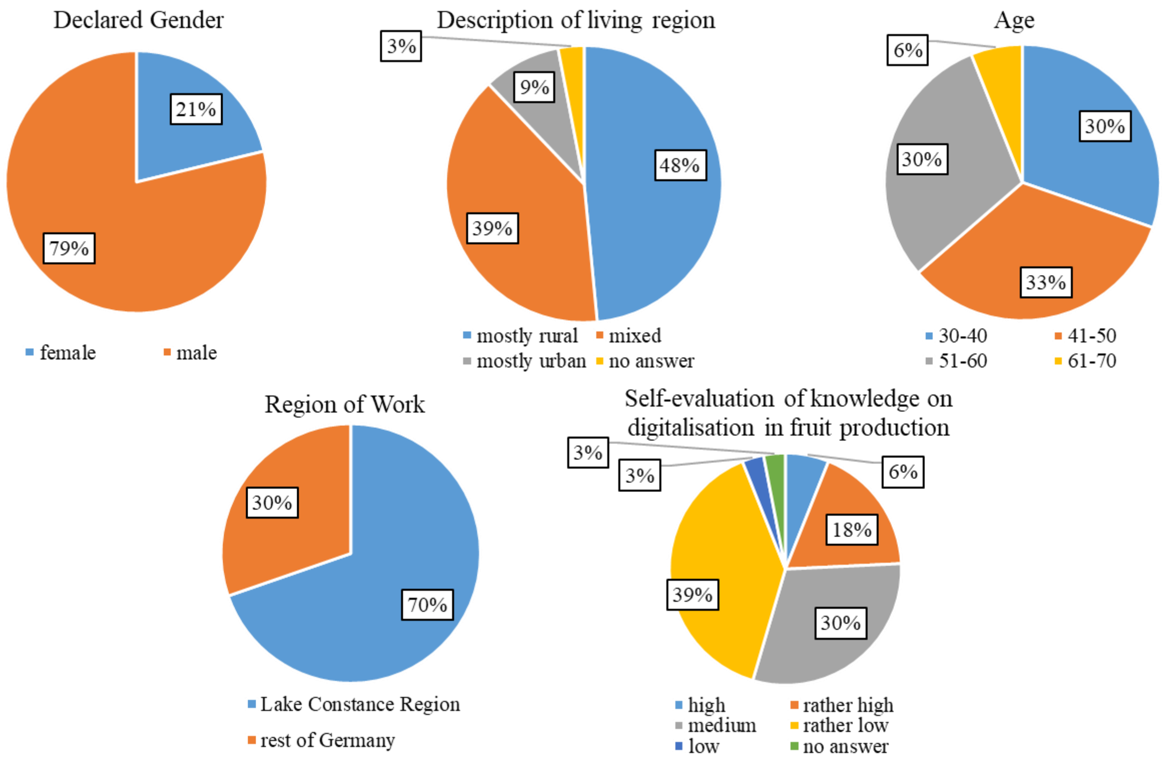

Figure 2. Characteristics of interviewed stakeholders (n=33)

8.3.4 Interview analysis

The interviews were transcribed and analysed using qualitative content analysis (Mayring, 2000) supported through MaxQDA 2020 software. Authors employed a two-part inductive coding process as outlined by Saldaña (2013). Structural coding was conducted as the first cycle to break the information into clear sections from within which the authors could further code. For example, for the question "In your opinion, would the use of digitalized technologies in fruit production change public opinion about the products or production methods?", stakeholders responded with either "yes", "no", "I don't know", or "it depends", and thus these four responses became the initial four structural codes. The second cycle of coding involved pattern coding. This coding type was the most suitable for the aims of this study and the open structure of the interview responses as it enabled the description of similarly coded responses through an emerged pattern: in other words, codes were grouped and regrouped as an iterative process to identify emerging patterns in the content per question (Figure 3). First, excerpts within each structural code were descriptively coded. For instance, within the “yes”-coded responses, the responses were given descriptive titles to best describe the excerpt, such as “reduction of PPP”. Through this descriptive coding, patterns began to emerge within the “yes” codes; thus, the sub-codes were subsequently grouped into overarching codes to describe these patterns. To continue with the example of the “reduction of PPP” coded excerpt, this stakeholder was describing impact through on-farm usage. Thus, the overarching code “impact through on-farm usage” was used to group this and similar responses. The other identified pattern within the “yes” codes was “impact through increased transparency”. All “yes” codes belonged to one of these two patterns. Then, within both of the overarchingcodes, a final pattern was identified, namely if the described impact was positive or negative. These patterns are elaborated upon further in the results.

Frequencies of codes per stakeholder group were calculated in an Excel spreadsheet and incorporated into the results as descriptive statistics. However, due to the small sample size and because many stakeholders provided multiple responses (e.g. “yes” and “no”) for the questions, the descriptive statistics provided are a minor portion of the results, intended to compliment the more extensive qualitative analysis.

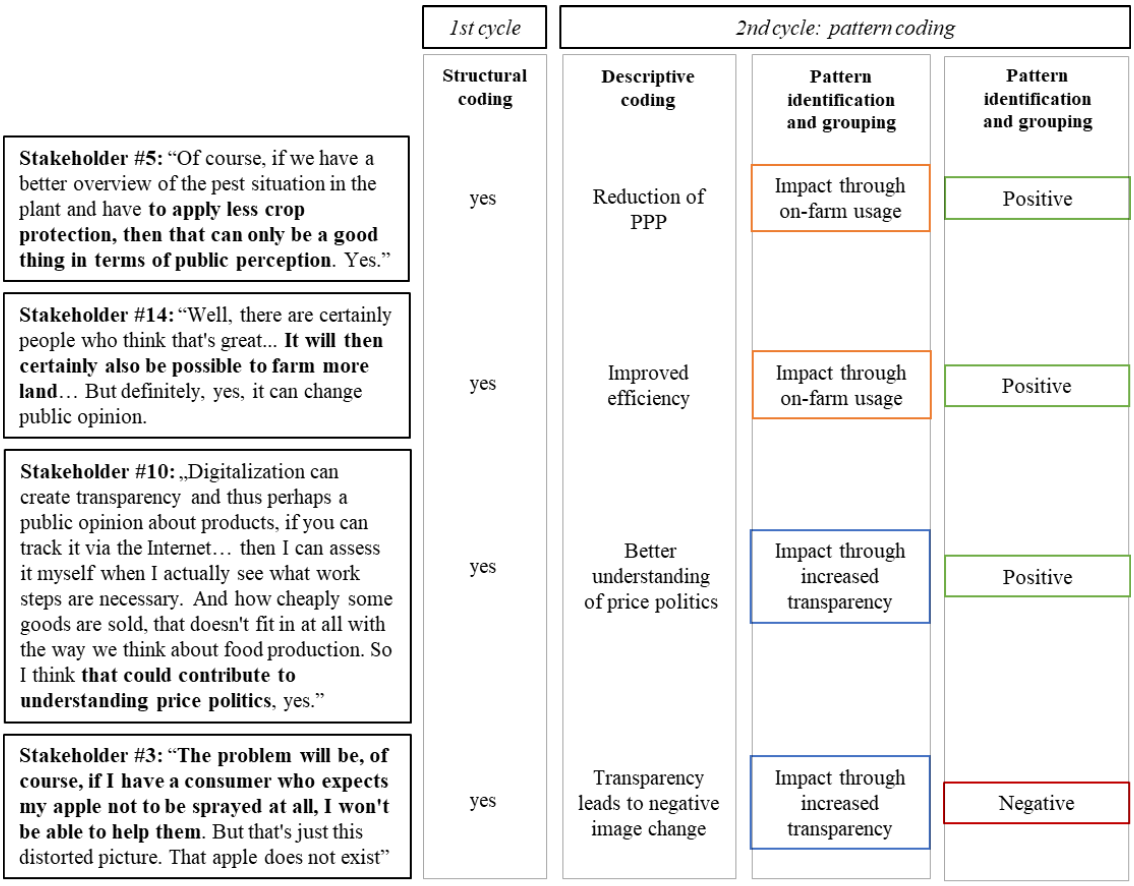

Figure 3. *Example of interview coding process using Pattern Coding* (Saldaña, 2013)

8.4 Results

Results of the interview responses are provided in the following paragraphs and are structured in the order of the research questions: first, the stakeholder perceptions of public opinion of fruit farming are examined. Second, stakeholder views on how the use of digitalized technologies in fruit farming can influence public opinion are addressed and the emerged themes are explored. The elaborations of the responses are qualitatively reported to explore viewpoints, explanations, and arguments from stakeholders.

8.4.1 Stakeholder perceptions of public opinion of fruit farming

Based on the responses to the semi-structured interview questions, authors could interpret the stakeholder perceptions of the public opinion of fruit farming. Stakeholders from all groups, regardless of their categorical response to the interview questions, expressed frustration with the public and their current lack of understanding of fruit production methods and agricultural production as a whole. A fruit wholesaler (Stakeholder [S]13) credited agriculture as a sector for this perceived inadequacy, rather than society: "*when we talk about public opinion, I think we have to say that agriculture as a whole has forgotten to take society with it in its development*". Other stakeholders described false information in the media to perpetuate inaccurate ideologies of agricultural production methods. An organic farmer (S20) reported: "*The public has no idea about agriculture anymore . . . there is no knowledge and what is being spread are the personal perceptions of individuals. You can also simply say that they are teachers. And we need to get the knowledge about agriculture, how it works or how it is done, what opportunities and difficulties there are, into the population*". Stigmas against agricultural production methods, which were reported to cause misunderstandings and low acceptance of agricultural production methods, lack of willingness to pay, and misguided pressure on politics were described to originate from narratives provided by the media. A damaging discourse surrounding the use of pesticides has been created at the sake of farmers, despite their invaluable role in feeding the population, described a consultant (S6): "*It is conveyed to society in such a way that the fruit grower gets the feeling that he has only sprayed poison. And that's his hobby, spraying poison and driving a tractor and polluting the environment. I don't know a single farmer who sprays without having to do it. Because it's unpleasant for everyone and it also costs money. But this social service, which actually benefits the world's population, has no social recognition here in our affluent state or in Central Europe*". A researcher (S3) credited marketing by retail chains to project an unattainable image that high-quality products can be made at a low-cost for the end consumer, and this is causing dangerous inaccuracies: "*nothing has diverged as much as the production methods in agriculture and fruit growing and the way they are marketed. That's why the consumer has been continuously misled*".

8.4.2 General stakeholder views on how digital technologies in fruit farming can impact public opinion

Across all stakeholder groups, 73% believed that digitalization could change the public opinion of general fruit production, regardless of the production system (Figure 4). All consultants and nearly all fruit farmers and representatives from nature, agriculture, and consumer associations reported this. Two stakeholders were undecided and responded “it depends”: “*not on the use of digitalized technologies, but rather how the collected data are used*” (fruit farmer, S28); “*the answer depends, because just using it won’t change anything if it’s not known to the public. That means there has to be some kind of marketing*” (technology developer, S33). Of the stakeholders who responded “no” (21% total), most were researchers. Five stakeholders (two researchers, two representatives from nature, agriculture, and consumer associations, and one wholesaler) responded with multiple answers; all but one responded first with “no”, then followed up with “yes” during their elaborations. Unless otherwise specified, both responses were considered to have equal value and therefore are included in the results of this study.

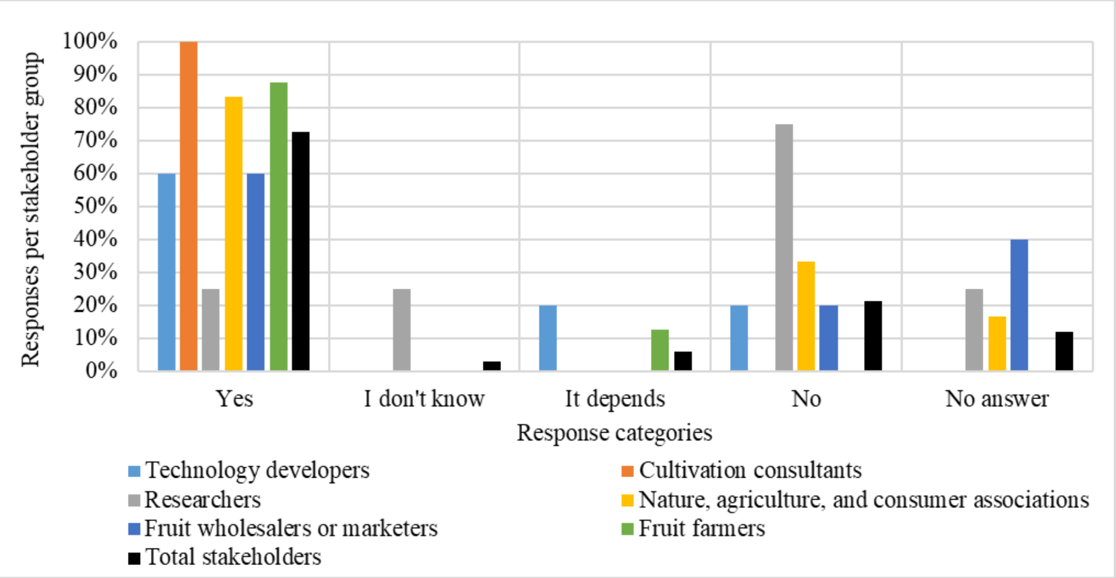

Figure 4. *Stakeholder views on if the use of digitalized technologies in fruit production would change public opinion about the products or production methods. Multiple answers were possible.*

Stakeholders were asked if their answer would differ when speaking about the use of digitalized technologies in organic fruit production. This phrasing of this question enabled an open discussion around production system differences. This question can also be interpreted as whether the production system makes a difference in the impact digitalization could have on public opinion of fruit farming. Nearly half (48%) of all stakeholders believed the production system plays a role in the impact digitalization could have on public opinion (Figure 5). For instance, a developer responded, “*I can only imagine that it will have an even stronger effect on the organic ones, because the higher price simply requires greater credibility* . . . I think it is perhaps even more valuable for organic farms to demonstrate this traceability and this modernity, and also this progress in principle, if they communicate it accordingly. Of course, it's also an exciting question, because this digitalization doesn't fit in with the dream of many people that farming has to be idyllic and small and with ten different animals on the farm, but yes". (S33). Meanwhile, 30% of stakeholders did not believe this, such as an organic farmer, who mentioned, "I don't think so, because practically the population or public opinion doesn't even know what technologies are being used . . . No, there is no difference. So, organic and IP will not differ", (S14). A greater number of stakeholders chose not to respond to this question than for the previous interview question, without justification. Researchers, for instance, either did not provide an answer or did not believe that the production system makes a difference in how digitalization could impact public opinion. The reasons provided by stakeholders will be explored in the following section.

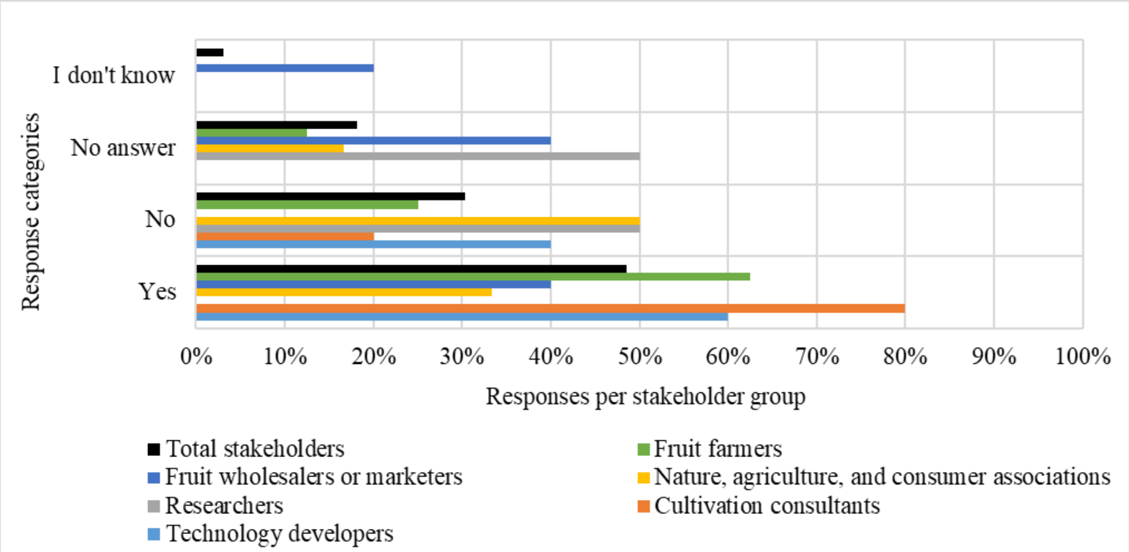

Figure 5. *Stakeholder views on whether production system plays a role in how digitalization could impact public opinion of fruit farming. Multiple answers were possible.*

8.4.3 Digitalization can impact public opinion: emerged themes

Within the responses from stakeholders who answered "yes" to the interview questions, "In your opinion, would the use of digitalized technologies in fruit production change public opinion about the products or production methods" and "Does your answer differ when we speak about the use of digitalized technologies in organic fruit production?", both positive and negative impacts were anticipated. Overall, positive impacts were described more often than negative. Cultivation consultants and fruit farmers were particularly optimistic in this regard, whereas representatives from nature, agriculture, and consumer associations believed negative impacts could occur more than any other group. However, the key stakeholder group, fruit farmers, expected negative impacts to occur with regard to digitalization in organic fruit production more than any other group. As previously mentioned, interviewed researchers either did not provide an answer to the question regarding differences between production systems, or they did not believe the production system played a role.

Two sub-categories for how this change could occur became apparent: (1) through increased transparency from the use of digital tools, and (2) direct on-farm impacts from the use of digital tools

(Figure 6). For instance, some stakeholders saw positive potential in the increased transparency from farm to fork through digital technologies, while others perceived possible risks that could occur when consumers have the opportunity to see into every day farming activities for the products they consume. Similarly, while the direct impacts from on-farm usage of tools (e.g. automated tractors or drones), such as reduced application of inputs, was seen as promising, adverse effects were also described, including farming practices being perceived as becoming more removed from nature. The reasons behind the categories and sub-categories are listed in Table 2 and will be detailed in the following sections.

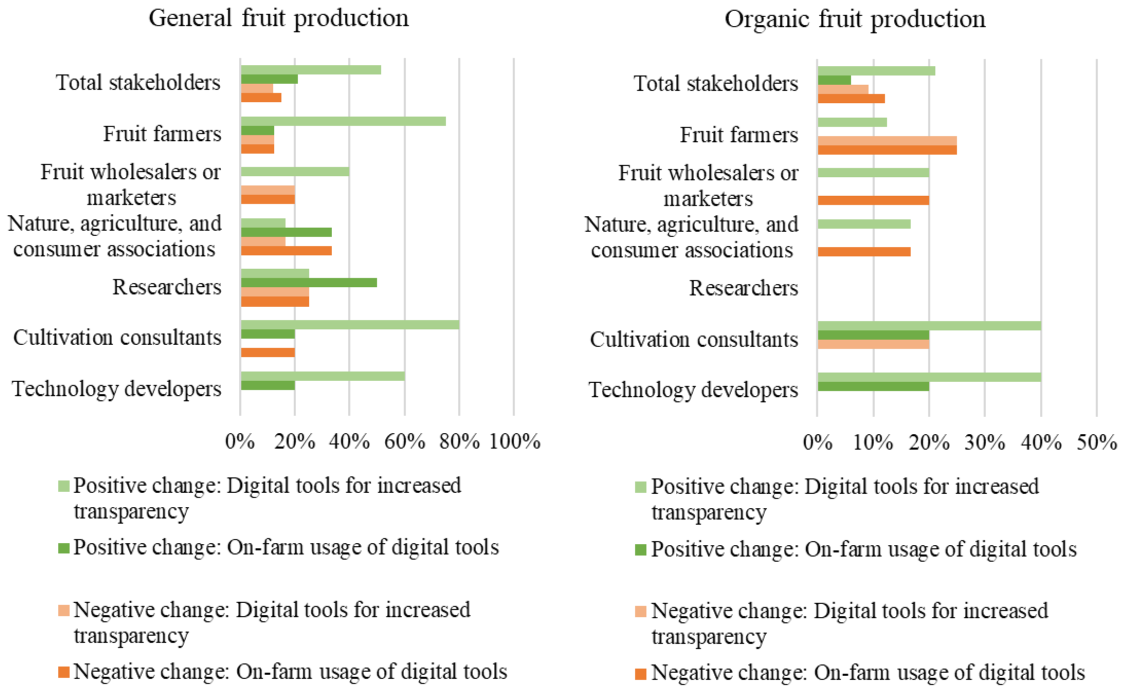

Figure 6. *Themes of perceived impacts (positive and negative, through increased transparency or on-farm usage of digital tools) that digitalized technology use in general (regardless of production system) and organic fruit production could have on public opinion, per stakeholder group. Multiple answers were possible.*

Table 2. *Reasons provided by stakeholders for how digitalized technology use in fruit production could impact public opinion, including specific effects for organic production. The number of stakeholders who mentioned this reason during the interviews is provided. Multiple reasons could be given.*

	Positive impact	**#**	**Negative impact**	**#**
	Digital tools for increased transparency			
	improved public understanding of farming practices	7	change of existing perception	5
	improved trust of farmers/farming practices	7		
	better understanding of price politics	2		
	unification of quality standards	1		
	greater understanding of IP production practices	3		
specific effects for organic production:	greater understanding of organic production practices	1	transparency communicates reality of organic methods	3
	more marketing chances for niche bio products	1		
	higher credibility for organic prices	1		
	organic consumers are easier to positively influence through transparency than non-organic consumers	1		
	On-farm usage of digital tools			
	reduction of inputs	3	trust human worker more than automated tool	1
	improved quality, price reduction	1	technologies concern citizens	1

	increased efficiency	1	more technology means more removed from nature	2
	improvement through environmental practices	4	labour reduction	1
	digitalization may reduce differences between production methods	2		
specific effects for organic production:			does not fit to 'natural' organic image	4

8.4.3.1 Positive impact on public opinion

Digital tools for increased transparency

Increased transparency through digital tool use was the most anticipated impact on public opinion among stakeholders (see Figure 6). Stakeholders reported improved trust of farmers and/or farming practices, better understanding of price politics, and unification of quality standards when describing the potential positive impacts on public opinion through increased transparency. For instance, digitalization was described to offer a chance for the public to learn about fruit production. "*I think that's an important thing for public opinion, that people can understand everything in detail and know that this is coming from the farmer*", described a developer (S30). Another developer mentioned that just using digitalized technologies, i.e. on-farm digital technology use, would not change public opinion on its own. Rather, the technologies should be used to "open the doors" of the farms to the public and communicate the reality of their production methods: "*Digitalization in the sense that we're talking about in the production chain doesn't help. Unless digitalization also describes communication with the outside world. Then yes. . . digitalization can have a positive influence on public opinion if digitalization is used for this purpose*" (S32). Specifically for organic fruit production, potential change was anticipated more often through improved transparency of the production method as a function of digital technologies, as this could help to justify the higher price of organic products in the eyes of the consumer. A consultant (S5) explained, "*As far as organic farming is concerned, I would say that if we can now, for example, as I have just described, transparently show how the organic farming system and plant protection work using a field index and corresponding evaluation software, then we will encounter very broad public approval*". Still, improved transparency was not exclusively perceived to favour organic production. A representative from a nature association (S7) described transparency as a motivation for conventional or IP farms to communicate the reality of their methods to the public, in order to achieve greater understanding of their cultivation practices: "*[farming] simply becomes more transparent, you can compare better, you can adhere to standards better, you can present standards and you can also say that these standards are being adhered to accordingly. Yes, digitalization is standardizing everything, so I think that conventional fruit production could score points in public opinion*."

On-farm usage of digital tools

Some stakeholders expressed optimism that the on-farm use of digital tools could positively influence public opinion of fruit cultivation products or production systems, particularly regarding the potential to improve environmental standards in production, such as precision application methods that could allow for reduction of agricultural inputs and increased on-farm efficiency. "*From my point of view, it's all about environmental quality. And if [digitalization] results in improvements, then public opinion will also improve*", reported a representative from a nature organization (S4). Researchers reported potential positive impacts through on-farm usage of digital tools more than any other stakeholder group, while fruit wholesalers or marketers did not anticipate any positive changes related to on-farm usage. A developer described increased efficiency through on-farm technologies to improve the quality of products over time while also reducing the costs of production and therefore price for the consumer (S31). Positive on-farm impacts on public opinion were also reported for organic fruit production, though only by stakeholders within the cultivation consultant and technology developer groups. Stakeholders expected the use of digitalized technologies to decrease the higher production costs of organic fruit farming, which they credited to the higher manual labour and lower yields compared to conventional or IP fruit farming, ultimately reducing the price- and acceptance-gap between conventional and organic products.

8.4.3.2 Negative impact on public opinion

Digital tools for increased transparency

While transparency enabled through digital technologies can offer a positive change through knowledge sharing, trust, and improved communication, the publication of farm-level information could also negatively influence the opinions of consumers. According to an IP farmer, "*Farms are becoming more and more transparent. This means that the quantities of pesticides and the application and so on are all becoming public. And that can go in one direction or the other under certain circumstances. So I see it in two ways*." (S24). Transparency could de-romanticize production methods for consumers. Stakeholders particularly described this risk for organic production, as consumers with disillusioned concepts of the production method might react negatively to the reality gained through increased transparency. A researcher reported, "*The problem will be, of course, if I have a consumer who expects my apple not to be sprayed at all, I won't be able to help them. But that's just this distorted picture. That apple does not exist*." (S3).

On-farm usage of digital tools

Negative impacts were anticipated through direct on-farm use of digital technologies. Mistrust of technologies, particularly flying or autonomous driving technologies like smart tractors or drones, was a common theme: "*And drones are not only a blessing, but also a bit of a curse in the eyes of some people. Yes, because it's simply uncomfortable. Not just because of the noise, but simply because you feel like you're being watched, you don't know what they're filming for*", reported a representative from an agricultural association (S19). The possibility of human labour reduction or replacement through the implementation of on-farm digital tools additionally concerned stakeholders, and was described to risk a negative impact on public image and societal acceptance of farming practices. More stakeholders reported organic fruit farming to be at risk for a negative impact through on-farm use of digital technologies than through increased transparency through digitalization. The presence of digital technologies in organic fruit farming was perceived to contradict the current public opinion: "*In terms of perception, of course, it's somehow bad when you say: 'Yes, the organic farmer, he's flying over there with the drone. Is that even organic? And does he have a computer-controlled harvesting machine? I thought they were using a ladder to get the fruit down from the high trunks' and things like that . . . they say that organic farming is actually like it was 100 years ago. At least that's how people imagine it. And digitalization doesn't fit in there*" explained a fruit wholesaler and marketer (S17).

8.4.4 Digitalization (alone) cannot impact public opinion: emerged themes

In comparison to the responses by stakeholders who believed digitalization can impact public opinion of fruit production, stakeholders who did not believe this provided limited explanations. Three themes emerged from these responses: (1) the use of digital technologies are "unseen" by the public; (2) society does not know/care how fruit is produced; and (3) information gained through digitalization is not interesting for the public. Stakeholders who answered "no" were often discouraged by the lack of digital knowledge among consumers, which limits the public's ability to learn about fruit production through increased transparency as a function of digitalization. Still, the majority of "no" responses centred on a perceived lack of societal understanding or interest in agricultural methods. Some stakeholders believed society is already too distanced from food production and digitalization cannot bridge this gap. A researcher (S11) mentioned that digitalization would not impact public opinion on fruit production, "*because the population or public opinion doesn't even know what [current] technologies are being used*". Another researcher (S3) expanded on this point by describing the digital literacy in the general public to be too low for any sort of impact: "*the consumer we're talking about now doesn't have any digital skills either. We are already talking about the fact that consumers are far too far removed from agricultural production processes and that food marketing is characterized by selling a myth of a manufactured world . . . Consumers are not interested in [digitalization] at all because they actually tend to say that even more technology, even more distance from the land, is not good . . . The consumer is educated to believe that modern technology is actually disruptive and feeds the agribusiness lobby, so to speak, at the expense of the consumer and lots of chemicals*." Researcher (S3) described this "myth of food production" to be a lie: "*As long as people believe that, I as a producer have actually lost completely. All these tools won't help me, I first need to build up a new image of production, new confidence in myself as a person in my business. These documentation tools can help me a little with that*". An organic farmer argued that, first and foremost, the foundational knowledge in society around agricultural production methods is in need of improvement: "*what we can do with digitalization, with digital technologies, is that we can document that we are doing* *everything in accordance with the law. But if people don't understand the meaning and purpose behind it, it's no better because of that*", reported an organic farmer (S20). While digital tools like social media can help to give a realistic picture to the fruit, this is only feasible if the farmers have the capacity to use the tools. Researcher S3 described this as an unrealistic task to add on top of the extensive daily workload of a farmer.

Impact on public opinion of fruit farming may not be contingent upon the use of digital technologies in fruit farming, but rather the narrative surrounding their use and impacts. "*On the producers' side, the only chance now is not to talk about digitalization or technology, but to talk about what they really do*." reported researcher S3. This researcher recommends that producers use digitalization to communicate to the public that they (1) understand the concerns of the public and (2) are taking all possible measures to reach their demands. Stakeholders suggested that a positive change on the public image of fruit production could occur if the communication about digitalization were to focus on environmental aspects. "*I can imagine that if the press were to report that the use of pesticides can be reduced with new technologies, then I think it would certainly have a positive impact on public opinion*," reported a researcher (S11). Still, the discourse on digitalized fruit production must remain neutral and informative to improve societal knowledge and build trust between producers and consumers. "*If the customer has the feeling that digitalization helps to grow the product in an even more environmentally friendly, climate-friendly and healthy way, then they are in favour of it. But if they just think: 'It's just a technology that observes us even more, controls us more. It calls certain things into question in terms of data protection', then there is simply a lack of transparency as far as the consumer is concerned*", described a representative from an agricultural organization (S19).

8.5 Discussion

8.5.1 Methodological considerations

Several methodological aspects limited this study. To begin, the average farm size in the region is significantly smaller than the national average, which may influence how digitalization was perceived. This region is known for its small-to medium- sized family farms, which have been found to lack digitalization (Regan et al., 2018) and to adopt digital technologies less frequently than larger farms due to structural challenges (Kernecker et al., 2020; Linsner et al., 2021). German family-run farms tend to favour well-established solutions over innovations (Cravotta & Grottke, 2019). The self-evaluation of knowledge on digitalization in fruit production ranged greatly, with most responses falling in the rather low (39%), medium (30%), and rather high (18%) knowledge categories. This was to be expected, as only some of the stakeholders work directly with digitalization, and others were selected based on their knowledge of the regional fruit value chain. Additionally, stakeholders were not provided with a definition or examples of digitalization in fruit production; therefore, their responses are dependent upon their personal interpretation of digitalization in fruit production. Considering that the adoption of digital technologies in the fruit sector is lagging behind other agricultural sectors (Ossevoort et al., 2016), variations in experience with the topic among stakeholders are to be expected. Digitalization in agriculture has been notoriously challenging to define, as numerous terms have emerged to explain the different forms of digitalized agricultural systems (Klerkx et al., 2019). While the variations in interpretations provided valuable insights for this study, they also suggest a need to disambiguate the term "digitalization" for all potential users within this sector. Finally, while the frequent criticisms expressed by stakeholders over societal knowledge on agricultural practices could have hinted towards a stakeholder bias, the authors of this study see value in these results as they are as follows: despite an overall negative outlook on the current state of public opinion, stakeholders still see the value that functions of digitalization can offer.

8.5.2 The digitalization narrative

Stakeholders in this study largely conveyed optimism that digitalization could create a positive change in the public perception of fruit production and lead to a variety of trickle-down impacts, such as improved price politics. On the other side, stakeholders who expressed frustration with society's current knowledge on agricultural production frequently credited media for this perceived lack and noted that digitalization's impact on public opinion of fruit production may be contingent upon the media's chosen narrative surrounding it. In this way, the narrative around the employment and effects of digital technologies in fruit farming may have a greater influence on public opinion of the industry than their actual use. Indeed, media reports hold immense power in how the public think about issues (McCombs & Valenzuela, 2021). Yet the supply of information is rarely neutral, as media have incentives to provide eye-catching, often controversial narratives around current topics (McCluskey & Swinnen, 2004). A study by Yuksel et al. (2017) found that society pays more attention to negative reporting, which is referred to as the bad-news hypothesis. Still, research shows that German media tend to support new technologies (e.g. Metag & Marcinkowski, 2014). A study by Mohr and Höhler (2023) conducted a content analysis of German media content published from 2016 to 2019 on digitalization in agriculture and found that the majority of analysed arguments were positive (59%), while almost 24% were negative and around 18% were neutral. Favourable media coverage of this topic was encouraged in the study by Mohr and Höhler as an opportunity to improve societal acceptance of digitalized agriculture. The stakeholders in this study expand this opportunity to include societal acceptance of agriculture methods in fruit production.

Furthermore, while technical details of agricultural processes are unlikely to interest the public (Pfeiffer et al., 2021), the potential for digitalization to improve environmental or social conditions, such as those anticipated by stakeholders in this study, can be used as an argument to support the use of digital technologies. Literature indicates that communication of the positive effects of digital technology use is a critical part of the narrative as digitalization progresses; without this narrative, studies initially yielded neutral or negative results on the impact on public perception. The representative study conducted by Wilmes et al. (2022) first indicated that German citizens perceive a negative effect of digital technologies on willingness to buy food products from large and conventional farms. However, when environmental arguments for the use of the technologies were introduced to the participants, a positive influence on the willingness to buy food products from those farming systems was observed. Furthermore, the outcomes of the study by Treiblmaier and Garaus (2023) highlighted that the benefits of blockchain technology use in the food supply chain could only be realized by informing the public of these benefits, such as through blockchain labels, which were found to have a positive effect on purchase intention through perceived product quality.

8.6 Implications and conclusions

8.6.1 Change through on-farm use of digital tools

Stakeholder responses to the interview questions demonstrated two categories of potential change–positive or negative–and two sub-categories for how this change could occur–through increased transparency or through the on-farm use of digital tools. Other functions of digitalized technologies that enable improved transparency, such as communication between farmers and other value-chain actors for knowledge exchange or improved management of farms through digitalized management systems, were not mentioned. While it can be assumed that the interviewed stakeholders did not value these missing functions to have a potential impact on public image, it is also possible that these tools were not known by stakeholders to belong to digitalized fruit production. The digital tools and their functions described to have potential positive impacts on public image, such as improved efficiency and reduction of PPP, were localized to on-farm activities and fit most closely to the concept of precision farming (Eastwood et al., 2019). This could imply that the stakeholders who responded optimistically regarding on-farm usage of digital technologies might be lacking information on the concept of digitalization in agriculture. While precision farming is a component of the broader concept of digital agriculture, it does not consider the transfer, collection, and/ or analysis of data to improve on- and off-farm activities and decision-making (Leonard et al., 2017) as a farm system technologization (DLG e.V. & Griepentrog, 2019), which is the typical understanding of digital agriculture (Ingram & Maye, 2020). Interestingly, most of the described negative impacts through on-farm usage of digital technologies, including mistrust of automated technologies and possible redundancy of human labourers, fit better to the concept of digital agriculture. These results suggest that it may not be the digitalization of fruit production as a whole that stakeholders perceive to impact public image, but rather specific aspects of digitalization, such as automation. Future research initiatives should continue to explore these aspects, the outcomes of which are valuable for understanding how public opinion on agriculture could be impacted by the use of digital tools in food production.

8.6.2. Change through increased transparency

Stakeholders in this study emphasized the risk that data transparency to consumers could create a negative impact on public opinion of fruit farming, depending on the consumers' prior knowledge and expectations. Increased transparency through digital technologies goes hand-in-hand with the topic of on-farm data use and governance. Some studies have found that digitalization of farming practices adds a new vulnerability for farmers regarding data ownership. Misuse of on-farm data may lead to reputation damage of the participating farmers. A number of studies reveal risks perceived by stakeholders in the agricultural sector to surround the ownership and sharing of on-farm data (e.g. Jakku et al., 2019; Lioutas et al., 2019; Regan, 2019; Wiseman et al., 2019). Improving the foundational knowledge of society around agricultural production methods, which could mitigate the risk of negatively influencing opinions of the public with incorrect conceptions of farming, was encouraged as a critical first step towards improved public acceptance. However, studies have found that access to more comprehensive information on a topic does not always lead to greater acceptance (Scholderer & Frewer, 2003; Weary & Von Keyserlingk, 2017; Wuepper et al., 2019). Opinions on agricultural practices are deeply rooted and are based on personal experience, knowledge, values, and beliefs (Te Velde et al., 2002). Because of this, simply providing more information on a topic is not likely to significantly improve public opinion (Grunert et al., 2003). Therefore, increasing foundational knowledge of agriculture through digitalization should not be the main priority of digitalization. Instead, direct engagement with the public could be more successful with mitigating public concerns than education strategies. This strategy has been successful in other agricultural sectors, such as animal husbandry (Weary & Von Keyserlingk, 2017). Digital technologies that would enable two-way communication between the public and farmer, such as digital platforms and apps that facilitate direct marketing and social innovations like community-supported agriculture (CSA), would support the expressed interests of the stakeholders. Nevertheless, the perceived deficit in digital literacy among both the farmers and the public suggest a necessary first-step of capacity building. This could include digital training for farmers through, for instance, the tool development companies, and the use of simplified, non-technical language in the public discourse, including media, around digitalized fruit cultivation. Additionally, the use of these tools must not significantly increase the already heavy workload of farmers, but rather ease the tensions between farmers and the public.

When asked about the role of digitalization and fruit production’s public image, stakeholders prioritized finding ways of fair communication, which on the one hand show a bit of honesty towards the consumer but also improve the image of the farmer. Public acceptance of digitalization has been found to not only be determined by the characteristics and impacts of the digital technologies but also on the trust of the farmers, who are given the responsibility to use digitalization in the best way possible (Pfeiffer et al., 2021). The main drivers of public acceptance of farming systems are citizens trust in those systems (Birkle et al., 2022); thus, building trust through the use of digitalized technologies would take a critical step towards improved societal acceptance of agriculture.

8.6.3 Digital transformation as an ongoing process

Considering the challenges posed by societal criticisms of modern agricultural practices and the persistent, rapid development of digital technologies for the sector, actors should seize the perceived opportunity to improve the public acceptance of fruit cultivation. At the same time, the possible risk of worsening public acceptance cannot be ignored, nor should the described contingency regarding the narrative around digitalization and the concerns over low foundational knowledge on agriculture. Lessons learned from previous rapid technological advancements in agriculture should be considered; for instance, one-sided technology driven approaches to the development and use of agri-biotechnology previously led to negative public acceptance issues (Krüger et al., 2018). This lesson is particularly critical to consider, given that there is evidence of a similar one-sided technology-push (versus market-pull) in the digital transformation of the German fruit cultivation sector (Gaber et al., 2024). On the other side, existing research also indicates how other sectors could counteract their previously low public acceptance through similar opportunities to those highlighted in this article. Trust and perceived benefits to modern practices have been found by Birkle et al. (2022) to be drivers towards acceptance of animal husbandry systems from German citizens. Similarly, knowledge, transparency, and communication between sectoral stakeholders and the public were found to increase trust in novel bio-economic products (Krüger et al., 2018).

In contrast to the rapid progression of digitalization, understanding the impact that it may have on public opinion of agriculture must take a slower approach. Values, such as public opinion and acceptance, are maintained within individuals, but are deeply embedded in the social-ecological context and evolve over time (Manfredo et al., 2017). Change, especially value shift in response to social-ecological change, is likely to be slow and over long periods of time (Kendal & Raymond, 2019; Manfredo et al., 2017). Particularly in established, traditional agricultural regions, such as in the Lake Constance region, the landscape interface, or the dynamic physical and cultural space resulting from the interaction between social and ecological systems, shapes and is shaped by the local value system (Horcea-Milcu et al., 2018). Changes to the landscape interface, such as the introduction of digital technologies to the fruit cultivation sector, and the resulting changes in actors' values may experience a "value change debt" or time lag (Horcea-Milcu et al., 2018). This value change debt suggests that the lasting impact on public opinion may not be determinable in-situ with the digital transformation of fruit cultivation, but will rather continue to evolve past the initial "boom" of development and implementation.

Understanding how digital technology use influences public opinions is still in its infancy. While many studies exist on the acceptance *of* digital technologies in various sectors and in agriculture, fewer studies exist on how digital technology use may *influence* the public acceptance or perception of the sectors. Although the results of this study provide novel insights into this topic and the first of its kind for the German fruit cultivation sector, the previously mentioned methodological considerations indicate the need for further research. As the digital transformation in fruit cultivation and agriculture as a sector is an ongoing process, it is important to consider that as researchers, we can analyse continuous change, yet impacts should be considered as interim and plenary (Fischer et al., 2021). The recording of these impacts during a transformation can serve for comparison between different phases of the transformation and may indicate which interventions impacted changes within the interim results during the process. Continuous monitoring of the impact of digital technology use on the public opinion of fruit products and production systems would provide a more comprehensive understanding of how these perceptions change over time.

Encouraging a gradual pace of change would be fruitful for understanding the impact that digital technologies may have on the public acceptance of agriculture, including fruit cultivation. Incremental approaches grounded in the findings of this study may best support this gradual change of public opinion of fruit cultivation over time. First, influential actors such as policy makers, industry leaders, and technologists should set realistic expectations for digitalization’s ability to shift public perception. The use of non-technical and factual language around digitalization in fruit production in the public discourse at these levels (government, industry, and research) and in the media would support this. This could also function to foster public trust of the information provided and discourage myths surrounding digital technology use in agriculture, which could negatively influence the public opinion. Given their influence, these groups should set the precedent for how the narrative around digital technology use in fruit cultivation and agriculture in general is used. Following the establishment of a consistent, factual narrative to the public and to the intended users, these actors should aim to provide and support training opportunities for users, such as farmers, on the use of digital tools to improve digital literacy at the farm level. Next, development efforts and support should focus on creating technologies that function to ease tensions between farmers and public, building trust towards farmers and their farming practices. Ongoing research initiatives to monitor the change in public opinion during and beyond this digital transformation, as well as differences in impacts based on specific aspects of digitalization like automation, are encouraged.

8.7 Conclusion

This study established novel insights on the anticipated impacts of digitalization on the public opinion of fruit cultivation. Digital technology use in fruit cultivation in the Lake Constance region may create both positive and negative impacts through increased transparency and on-farm use of the tools, according to stakeholders in this study. In addition to an honest discourse surrounding the use of digital technologies in fruit production, authors emphasize that enabling personal dialogue between the public and farmers should be a central goal of digitalization to improve the public image of agriculture. Digitalization can be a tool for fair, honest communication directly from farmer to consumer, under the right conditions. Access and use by farmers should be supported through trainings and straightforward, efficient operation. However, to impact public opinion or to work against stigmas around agricultural production, digitalization is not the focus, but rather a means to an end. Ultimately, digitalization cannot be viewed as a silver bullet, as it is sometimes perceived, for current challenges in fruit cultivation like societal acceptance; due to the complex nature of public image and societal acceptance of the agriculture and food sector, any change will be gradual and cannot be impacted by digitalization alone.

8.8 References

Adarsch, A., Pranav, P. M., & Manjunath, C. R. (2018). Fruit farm surveillance using drones. *International Journal of Trend in Scientific Research and Development*, 2(4), 351–357. https://doi.org/10.31142/ijtsrd12973

Augustenberg, L. T. (2023). Integrierter Pflanzenschutz, 2023: Erwerbsobstbau.

Baden Württemberg, S. L. (2022a). *Baumobstfläche nach Obstart: Landkreis Bodensee 2017 und 2022. Bodennutzung.* https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502308x.tab?R=KR435

Baden Württemberg, S. L. (2022b). *Baumobstfläche nach Obstart: Landkreis Konstanz 2017 und 2022.* https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/ 0502308x.tab?R=KR335

Baden Württemberg, S. L. (2022c). *Baumobstfläche nach Obstart: Landkreis Ravensburg 2017 und 2022.* https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/ 0502308x.tab?R=KR436

Baeten, J., Donné, K., Boedrij, S., Beckers, W., & Claesen, E. (2008). Autonomous fruit picking machine: A robotic apple harvester BT. In C. Laugier & R. Siegwart (Eds.), *Field and service robotics: Results of the 6th international conference* (pp. 531–539). Springer. https://doi.org/10.1007/978-3-540-75404-6_51

Balmann, A. (2016). *Über Bauernhöfe und Agrarfabriken: Kann die Landwirtschaft gesellschaftliche Erwartungen erfüllen?* https://ageconsearch.umn.edu/record/ 251889/

Barbole, D. K., Jadhav, P. M., & Patil, S. B. (2022). A review on fruit detection and segmentation techniques in agricultural field BT. In J.-I.-Z. Chen, J. M. R. S. Tavares, A. M. Iliyasu, & K.-L. Du (Eds.), *Second International conference on image processing and capsule networks* (pp. 269–288). Springer International Publishing.

Bayerisches Landesamt für Statistik. (2018). *Baumobstflächen und -bestände in Bayern.* https://www.statistik.bayern.de/mam/produkte/veroffentlichungen/statistische_berichte/c1800c_201751_16735.pdf

Biegert, K. (2022). *Smart horticulture: Application of sensors and modelling to predict fruit growth, quality and storage behaviour of 'braeburn' apples* [Doctoral dissertation]. Hochschule Geisenheim University.

Birkle, I., Klink-Lehmann, J., & Hartmann, M. (2022). Different and alike: Level and determinants of public acceptance of fattening pig, beef cattle and broiler farming in Germany. *Meat Science,* 193(March), 108946. https://doi.org/10.1016/j.meatsci. 2022.108946

Bitkom, D., & Bauernverband, R. (2020). *Schon 8 von 10 Landwirten setzen auf digitale Technologien.* https://www.bitkom.org/Presse/Presseinformation/Schon-8-von-10- Landwirten-setzen-auf-digitale-Technologien

Bodensee, S. (2013). Zukunftsfähiger Bodensee: Jahresbericht 2013. https://www.bod ensee-stiftung.org/wp-content/uploads/BoSti_Jahresbericht_13_0.pdf

Bryman, A. (2012). *Social Research Methods* (Vol. 4). Oxford University Press.

Bundesministerium für Ernährung und Landwirtschaft. (2016). Der Gartenbau in Deutschland: Auswertung des Gartenbaumoduls der Agrarstrukturerhebung 2016. Der Gartenbau in Deutschland. https://www.bmel.de/SharedDocs/Downloads/Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile

Bund für Umwelt und Naturschutz Deutschland. (2019). Chancen und Risiken der Digitalisierung in der Landwirtschaft: Diskussionspapier des BAK Landwirtschaft. In *Chancen und Risiken der Digitalisierung in der Landwirtschaft*. https://doi.org/10.5771/9783748903604-77

Cerda, A. A., García, L. Y., Ortega-Farías, S., & Ubilla, Á. M. (2012). Consumer preferences and willingness to pay for organic apples. *Ciencia e Investigación Agraria*, *39*(1), 47–59. https://doi.org/10.4067/s0718-16202012000100004

Chemnitz, C., Wenz, K., & Haffmans, S. (2022). *Pestizidatlas 2022: Daten und Fakten zu Giften in der Landwirtschaft*. Heinrich-Böll-Stiftung. https://www.boell.de/de/2022/01/04/pestizidatlas

Cravotta, S., & Grottke, M. (2019). Digitalization in German family firms – some preliminary insights. *Journal of Evolutionary Studies in Business*, *4*(1), 1–25. https://doi.org/10.1344/jesb2019.1.j051

Das Grüne Lexikon Hortipendium. (2021). *Gemüseanbau: Bio oder Konventionell*. https://hortipendium.de/Gemüseanbau:_Bio_oder_Konventionell

DESIRA. (2019). *The Project: About DESIRA*. https://desira2020.eu/the-project/

Deutsche Landwirtschafts-Gesellschaft. (2018). *Digitale Landwirtschaft: Ein Positionspapier der DLG. Digitale Landwirtschaft*. https://www.dlg.org/fileadmin/downloads/fachinfos/DLG_Position_Digitalisierung.pdf

Duncan, D. W., & Broyles, T. W. (2006). A comparison of student knowledge and perceptions toward agriculture before and after attending a Govenor's school for agriculture. *NACTA Journal*, *50*(1), 16–21.

Eastwood, C., Klerkx, L., Ayre, M., & Dela Rue, B. (2019). Managing Socio-Ethical Challenges in the Development of Smart Farming: From a Fragmented to a Comprehensive Approach for Responsible Research and Innovation. *Journal of Agricultural and Environmental Ethics*, *32*(5–6), 741–768. https://doi.org/10.1007/s10806-017-9704-5

Fischer, C., Heuberger, M., & Heine, M. (2021). Schwerpunkt the impact of digitalization in the public sector. 1–21.

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach*. Pitman Publishing.

Fu, S., Ma, R., He, G., Chen, Z., & Liu, H. (2023). A study on the influence of product environmental information transparency on online consumers' purchasing behavior of green agricultural products. *Frontiers in Psychology*, *14*(April), 1–11. https://doi.org/10.3389/fpsyg.2023.1168214

Gaber, K., Rösch, C., & Bieling, C. (2024). Digital transformation of fruit farming in Germany: Digital tool development, stakeholder perceptions, adoption, and barriers. *NJAS: Impact in Agricultural and Life Sciences*, *96*(1). https://doi.org/10.1080/27685241.2024.2349544

Genuss Bayern. (2024). *Obst vom Bodensee*. https://www.spezialitaetenland-bayern.de/spezialitaeten/obst-vom-bodensee/

Goodman, L. A. (1961). Snowball Sampling. *Annals of Mathematical Statistics*, *32*(1), 148–170. https://doi.org/10.1214/aoms/1177705148

Grimminger, R., Krawutschke, M., & Berger, S. (2018). *Mehr Bio vom Bodensee durch Tradition und Innovation*. Landratsamt Bodenseekreis.

Grunert, K. G., Bredahl, L., & Scholderer, J. (2003). Four questions on European consumers' attitudes toward the use of genetic modification in food production. *Innovative Food Science and Emerging Technologies*, *4*, 435–445. https://doi.org/10.1016/S1466-8564

Horcea-Milcu, A. I., Abson, D. J., Dorresteijn, I., Loos, J., Hanspach, J., & Fischer, J. (2018). The role of co-evolutionary development and value change debt in navigating transitioning cultural landscapes: The case of Southern Transylvania. *Journal of Environmental Planning and Management,* 61(5–6), 800–817. https://doi.org/10. 1080/09640568.2017.1332985

Igo, C., & Frick, M. (1999). A case study assessment of standard and benchmarks for implementing food and fiber systems literacy. Proceedings of the 18th Annual Western Region Agricultural Education Research Meeting (Vol. 18). https://citeseerx. ist.psu.edu/document?repid=rep1&type=pdf&doi= 4b655d71ebd8148a28097292a67183e0571ebd23

Ingram, J., & Maye, D. (2020). What Are the Implications of Digitalisation for Agricultural Knowledge? *Frontiers in Sustainable Food Systems*, *4*(May), 1–6. https://doi.org/10.3389/fsufs.2020.00066

Jakku, E., Taylor, B., Fleming, A., Mason, C., Fielke, S., Sounness, C., & Thorburn, P. (2019). "If they don't tell us what they do with it, why would we trust them?" trust, transparency and benefit-sharing in smart farming. *NJAS: Wageningen Journal of Life Sciences*, *90–91*, 100285. https://doi.org/10.1016/j.njas.2018.11.002

Johnson, G., Scholes, K., & Whittington, R. (2008). Strategic purpose. *Exploring corpo- rate strategy* (Vol. 8, pp. 132–172). Pearson Education Limited.

Kassanuk, T., & Phasinam, K. (2022). Design of blockchain based smart agriculture framework to ensure safety and security. In *Materials Today: Proceedings* (Vol. 51, pp. 2313–2316). https://doi.org/10.1016/j.matpr.2021.11.415

Kendal, D., & Raymond, C. M. (2019). Understanding pathways to shifting people's values over time in the context of social-ecological systems. *Sustainability Science*, 14(5), 1333–1342. https://doi.org/10.1007/s11625-018-0648-0

Kernecker, M., Knierim, A., Wurbs, A., Kraus, T., & Borges, F. (2020). Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precision Agriculture*, *21*(1), 34–50. https://doi.org/10.1007/s11119-019-09651-z

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences*, *90–91*(November), 100315. https://doi.org/10.1016/j.njas.2019.100315

Kodors, S., Lacis, G., Zhukov, V., & Bartulsons, T. (2020). Pear and apple recognition using deep learning and mobile. *Engineering for Rural Development*, *19*(May), 1795–1800. https://doi.org/10.22616/ERDev.2020.19.TF476

Kösler, J. (2023). Statistisches Monatsheft Baden-Württemberg: Der baden-württembergische Baumobstanbau.

Krüger, A., Schäfers, C., Schröder, C., & Antranikian, G. (2018). Towards a sustainable biobased industry - highlighting the impact of extremophiles. *New Biotechnology,* 40, 144–153. https://doi.org/10.1016/j.nbt.2017.05.002

Kühl, S., Bayer, E., & Schulze, M. (2023). The role of trust, expectation, and deception when buying organic animal products. *Animal Frontiers*, *13*(1), 40–47. https://doi.org/10.1093/af/vfac080

Landwirtschaft, Z. (2021). *The future of agriculture: A common agenda.* https://www. bundesregierung.de/resource/blob/975226/1982458/1f7412d70d982c2307340abb5 ba941c0/2021-11-17-landwirtschaft-data.pdf?download=1

Landwirtschaftliche Rentenbank. (2018). Geschäftsbericht 2018. Landwirtschaftliche Rentenbank.

Lang, M., & Rodrigues, A. C. (2022). A comparison of organic-certified versus non-certified natural foods: Perceptions and motives and their influence on purchase behaviors. *Appetite*, *168*(July 2021), 105698. https://doi.org/10.1016/j.appet.2021.105698

Leonard, E., Rainbow, R., Trindall, J., Baker, I., Barry, S., Darragh, L., Darnell, R., George, A., Heath, R., Jakku, E., Laurie, A., Lamb, D., Llewellyn, R., Perrett, E., Sanderson, J., Skinner, A., Stollery, T., Wiseman, L., Wood, G., & Zhang, A. (2017). *Accelerating precision agriculture to decision agriculture: Enabling digital agriculture in Australia.* https://www.crdc.com.au/sites/default/files/CRD18001-001 CRDC

Linsner, S., Kuntke, F., Steinbrink, E., Franken, J., & Reuter, C. (2021). The Role of Privacy in Digitalization – Analyzing Perspectives of German Farmers. *Proceedings on Privacy Enhancing Technologies*, *2021*(3), 334–350. https://doi.org/10.2478/popets-2021-0050

Lioutas, E. D., Charatsari, C., La Rocca, G., & De Rosa, M. (2019). Key questions on the use of big data in farming: An activity theory approach. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100297. https://doi.org/10.1016/j.njas.2019.04.003

Manfredo, M. J., Bruskotter, J. T., Teel, T. L., Fulton, D., Schwartz, S. H., Arlinghaus, R., Oishi, S., Uskul, A. K., Redford, K., Kitayama, S., & Sullivan, L. (2017). Why social values cannot be changed for the sake of conservation. *Conservation Biology*, 31(4), 772–780. https://doi.org/10.1111/cobi.12855

Marinoudi, V., Lampridi, M., Kateris, D., Pearson, S., Sørensen, C. G., & Bochtis, D. (2021). The future of agricultural jobs in view of robotization. *Sustainability (Switzerland)*, *13*(21). https://doi.org/10.3390/su132112109

Mayring, P. (2000). Qualitative Content Analysis. *Forum: Qualitative Social Research*, *1*(2), 10.

McCluskey, J. J., & Swinnen, J. F. M. (2004). Political Economy of the Media and Consumer Perceptions of Biotechnology. *American Journal of Agricultural Economics*, *86*(5), 1230–1237. https://doi.org/https://doi.org/10.1111/j.0002-9092.2004.00670.x

McCombs, M., & Valenzuela, S. (2021). *Setting the agenda: Mass media and public opinion* (3rd ed.). Polity Press. https://books.google.de/books?hl=de&lr=&id= E-UJEAAAQBAJ&oi=fnd&pg=PT3&ots=Sr0lpKiKS9&sig=HXJCC93ADKDLWvJ 1xCfpVIBfzaM&redir_esc=y#v=onepage&q&f=false

Mendelow, A. L. (1981). Environmental scanning - the impact of the stakeholder concept. In *Proceedings of the international conference on information systems* (pp. 407–417).

Metag, J., & Marcinkowski, F. (2014). Technophobia towards emerging technologies? A comparative analysis of the media coverage of nanotechnology in Austria, Switzerland and Germany. *Journalism*, *15*(4), 463–481. https://doi.org/10.1177/1464884913491045

Miranda, J. C., Gené-Mola, J., Zude-Sasse, M., Tsoulias, N., Escolà, A., Arnó, J., Rosell-Polo, J. R., Sanz-Cortiella, R., Martínez-Casasnovas, J. A., & Gregorio, E. (2023). Fruit sizing using AI: A review of methods and challenges. *Postharvest Biology and Technology*, *206*(September), 112587. https://doi.org/10.1016/j.postharvbio.2023.112587

Mohr, S., & Höhler, J. (2023). Media coverage of digitalization in agriculture - an analysis of media content. *Technological Forecasting and Social Change*, *187*, *122238.* https://doi.org/10.1016/j.techfore.2022.122238

Nesheim, M. C., Oria, M., & Yih, P. T. (2015). A framework for assessing effects of the food system. *A Framework for Assessing Effects of the Food System*. https://doi.org/ 10.17226/18846

Nordmark, L., Skjöldebrand, C., Johansson, C., Segerström, M., Tahir, I., Gilbertsson, M., Ellner, F., Oskarsson, M., Hydbom, O., & Jensen, J. (2021). Launch of IoT and artificial intelligence to increase the competitiveness in Swedish apple and grapevine production. *Acta Horticulturae*, 1314, 235–240. https://doi.org/10.17660/ ActaHortic.2021.1314.30

Ossevoort, R., Verdouw, C., Frans De Jong, P., Hennen En, W., & Robbemond, R. (2016). *Fruit 4.0: De vruchten van meer technologie Technologie-roadmap*. http://library.wur.nl/WebQuery/wurpubs/fulltext/385030

Pfeiffer, J., Gabriel, A., & Gandorfer, M. (2021). Understanding the public attitudinal acceptance of digital farming technologies: a nationwide survey in Germany. *Agriculture and Human Values, 38*(1), 107–128. https://doi.org/10.1007/s10460-020-10145-2

Regan, Á. (2019). 'Smart farming' in Ireland: A risk perception study with key governance actors. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100292. https://doi.org/10.1016/j.njas.2019.02.003

Regan, Á., Green, S., & Maher, P. (2018). Smart Farming in Ireland: Anticipating positive and negative impacts through a qualitative study of risk and benefit perceptions amongst expert actors in the Irish agri-food sector. In *13th European IFSA sympo- sium: Theme 4-smart technologies in farming and food systems, July 2018* (pp. 1–18). http://ifsa.boku.ac.at/cms/fileadmin/Proceeding2018/Theme4_Regan.pdf

Román, S., Sánchez-Siles, L. M., & Siegrist, M. (2017). The importance of food naturalness for consumers: Results of a systematic review. *Trends in Food Science & Technology*, *67*, 44–57. https://doi.org/https://doi.org/10.1016/j.tifs.2017.06.010

Rumble, J. N., & Irani, T. (2016). Opening the Doors to Agriculture: The Effect of Transparent Communication on Attitude. *Journal of Applied Communications*, *100*(2). https://doi.org/10.4148/1051-0834.1030

Saldaña, J. (2013). The Coding Manual for Qualitative Researchers. Sage.

Scholderer, J., & Frewer, L. J. (2003). The biotechnology communication paradox: Experimental evidence and the need for a new strategy. *Journal of Consumer Policy*, *26*(2), 125–157.

Seifen, N. (2021, August). Apfel4.NULL: Einsatz von sensoren für eine nachhaltige Produktion und Lagerung (pp. 16–17). Besseres Obst.

Siefen, N., McCormick, R. J., Vogel, A. M., & Biegert, K. (2023). Effects of laser scanner quality and tractor speed to characterise apple tree canopies. *Smart Agricultural Technology, 4*(November 2022), 100173. https://doi.org/10.1016/j.atech.2023. 100173

Sonntag, W. I., Ermann, M., Spiller, A., & von Meyer-Höfer, M. (2021). Im Streit um die Nutztierhaltung: Gesllschaftsorientierte Kommunikationsstrategien für die Agrar- und Ernährungswirtschaft. *German Journal of Agricultural Economics*, *70*(1), 1–16. https://www.gjae-online.de/de/articles/im-streit-um-die-nutztierhaltung-gesellschaftsorientierte-kommunikationsstrategien-fur-die-agrar-und-ernahrungswirtschaft/

Spykman, O., Emberger-Klein, A., Gabriel, A., & Gandorfer, M. (2022). Autonomous agriculture in public perception - German consumer segments' view of crop robots. *Computers and Electronics in Agriculture, 202*(September), 107385. https://doi.org/10.1016/j.compag.2022.107385

Statistische Ämter des Bundes und der Länder. (2019). *Landwirtschaftliche Betriebe mit Anbauflächen gartenbaulicher Erzeugnisse.* https://www.statistikportal.de/en/node/266

Stefas, N., Bayram, H., & Isler, V. (2016). Vision-based UAV navigation in Orchards**This work is supported in part by NSF awards 1111638, 1525045 and the MnDrive initiative. The authors thank professors Emily Hoover, Cindy Tong and James Luby from the department of horticultural science, University of Minnesota for access to their orchards and useful discussions. We also thank dr. Krishna Doddapaneni for his help with the experiments. IFAC-Papersonline, 49(16), 10–15. https://doi.org/10. 1016/j.ifacol.2016.10.003

Te Velde, H., Aarts, N., & Van Woerkum, C. (2002). Dealing with ambivalence: farmers' and consumers' perceptions of animal welfare in livestock breeding. Journal of agricultural and environmental ethics, 15(2), 203-219. *Journal of Agricultural and Environmental Ethics*, *15*(2), 203–219.

Treiblmaier, H., & Garaus, M. (2023). Using blockchain to signal quality in the food supply chain: The impact on consumer purchase intentions and the moderating effect of brand familiarity. *International Journal of Information Management*, *68* (April 2022), 102514. https://doi.org/10.1016/j.ijinfomgt.2022.102514

von Veltheim, F. R., & Heise, H. (2021). German Farmers' Attitudes on Adopting Autonomous Field Robots: An Empirical Survey. *Agriculture 2021, Vol. 11, Page 216*, *11*(3), 216. https://doi.org/10.3390/AGRICULTURE11030216

Weary, D. M., & Von Keyserlingk, M. A. G. (2017). Public concerns about dairy-cow welfare: How should the industry respond? *Animal Production Science*, *57*(7), 1201–1209. https://doi.org/10.1071/AN16680

Weible, D., Christoph-Schulz, I., Salamon, P., & Zander, K. (2016). Citizens' perception of modern pig production in Germany: a mixed-method research approach. *British Food Journal*, *118*(8), 2014–2032. https://doi.org/10.1108/BFJ-12-2015-0458

Wilmes, R., Waldhof, G., Breunig, P., & Uludag, A. (2022). Can digital farming technol- ogies enhance the willingness to buy products from current farming systems? *PLoS One*, *17*(11), 1–20. https://doi.org/10.1371/journal.pone.0277731

Wiseman, L., Sanderson, J., Zhang, A., & Jakku, E. (2019). Farmers and their data: An examination of farmers' reluctance to share their data through the lens of the laws impacting smart farming. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100301. https://doi.org/10.1016/j.njas.2019.04.007

Wolters, E. A., Steel, B. S., Anderson, S., & Moline, H. (2021). The future of food: Understanding public preferences for the management of agricultural resources. *International Journal of Environmental Research and Public Health*, *18*(13), 6707. https://doi.org/10.3390/ijerph18136707

Wuepper, D., Wree, P., & Ardali, G. (2019). Does information change German consumers' attitudes about genetically modified food? *European Review of Agricultural Economics*, *46*(1), 53–78. https://doi.org/10.1093/erae/jby018

Yap, T. L., Nayak, R., Vu, N. T. H., Bui, D. T., Pham, T. T. T., & Allen, D. W. E. (2023). Adopting blockchain-based traceability in the fruit supply chain in a developing economy: Facilitators and barriers. *Information Technology and People*, *38*, 419–441. https://doi.org/10.1108/ITP-02-2023-0168

Yue, C., Alfnes, F., & Jensen, H. H. (2009). Discounting Spotted Apples: Investigating Consumers' Willingness to Accept Cosmetic Damage in an Organic Product. *Journal of Agricultural and Applied Economics*, *41*(1), 29–46. https://doi.org/10.1017/S1074070800002534

Yuksel, H., Karantininis, K., & Hess, S. (2017). Reconsidering Media Discourses on Food Crisis from a Quantitative Perspective. *Journal of Food Products Marketing*, *23*(4), 398–415. https://doi.org/10.1080/10454446.2014.1000449

Zander, K., Isermeyer, F., Bürgelt, D., Christoph-Schulz, I., Salamon, P., & Weible, D. (2013). *Erwartungen der Gesellschaft an die Landwirtschaft.* Thünen.

Zhang, C., Valente, J., Kooistra, L., Guo, L., & Wang, W. (2021). Orchard management with small unmanned aerial vehicles: A survey of sensing and analysis approaches. In *Precision agriculture.* Springer US. https://doi.org/10.1007/s11119-021-09813-y

Zhang, J., Kang, N., Qu, Q., Zhou, L., & Zhang, H. (2024). Automatic fruit picking technology: A comprehensive review of research advances. *Artificial Intelligence Review, 57*(3), 54. https://doi.org/10.1007/s10462-023-10674-2

Zhang, Q., Karkee, M., & Tabb, A. (2019). The use of agricultural robots in orchard management. In J. Billingsley (Ed.), *Robotics and automation for improving agriculture* (pp. 187–214). Burleigh Dodds Science Publishing. https://doi.org/10.19103/as. 2019.0056.14

Zimbelman, R. G., Wilson, L. L., Bennett, M. B., & Curtis, S. E. (1995). Public image of animal agriculture in the United States. *Livestock Production Science, 43*(2), 153–159. https://doi.org/10.1016/0301-6226(95)00040-R

8.9 Appendix

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the DESIRA Project, funded by the European Commission under Grant Agreement No. 818194.

ORCID

Kirsten Gaber http://orcid.org/0000-0002-6768-9047

Christine Rösch http://orcid.org/0000-0003-3908-1218

Claudia Bieling http://orcid.org/0000-0001-5001-4150

Consent for publication

Informed consent was obtained from all individual participants interviewed for the study.

Abbreviations

CSA	Community Supported Agriculture
PPP	Plant Protection Product
IP	Integrated Production
S	Stakeholder (for interview excerpts)

9. Discussion

My intention for this discussion chapter is to contextualize the results of the dissertation, to answer the research questions by synergizing the findings and discussions of the three articles, and to draw implications for future research and development of digitalization in fruit production. The research questions have been addressed in the articles (see Figure 1) and will be further discussed in this section, particularly in the recommendations section. From a researcher's perspective, I aim to go beyond a normative response to the obtained results by addressing them through a critical lens. To this end, I begin the discussion section with a critical appraisal of digitalization in the context of the results, which goes beyond the case study area by discussing the results in relation to themes found in literature in other sectors and regions. Based on these considerations, recommendations for further research and sustainable development of digital technologies for fruit cultivation are discussed.

9.1 Critical appraisal of digitalization for sustainable agriculture in the context of the results

A common discourse around digitalization in agriculture is that efficiency may be improved through technical advances and precision measurements, improving the overall productivity of the system, which is often linked to improved sustainability. However, as introduced in Chapter 1 and touched upon throughout the articles, digitalization of agriculture simultaneously creates risks that threaten the future of these systems. Digitalization does not define agricultural transformation; rather, digital transformation is part of agricultural transformation, along with other trends or entities that are, like digitalization, actively driving change and shaping structures within and around agriculture. At the same time, as found in the research in article 1 (Chapter 6), the development of digital tools has been driven by economic goals such as increased agricultural productivity, including signs of a technology-push model in the case of fruit cultivation. Based on those findings and the surrounding literature, environmental and social goals are not the aim of the digital transformation; instead, it could be argued that these goals are more of a guise under which digitalization is being sold. Prause et al. (2021) suggest that governmental actors and organizations use environmental and climate issues as justification for their financial and political endorsement of digital developments in the food commodity chain. Other approaches and solutions to food production at the face of numerous sustainability challenges are more difficult to explore because of the political and market emphasis on digital solutions as a model for the future of agriculture (Hackfort, 2023).

Nevertheless, as concluded in article 2 (Chapter 7), considering the urgency of the sustainability challenges and the optimism expressed by stakeholders that digital tools could aid fruit cultivation in the face of the challenges, digitalization must be considered, among other transformative processes, as a pathway to a more sustainable agricultural sector. Digitalization should be seen as a tool to mitigate urgent environmental and socio-economic strategies and must be researched and developed evenly across sectors, regions, production systems, farm size and user demographics so that the potential benefits of digitalization can be reaped by those who implement them. Still, fully digitalizing agriculture is not a solution. While development of digital technologies in agriculture is rapidly progressing, the observed risks and remaining uncertainties are too numerous to suggest that a fully digitalized agricultural system could create a net-improvement on sustainability.

9.1.1 Environmental risks

It is notable that nearly all stakeholders in this study (over 90%) believed that digitalization could have a positive impact on environmental challenges in fruit production (article 2). One of the few stakeholders who believed digitalization may negatively impact the environmental challenges discussed that digitalization does not currently offer a solution for the challenge of biodiversity. Indeed, potentials for biodiversity conservation through digitalization tend to be neglected as they are not currently profitable (Kliem et al., 2023). Stakeholders in a transdisciplinary project on digitalization in German agriculture by Zscheischler et al. (2022) expressed a more negative view on the same concern: the digital transformation of agriculture was described to lead to biodiversity loss, as the use of digitalized data is not optimized to improve biodiversity in agriculture. Other identified risks of digitalization in this study included decreased diversity (such as biodiversity and cultural diversity) in agricultural landscapes through the homogenization of agricultural management practices to be a risk of digitalization (Zscheischler et al., 2022).

Given the results of article 1, including the observed spectrum of knowledge on digitalization in agriculture, it is possible that stakeholders were not able to identify possible environmental rebound effects. However, upon review of existing literature, the heralded opportunities of digitalization may lead to environmental issues that could exacerbate the existing environmental challenges, even if stakeholders were not able to identify this at the time of the interviews. Stakeholders mainly described the increased environmental efficiency and productivity to have a positive impact on sustainability; however, as discussed in article 2 (Chapter 7), digitalization must be cautious to not push the current growth paradigm of more productivity and efficiency, as this could further intensify and homogenize agriculture, leading to the damaging environmental and socio-cultural effects of decreased diversity.

From a historical perspective, major technical transitions in agriculture, including mechanization and genetic engineering, have been associated with unwanted impacts like environmental degradation (Chiles et al., 2021; Martens & Zscheischler, 2022). Therefore, it can be assumed that the digital transformation of agriculture will also experience rebound effects. Such rebound effects, defined as the adverse effect that may partially reduce or even outweigh the intended savings (Coroama & Pargman, 2020), have already been observed. These include greater impacts on land use such as intensification and homogenization, as well as impacts from the production of the technologies themselves, such as higher energy requirements, ionising radiation, and mineral resource use (Chemnitz et al., 2022; Huck et al., 2024).

In their study on the chances and risks of digitalization in agriculture, Kliem et al. (2023) observed a large gap between the potential benefits and the empirical observations for digitalization in German agriculture. Based on the results of this study, I expand on this statement: a large gap also exists between the potential *risks* and the empirical observations. As the digital transformation continues, it is unclear if this gap will close or, rather, become larger. This further underscores the value of empirical case-study research as a time-stamp of the perspectives of stakeholders at this stage in the digital transformation, as well as the importance of transparent communication and basic, foundational knowledge surrounding digitalization- including its risks- to the intended users and the public.

9.1.2 Socio-economic risks

Social structures within and outside of the agricultural sector will undoubtedly be influenced by digitalization, yet the extent and direction is still unclear. Digitalized information access and networking has yet to close existing gaps between wealthy and poor, women and men, and the global North and South (Enders & Groschke, 2018). It is not possible to separate gender equality from the social aspects of sustainability: the social understanding of the term sustainability, which profoundly concerns humans and their responsible and just treatment for a positive future (Enders & Groschke, 2017), involves the issue of gender equality (Enders & Groschke, 2018). Providing equal access to productive resources in agriculture across genders is anticipated to positively impact agricultural output, which works towards both sustainable development goals (SDGs) 5 (gender equality) and 2 (sustainable agriculture) (Bundesministerium für Ernährung und Landwirtschaft, 2020c). Still, despite its importance and the risks associated with neglecting or excluding groups from the digital transformation, research on digitalization and gender is underrepresented (Oliveira, 2017). As previously detailed in the limitations section of the methodology chapter, I endured challenges in reaching female stakeholders for interest in participation in the interview series. Considering that 89% of German farms are led by males (Bundesministerium für Ernährung und Landwirtschaft, 2020c), the conditions for reaching equal gender representation within the farmer stakeholder group were sub-optimal to begin with. Notably, interviewed stakeholders did not mention gender issues as a socio-economic challenge nor in their discussions regarding whether digitalization could mitigate the named challenges. This implies that gender equality issues were not of great concern to the regional stakeholders in the context of the interview questions. However, when considering the differences in perceptions on digitalized fruit production between gender groups, gender becomes a pertinent topic of discussion. For instance, as highlighted in article 1, knowledge gaps were reported barriers to adoption. I observed differences in the self-assessment of knowledge on digitalization based on gender. The highest level of knowledge self-assigned by a female stakeholder was ‘medium’ (five of the seven female stakeholders described themselves to even have ‘rather low’ knowledge), whereas all ‘high’ and ‘rather high’ self-assessments were from male stakeholders. Although this self-assessment alone cannot significantly indicate larger trends, this observation is relevant regarding gender differences in knowledge and involvement in the digital transformation, and hints towards potential deeper societal impacts that digitalization could create. Enders and Groschke (2018) argue that current digital technology development is enhancing gender stereotypes, and that the digital world thus remains a reflection of analog (power) relations. As the digital transformation continues, gender differences in access and knowledge regarding digitalization risk perpetuating or worsening gender inequalities.

Stakeholders communicated concerns relating to inequalities surrounding trust, monopolization of power, handling of farm data, and monitoring from agribusinesses through their digital technologies. These concerns echo those found in existing literature on the risks associated with digital agriculture. Beyond gender inequalities, digitalization may work to deepen unfair distributions between large agricorporations and owners of small farms (Michelsen, 2018). The emergence of digital agricultural data has created a new resource for value extraction, which works to deepen the power imbalances between corporate actors and farmers (Hackfort, 2023). As an example, when farmers use certain digital platforms, they may be limited to their product choices, as some only offer their own or cooperating partners' products like seeds and fertilizers, deepening the dependence of farmers on these companies (Michelsen, 2018). Such so-called 'lock-ins' that reinforce power relations and dependence on agro-industrial farming models have been recognized in other empirical case studies in Germany (e.g. Hackfort, 2023; Prause et al., 2021). Furthermore, in the digital age, the corporations with the most power are those with the most information; thus, to remain competitive, actors in agribusiness (such as seed, fertilizer, and machinery suppliers) are being forced to cooperate with each other or even take over other companies in order to access the most farm-related data possible (Michelsen, 2018). The current framework of policy regulations does not allow for an equitable distribution of the advantages from the valuation of agricultural data, nor does it effectively dismantle corporate concentration and dependency; thus, policy makers must play a more active role in reconciling these power imbalances (Hackfort, 2023). Additionally, a democratic handling of farm data, for instance by including civil society representatives and farmers in the decision making processes for the use of data in the digital platforms, would help rebalance the power asymmetries (Michelsen, 2018).

The majority of named socio-economic sustainability challenges in the Lake Constance fruit cultivation sector belonged to the category 'transition and societal acceptance of agriculture' (see Chapter 7), which included a sub-category related to structural change of agriculture. Structural agricultural change is reflected in European agriculture in the declining number of farms and farm size growth (Neuenfeldt et al., 2019), among other changes, placing small farms like those in the Lake Constance region particularly at risk of being affected. Technology development in agriculture is driving structural change (Nowack et al., 2023) and thus also altering functions and identities of farm owners. Some studies argue that digitalization will modify the culture of farming from being experience and knowledge driven to being a data-driven approach (Butler & Holloway, 2016; Carolan, 2017, 2019; Eastwood et al., 2012; Klerkx et al., 2019b). Farmers depending on data-driven advising and new work standardization brought about by digital technologies may cause farm laborers to lose their skills and their knowledge of agriculture and ecology (Prause et al., 2021). This restructuring of farmer identity and skillset has been recognized in various studies on agricultural technologies and societal change. For instance, the unintended rebound-effect of digitalization in which lowered skill requirements are needed to conduct a specific activity has been defined by Coroama and Pargman (2020) as a ‘skill rebound’. Rotz et al. (2019) describe some farmers to become ‘digital labourers’ through the rise of farm data management platforms. While these farmers who share data with these platforms still own their land, they essentially rent their data to these companies who make a profit from them, considering that data management platforms must transform copious amounts of farm data into useful outputs for farmers and thus valorize on-farm data (Rotz et al., 2019). In a greater sense, these authors argue that data management companies are making capital gains at the sake of farmers and farm workers who bear the livelihood impacts of agriculture. Furthermore, if robotics and automation reduce the need for farm workers, their bargaining power and political support also decrease in significance (Carolan, 2019; Prause et al., 2021). Although stakeholders did not discuss the complete replacement of farm workers with digitalized technologies, some did express concerns that labour availability may decrease in the coming years due to structural change or in the anticipation of another global crisis (like the COVID-19 pandemic – see methodological limitations section 4.4). These concerns may impact adoption tendencies in the future, as farmers have been found to be more likely to consider technology adoption when labour was scarcer (Degieter et al., 2023). Conversely, Rotz et al. (2019) argue that farmers without access to migrant labour and who additionally lack access to digital technologies are at risk of agricultural marginalization. The results of this work, such as the named barriers to adoption in article 1 (access barriers such as limited digital knowledge, financial barriers, deficient digital infrastructure, lack of appropriate tools), emphasize that farmers in the lake Constance region may be particularly at risk of being marginalized in this digital transformation.

The fruit cultivation sector in the Lake Constance region is deeply rooted in regional pride and tradition. As detailed in article 2 (Chapter 7), the regional and historical contexts inherently impact the stakeholders’ perceptions of current sustainability challenges and digitalization’s ability to mitigate them. While the majority of stakeholders perceived digitalization to have the ability to mitigate the numerous environmental and socio-economic challenges in the region, the associated risks, including perpetuating or worsening inequalities, corporate lock-ins, monopolies, restructuring of farmer identity, and loss of traditional knowledge threaten the loss of the existing cultural landscape in the region. These considerations and those in the results and discussion sections of the articles suggest that the socio-economic risks for digitalization in the fruit cultivation sector of the Lake Constance region outweigh the potential benefits. At the interface of adoption and power inequalities, it would not be completely accurate to state that farmers decide their own participation in the digital transformation by adopting or not adopting technologies. In articles 2 and 3 (Chapters 7 and 8), stakeholders credited personal choice and mindset of the farmer as playing a large role in the adoption tendencies of digital technologies and the mitigation strategies for environmental challenges. As the digital transformation continues, external forces place immense pressure on the potential users of the technologies in that, for instance, if farmers do not adopt digital technologies, they may not be able to remain competitive for markets at local or global scale, or they may have fewer choices for technology developers or providers through the monopolization of the industry. Furthermore, the potential backlash from consumers or tourists, in the case of the Lake Constance region and other agro-tourism areas, further complicates the decision for or against adoption. At the same time, digital technologies for fruit cultivation were not found to be suitable for the interests and abilities of the stakeholders in this region, excluding them from participating fairly in the transformation. Thus, the way forward must be a re-focusing of the goals of digitalization through reflection of the presented opportunities, risks, and uncertainties, as well as the urgency of sustainability challenges today. This refocusing must additionally take other options, perhaps combinations, of tactics into account to remain competitive, sustainable, and retain tradition/cultural landscape values.

9.2 Recommendations

In order for digital technologies in fruit cultivation to actively contribute to improved sustainability, I have drawn a number of conclusions from the results, which I have communicated in the form of recommendations. The articles within this dissertation each include recommendations based on the respective results and article contexts. A summative section specific to policy implications can be found in the conclusion chapter. The synergized suggestions across all three articles are as follows:

1. To avoid the marginalization of actors along the fruit value chain through exclusion from the digital transformation, technology development for fruit cultivation must be more user-oriented by considering the barriers, risks, and opportunities perceived by the intended users. This includes region-specific requirements, such as the technical support language and physical barriers such as small land parcels in the Lake Constance region compared to other German fruit cultivation areas. Of equal importance, trainings on the use of digital technologies for operators such as farmers would enable informed decision making for or regarding adoption, reduce the knowledge barrier for those intending to adopt the technologies, and ensure longevity of use (and therefore sustainability of the products and methods) among adopters.

2. Foundational knowledge of both agricultural production and digitalization in agriculture must be improved. This could function to lessen or even eradicate myths surrounding agricultural production that may be the cause of tensions between farmers and consumers and to demystify digitalization for users and the public. As highlighted in article 3 (Chapter 8), improving the foundational knowledge of agriculture alone may not impact the societal acceptance or public opinion towards fruit farming, but using digitalization to showcase how

fruit farmers are listening to the publics concerns and taking measures to adapt to challenges may create a positive impact.

3. While the majority of stakeholders were optimistic that digital technologies could mitigate the numerous sustainability challenges in fruit cultivation, known risks and existing barriers imply that alternative and hybrid solutions to digitalization may be more suitable and allow for more resilience for the users and therefore the agricultural system.

These recommendations and their implications, as well as suggestions for further research, will be discussed and expanded upon in the following sections.

9.2.1 Communication and knowledge

Improved communication to all actors on digitalization in the context of agriculture must be supported, as the current general knowledge level is deficient. This was evident in the interviews and the surrounding scientific literature: a common understanding of digitalization in fruit production among stakeholders did not exist and various terms related to digitalization were used synonymously. Digitalization in agriculture has been notoriously challenging to define, as numerous terms have emerged to explain the different forms of digitalized agricultural systems (Klerkx et al., 2019). While the variations in interpretations provided valuable insights for this study regarding stakeholder knowledge levels, they also suggest a need to disambiguate the term ‘digitalization’ for all potential users within this sector and for the general public. By reducing the number of terms used and prioritizing consistent, factual reporting on how digitalization is used in agriculture, including opportunities and risks, tensions between the public and farmers caused by misunderstandings or deficient knowledge can also be eased.

The findings, particularly in article 3 (Chapter 8), suggest that the described impact on public opinion may depend on the storyline around the use of digital technologies and its effects. The potential for digitalization to improve environmental or social conditions of fruit farming could support the societal acceptance of digital technology use in farming. Thus, fact-based, simplified, and digestible media coverage on the use of digitalization in fruit cultivation, showcasing farmers and their consideration of the various sustainability challenges through, for instance, the use of digitalized technologies, could be an opportunity to improve societal acceptance of fruit cultivation methods. Studies by Saleh et al. (2024) and Hueppe and Zander (2024) also concluded that public acceptance (of plant protection measures applied by farmers and of purchasing imperfect fruit, respectively) may be increased by direct communication to the consumers and public about the positive sustainability impact of these actions. At the same time, digitalization itself should prioritize building trust between farmers and consumers and honest communication regarding fruit production. Direct engagement with the public could be more successful than education strategies in mitigating public concerns, such as two-way communication between public and farmer (as recommended in Chapter 8) that could build trust, increase agricultural knowledge, and decrease tensions, potentially leading to related trickle-down effects like improved price politics.

Improving foundational knowledge on digitalization for farmers is a critical next step in the progression of the digital transformation of agriculture. Quality and access to information for intended users regarding the existing, available tools must be improved to enable informed decision making with regards to adoption. Inequalities and access to digital technologies were perceived in regards to farmer and farm labourer knowledge levels. Specifically, lack of digital knowledge (and the associated fear, for instance among the older generation of farmers) and the steep learning curve when adopting new technologies were described to be significant barriers to adoption. Martens and Zscheischler (2022) reference the ways in which governments describe digitalization to be at a development stage with digitally literate farmers with access to functioning infrastructure, while in reality, actors applying the new technologies are still establishing the necessary conditions for implementation (Higgins & Bryant, 2020). It is known that digital literacy increases the likelihood that farmers adopt technologies (Michels et al., 2020a). Additionally, research has shown that German farmers are willing to pay for digitalization training courses (Michels et al., 2019). Still, 43% of farmers in Germany have not taken part in trainings on digitalization in agriculture but are interested, according to a representative survey of German farmers (Rohleder & Meinel, 2024). The smallest farm size cohort in the study had the greatest resistance to training: 41% have not taken part in and are not interested (Rohleder & Meinel, 2024). This implies that additional efforts must be taken to make trainings for farmers of all farm sizes accessible so to reduce external barriers. Furthermore, neutral and non-biased parties, such as public research or non-profit organizations, rather than technology development companies who have a financial interest in adoption rates, should supply trainings.

9.2.2 Further research

Chapters 6-8 provide recommendations for future research initiatives based on the contexts of each article. These include conducting studies with representative sample sizes of fruit farmers and other stakeholders; research on the potential for digitalization to bridge the existing gaps in sustainability challenges between farm sizes and production systems; and research to explore if specific capabilities of digitalization, such as automation, rather than digitalization of fruit production as a whole may impact public opinion on fruit cultivation. Based on the results of this dissertation, I believe one recommendation for future research to be the most relevant in the overall context of the work. Specifically, further participatory research and cooperation between users and developers in the fruit value chain was encouraged in the conclusions of article 1 (Chapter 6) to amend the discrepancies between expectations of digital technologies in fruit production and the reality, improving the usability of the tools.

To this end, future research with a more transdisciplinary, transformative, solution-oriented approach that engages a variety of actors and the public could satisfy a number of the recommendations of this dissertation. Transdisciplinary projects for digitalization in German agriculture have been conducted before, such as the previously described transdisciplinary project by Zscheischler et al., (2022), which was able to look beyond individual technologies and instead at the digital transformation of agriculture as a whole. Still, to the best of my knowledge, such projects do not yet exist for the German fruit cultivation sector. The research conducted in the context of this dissertation was qualitative, empirical, descriptive-analytical research within the setting of sustainability research. Aspects of this work transcended disciplinary borders, such as the selection of interviewed stakeholders, and the related work conducted in the DESIRA project (described in Chapter 3) included transdisciplinary, transformative research approaches. Transdisciplinarity has been defined by Lang et al. (2012, p.26) as "a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge." The discourse around transdisciplinarity confirms that its concepts are appropriate for understanding the complexity associated with transformational change (Bergmann, 2021; Horcea-Milcu et al., 2020; Marshall et al., 2018). Transdisciplinarity is used in research to address knowledge demands for complex problems in society (Hirsch Hadorn et al., 2006). Since the notion of transdisciplinary research (TDR) first emerged, its advantages have been praised in relation to solving complex real-world challenges (Zscheischler & Rogga, 2015). One particularly relevant praise is the improvement in stakeholders' ability to make decisions (Walter et al., 2007; Zscheischler & Rogga, 2015).

Transformative sustainability research (TSR) approaches could take the sustainability science research conducted within this dissertation from descriptive-analytical to transformational, as described in section 4.1, which aims to transform problems towards solutions that are real-world changes depending on actions executed by non-research stakeholders (Wiek & Lang, 2016). Complementing descriptive-analytical research that is problem-oriented with research that is solution-oriented could enhance sustainability science's contribution to addressing pressing sustainability issues (Lang & Wiek, 2022). Specifically, an 'in-situ and engaging' solution-oriented sustainability research approach (Lang & Wiek, 2022) such as real-world labs (RWL) (Schäpke et al. 2018), in which scientists and potential implementers collaborate on experiments to test solution options, would be a suitable approach to take the results of this work a step further. RWLs aim to contribute to sustainability transformations and provide a particular setting for experiments in time, local, resources, and relationships (Bergmann et al., 2021). Enabling a mutual learning experience between actors could tackle a number of the recommendations in this work. For instance, collaborative research and experimentation would assist in the issues related to digital literacy and could enable greater empowerment and informed decision making for potential users of the technologies. Settings such as a RWL for digitalization in fruit cultivation could additionally allow for testing the feasibility of the concepts, such as recommendations for digital technology characteristics in Chapter 6. Exchange between relevant actors such as users and designers could enable a more user-oriented design of technologies as well as building trust between actors and actor groups.

9.2.3 Alternative and hybrid solutions for a sustainable digital transformation

A critical outcome of the results, fortified by the previous critical appraisal section in this discussion, is that digital technologies should not be seen as a panacea (Townsend et al., 2019). Farming systems cannot rely solely on the use of digital tools to address sustainability concerns; they also need to take into account a variety of other strategies. In the same way, the adoption of digital technologies alone is not the only strategy for modernizing agriculture.

Digital technologies can be combined with current techniques to produce hybrid skills that blend digital and analogue abilities (Burton & Riley, 2018). The term *hybrid intelligence* by Berger et al. (2024, p.19) comes to mind: “when people and computer systems interact with each other and their respective strengths are used in a complementary way.” A distribution of agri-food tasks between robots and humans has been suggested as the most acceptable and fair method to realize societal goals and respond to modern challenges (van der Burg et al., 2024). Focusing political and financial efforts on the development and adoption of alternative digital tools such as hybrid models may be a valuable strategy to mitigate sustainability challenges in fruit production while avoiding the recognized risks associated with digitalization. Prause and Egger (2023) describe other suitable alternative digital tools to include digitally-enabled direct marketing, digitally-supported community supported agriculture (CSA), digital platforms that are open-source to avoid power lock-ins, and small-scale robotics to alleviate labourers from monotonous tasks and thus make farm labour more appealing.

At the same time, social innovations developed in close relation to technological innovations in food production have emerged as a technological niche system in recent years (Prause & Egger, 2023). Social innovations can be defined as any new approach to a social issue that is more equitable, sustainable, efficient, or effective than current approaches and that primarily benefits society as a whole rather than individual people (Phills et al., 2008; Zu, 2013). Social innovations are a powerful tool to connect producers and consumers without intermediaries, which could build trust between these parties (da Silva et al., 2024). These tools that focus on the collaboration, capacity building, and empowerment of farmers should therefore also be accessible considering the discussed barriers to adoption, such as cost and language. In this way, hybrid intelligence between social and technological innovations may also be a solution to the urgent issue of societal acceptance in fruit cultivation and agriculture as a sector.

Hybrid intelligence may be a promising approach to solving a number of the urgent sustainability challenges in fruit cultivation, while retaining some of the values that are at risk in the digital transformation, such as farmer autonomy and equal power distributions. The expressed concern over labour availability due to unappealing physical labour and lack of regional farm labourers (article 2) was discussed with optimism regarding the possibilities that automated farm machinery could offer in making work more accessible for a wider scope of potential labourers, such as people with mental or physical disabilities, therefore increasing local job opportunities. Digital platforms, AI-based recommendations, and semi-automatic robots can also enable optimisation and information dissemination, which could allow for people without formal education in the sector to engage in agriculture (Prause & Egger, 2023). Furthermore, hybrid solutions create less reliance on digital technologies, therefore retaining more levelled power balances between the farmer and the technology companies, ultimately allowing for greater resilience of the system when compared to fully-digitalized agricultural systems.

Nevertheless, even with alternative or hybrid approaches to the digital transformation in agriculture, risks as discussed in the critical appraisal are still possible. We should not lose sight of the goal of digitalization in agriculture, which must be re-prioritized from efficiency and productivity gains towards mitigating the most urgent sustainability challenges. Solutions to complex sustainability problems are not simple technical fixes, nor are they quick fixes, particularly regarding the socio-economic sustainability challenges related to values and acceptance. Lasting changes in values is slow and is a result of other changes in the environment, considering that it comes from new behaviours rather than preceding them (Horcea-Milcu et al., 2019; Manfredo et al., 2017).

10. Conclusion

Digital technologies have the potential to positively contribute to the complex and urgent sustainability challenges in fruit cultivation, according to the majority of stakeholders in the Lake Constance region. Simultaneously, digitalization poses serious threats to the environmental and especially the socio-economic and socio-cultural sustainability of fruit cultivation, particularly in small-scale fruit landscapes such as the case study region. Using digitalization to solve sustainability challenges may worsen the issues, such as a potential reduction in societal acceptance of both conventional and organic production methods through increased transparency or deepened power imbalances between agri-corporations and farmers. On a socio-economic level, risks seem to outweigh opportunities for digitalization in fruit cultivation. At the same time, a gap between potential benefits, risks, and empirical observations exists for digitalization in German fruit cultivation. With consideration of the economic and cultural roles that fruit production systems play in German agriculture and the case study region, it is critical to regard these issues during the digital transformation of agriculture. As digitalization progresses, necessary steps are required in order to enable a sustainable, fair transformation for all sectors, including fruit cultivation. I encourage a refocusing of the priorities and goals of digitalization from technology-push driven to market-pull, considering the needs and abilities of users. The refocusing must place the farmers and other users along the value chain at the center, rather than the interests of political bodies or technology developers. Technological development must prioritize suitable technologies for fruit cultivation that consider barriers, abilities, production system, and farm size, as well as opportunities for alternative and hybrid solutions. These developments should focus on mitigating the urgent sustainability challenges and be cautious to not perpetuate unsustainable paradigms related to inequality or increased productivity and efficiency. Further collaborative and transdisciplinary research methods would enable farmer autonomy and empowerment, improve sustainability, and create a more user-oriented digital transformation. Finally, these tactics must be coupled with a factual narrative around the use of digital technologies in agriculture to both the users and to the public, prioritizing building trust towards farmers.

The current political framework lacks adequate strategies to support sustainability challenges facing fruit cultivation in the digital transformation. All agricultural sectors must have support systems in place to reduce the risk of a sectoral digital divide. Therefore, I have provided a categorized summary of the policy recommendations based on the outcomes of this dissertation.

10.1 Policy implications: knowledge and capacity building

Providing intended users, particularly farmers, with capacity building measures such as trainings for digital technology use must be a top priority for policy makers. Additional efforts must be taken to make trainings for farmers of all farm sizes accessible in order to reduce external barriers. Capacity building efforts are also encouraged through knowledge transfer and communication: with the progression of digitalization in agriculture, digital literacy should be improved in the general public to foster understanding of modern agricultural production processes, rather than increase the existing knowledge gap between consumers and food production. Communication, including at the governmental level, should focus on fact-based, simplified, and digestible information on the use of digitalization in fruit cultivation and agriculture in general.

10.2 Policy implications: research and development

To lessen disparities in development and adoption, government policies must financially support user investment and development initiatives for the fruit sector. This support should specifically target small farms and share efforts equally across IP and organic production systems, taking into account the documented variances in barriers to adoption according to farm size and production system. Technology design that specifically addresses the needs and capacities of small fruit farms, such as those in the Lake Constance region, is necessary to reduce the differences in opportunities and challenges based on farm size in digitalized fruit farming and must be supported by policy. Examples of these needs include non-exclusive market policies and cost-effective technical solutions. Agriculture policy and financing frameworks, inclusive of targeted research programs, must offer equal attention to environmental and socio-economic concerns, as the latter, particularly related to digitalization, are not adequately addressed despite their abundance and complexity. I encourage national funding programs to further investigate the interface between fruit production, digitalization, and sustainability, in particular through transdisciplinary research approaches. Additionally, targeted research and development of alternative digital solutions, such as hybrid solutions that prioritize maintaining or even improving the knowledge, skills, autonomy, and/or well-being of the user, should be supported by policy frameworks. These solutions enable increased resilience to the threats of digitalization.

11. References

Abadi Ghadim, A., & Pannell, D. J. (1999). A conceptual framework of adoption of an agricultural innovation. *Agricultural Economics*, *21*(2), 145–154. https://doi.org/10.1016/s0169-5150(99)00023-7

Adarsch, A., Pranav, P. M., Manjunath, C. R., & Soumya, K. N. (2018). Fruit farm surveillance using drones. *International Journal of Trend in Scientific Research and Development*, *2*(4), 351–357. https://doi.org/10.31142/ijtsrd12973

Arvanitis, K. G., & Symeonaki, E. G. (2020). Agriculture 4.0: The role of innovative smart technologies towards sustainable farm management. *The Open Agriculture Journal*, *14*(1), 130–135. https://doi.org/10.2174/1874331502014010130

Ayris, K., Jackman, A., Mauchline, A., & Rose, D. C. (2024). Exploring inclusion in UK agricultural robotics development: Who, how, and why? *Agriculture and Human Values*, *0123456789*. https://doi.org/10.1007/s10460-024-10555-6

Bacco, M., Brunori, G., Ferrari, A., Koltsida, P., & Toli, E. (2020). IoT as a Digital Game Changer in rural areas: The DESIRA conceptual approach. *GIoTS 2020 - Global Internet of Things Summit, Proceedings*, 0–5. https://doi.org/10.1109/GIOTS49054.2020.9119674

Baeten, J., Donné, K., Boedrij, S., Beckers, W., & Claesen, E. (2008). Autonomous fruit picking machine: A robotic apple harvester. In Laugier, C., Siegwart, R. (Eds.), *Field and service robotics. Springer Tracts in Advanced Robotics: Vol. 42.* (pp. 531–539). Springer. https://doi.org/10.1007/978-3-540-75404-6_51

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Van Der Wal, T., Soto, I., Gómez-Barbero, M., Barnes, A., & Eory, V. (2017). Precision agriculture technologies positively contributing to ghg emissions mitigation, farm productivity and economics. *Sustainability (Switzerland)*, *9*(8), 1–28. https://doi.org/10.3390/su9081339

Bannier, H.-J., & Naturschutzbund Deutschland. (n.d.). *Erziehung muss sein: Der richtige Schnitt von Obstbäumen auf der Streuobstwiese*. Pflege und Bewirtschaftung. Retrieved July 22, 2024, from https://www.nabu.de/natur-und-landschaft/landnutzung/streuobst/pflege/04617.html

Barbole, D. K., Jadhav, P. M., & Patil, S. B. (2022). A review on fruit detection and segmentation techniques in agricultural field. In Chen, J.IZ., Tavares, J.M.R.S., Iliyasu, A.M., Du, KL. (Eds.), *Second international conference on image processing and capsule networks (ICIPCN 2021). Lecture Notes in Networks and Systems: Vol 300.* Springer.

Barnes, A., De Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T., & Gómez-Barbero, M. (2019). Influencing factors and incentives on the intention to adopt precision agricultural technologies within arable farming systems. *Environmental Science and Policy*, *93*(January), 66–74. https://doi.org/10.1016/j.envsci.2018.12.014

Barth, M., Gossen, M., Lang, D. J., & Santarius, T. (2023). Sustainable digitalization – fostering the twin transformation in a transdisciplinary way. *GAIA - Ecological Perspectives for Science and Society*, *32*, 6–9. https://doi.org/10.14512/gaia.32.S1.3

Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, *3*(4), 254–256. https://doi.org/10.1038/s41893-020-0510-0

Batte, M. T., & Ehsani, M. R. (2006). The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. *Computers and Electronics in Agriculture*, *53*(1), 28–44. https://doi.org/10.1016/j.compag.2006.03.004

Bayerisches Landesamt für Statistik. (2016). Landwirtschaftaliche Betriebe mit ökologischem Landbau in Bayern 2016. In *Statistische Berichte* (Issue August). www.statistik.bayern.de

Bayerisches Landesamt für Statistik. (2018). *Baumobstflächen und -bestände in Bayern 2017*. https://www.statistik.bayern.de/mam/produkte/veroffentlichungen/statistische_berichte/c1800c_201751_16735.pdf

Bayerisches Landesamt für Statistik. (2022). *Landkreis Lindau (Bodensee)*. https://www.statistik.bayern.de/mam/produkte/statistik_kommunal/2021/09776.pdf

Berger, T., Bieling, C., Beck, S., & Birner, R. (2024). Kollektive menschliche und kunstliche lntelligenz in Landwirtschaft und landlichen Raumen. *Ländliche Räume*, 18–20. https://www.asg-goe.de/pdf/LR224.pdf

Bergmann, M. (2021). Ein Projekt beginnen: Konzeptionelle und methodische Hinweise für transdisziplinäre Forschung in Gesundheitsförderung und Prävention. In Niederberger, M. Finne, E. (Eds.), *Forschungsmethoden in der Gesundheitsförderung und Prävention* (pp. 781–809). Springer Nature. https://link.springer.com/book/10.1007/978-3-658-31434-7

Bergmann, M., Schäpke, N., Marg, O., Stelzer, F., Lang, D. J., Bossert, M., Gantert, M., Häußler, E., Marquardt, E., Piontek, F. M., Potthast, T., Rhodius, R., Rudolph, M., Ruddat, M., Seebacher, A., & Sußmann, N. (2021). Transdisciplinary sustainability research in real-world labs: Success factors and methods for change. *Sustainability Science*, *16*(2), 541–564. https://doi.org/10.1007/s11625-020-00886-8

Bijker, W. E., & Pinch, T. J. (1984). The social construction of facts and artefacts: Or how the sociology of science and the sociology of technology might benefit each other. *Social Studies of Science*, *14*(3), 399-441. https://doi.org/10.1177/030631284014003004

Binici, T., Zulauf, C. R., Kacira, O. O., & Karli, B. (2006). Assessing the efficiency of cotton production on the Harran Plain, Turkey. *Outlook on Agriculture*, *35*(3), 227–232. https://doi.org/10.5367/000000006778536729

Birner, R., Daum, T., & Pray, C. (2021). Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Applied Economic Perspectives and Policy*, *43*(4), 1–26. https://doi.org/10.1002/aepp.13145

Bitkom. (2019). *Landwirte bringen digitalen Fortschritt in den ländlichen Raum*. Bitkom e.V. https://www.bitkom.org/Presse/Presseinformation/Landwirte-bringen-digitalen-Fortschritt-den-laendlichen-Raum

Bode, J. (1997). Der Informationsbegriff in der Betriebswirtschaflslehre. *Schmalenbachs Zeitschrift für Betriebswirtschaftliche Forschung: ZfbF*, *49*(5), 449–468.

Bodensee-Stiftung. (2013). *Zukunftsfähiger Bodensee: Jahresbericht 2013*. https://www.bodensee-stiftung.org/wp-content/uploads/BoSti_Jahresbericht_13_0.pdf

Bodensee-Wasserversorgung. (2022). *Trinkwasseranalyse 2022*. https://www.bodensee-wasserversorgung.de/fileadmin/user_upload/Trinkwasseranalyse_2022.pdf

Bodensee.de. (n.d.). *Die Anbaugebiete*. Erlebt den Bodensee. Retrieved July 15, 2024, from https://www.bodensee.de/erleben/genuss/die-anbaugebiete

Bogoeski, V. (2022). Continuities of exploitation: Seasonal migrant workers in German agriculture during the COVID-19 pandemic. *Journal of Law and Society*, *49*(4), 681–702. https://doi.org/10.1111/jols.12389

Bronson, K., & Sengers, P. (2022). Big tech meets big ag: Diversifying epistemologies of data and power. *Science as Culture*, *31*(1), 15–28. https://doi.org/10.1080/09505431.2021.1986692

Brundtland, G. H. (1987). *Report of the world commission on environment and development: Our common future.* United Nations. https://doi.org/10.4324/9781351279086-15

Bund für Umwelt und Naturschutz Deutschland. (n.d.). *Geschichte des Streuobstanbaus*. Retrieved May 17, 2024, from https://www.bund-friedrichshafen.de/themenprojekte/streuobstgartenweilermuehle/lehrpfad/geschichte-des-streuobstanbaus/

Bundesamt für Kartographie und Geodäsie. (2021). *Dokumentation VK2500-LRK und VK2500-L*. https://sg.geodatenzentrum.de/public/gdz/dokumentation/deu/vk2500.pdf

Bundesanstalt für Landwirtschaft und Ernährung. (n.d.). *Vermarktungsnormen für frisches Obst und Gemüse*. Ernährung und Lebensmittel. https://www.ble.de/DE/Themen/Ernaehrung-Lebensmittel/Vermarktungsnormen/Obst-Gemuese/obst-gemuese_node.html

Bundesanstalt für Landwirtschaft und Ernährung. (2017). *Vermarktung*. Landwirtschaft. https://www.oekolandbau.de/landwirtschaft/pflanze/spezieller-pflanzenbau/obstbau/grundlagen-kern-und-steinobst/vermarktung/

Bundesinformationszentrum Landwirtschaft (2020). *Wie viele landwirtschaftliche Betriebe gibt es in Deutschland?* Bundesinformationszentrum Landwirtschaft. Bundesanstalt für Landwirtschaft und Ernährung. https://www.praxis-agrar.de/service/infografiken/wie-viele-landwirtschaftliche-betriebe-gibt-es-in-deutschland?sword_list%5B0%5D=Anzahl&sword_list%5B1%5D=und&sword_list%5B2%5D=größe&sword_list%5B3%5D=landwirtschaftlicher&sword_list%5B4%5D=betriebe&sword_l

Bundesinformationszentrum Landwirtschaft. (2024). *Warum benötigt die Landwirtschaft so viele ausländische Saisonarbeitskräfte?* Bundesanstalt für Landwirtschaft und Ernährung. https://www.landwirtschaft.de/wirtschaft/beruf-und-betrieb/landwirtschaft-als-beruf/warum-benoetigt-die-landwirtschaft-so-viele-auslaendische-saisonarbeitskraefte

Bundesministerium für Bildung und Forschung. (2015). *Apfel ist nicht gleich Apfel: ökologische & soziale Auswirkungen von Äpfeln, unter Berücksichtigung unterschiedlicher Anbaumethoden*. https://wupperinst.org/fa/redaktion/downloads/projects/Mundraub_Apfel_Factsheet.pdf

Bundesministerium für Ernährung und Landwirtschaft. (2016). *Der Gartenbau in Deutschland: Auswertung des Gartenbaumoduls der Agrarstrukturerhebung 2016*. https://www.bmel.de/SharedDocs/Downloads/Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile

Bundesministerium für Ernährung und Landwirtschaft. (2019a). *69. Anbau, Ertrag und Ernte von Obst* (Table Number 3081400-0000)[Data set]. Bundesanstalt für Landwirtschaft und Ernährung (BLE). https://www.bmel-statistik.de/fileadmin/daten/3081400-0000.xlsx

Bundesministerium für Ernährung und Landwirtschaft. (2019b). *Verwendung der Obsternte* (Table Number 3081500-0000)[Data set]. Bundesanstalt für Landwirtschaft und Ernährung (BLE). https://www.bmel-statistik.de/fileadmin/daten/3081500-0000.xlsx

Bundesministerium für Ernährung und Landwirtschaft. (2020). *Landwirtschaftliche Arbeitskräfte*. https://www.bmel-statistik.de/landwirtschaft/landwirtschaftliche-arbeitskraefte

Bundesministerium für Ernährung und Landwirtschaft. (2022). *Organic Farming in Germany*. http://www.bmelv.de/SharedDocs/Downloads/EN/Agriculture/OrganicFarming/Organic-Farming-in-Germany.pdf?__blob=publicationFile

Burton, R. J. F., & Riley, M. (2018). Traditional Ecological Knowledge from the internet? The case of hay meadows in Europe. *Land Use Policy*, *70*, 334–346. https://doi.org/10.1016/j.landusepol.2017.10.014

Busse, M., Doernberg, A., Siebert, R., Kuntosch, A., Schwerdtner, W., König, B., & Bokelmann, W. (2014). Innovation mechanisms in German precision farming. *Precision Agriculture*, *15*(4), 403–426. https://doi.org/10.1007/s11119-013-9337-2

Butler, D., & Holloway, L. (2016). Technology and restructuring the social field of dairy farming: Hybrid capitals, ‘stockmanship’ and automatic milking systems. *Sociologia Ruralis*, *56*(4), 513–530. https://doi.org/10.1111/soru.12103

Carolan, M. (2017). Publicising food: Big data, precision agriculture, and co-experimental techniques of addition. *Sociologia Ruralis*, *57*(2), 135–154. https://doi.org/10.1111/soru.12120

Carolan, M. (2019). Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture. *The Journal of Peasant Studies*, *47*(1), 184–207. https://doi.org/10.1080/03066150.2019.1584189

Chemnitz, C., Wenz, K., & Haffmans, S. (2022). *Pestizidatlas 2022: Daten und Fakten zu Giften in der Landwirtschaft*. Heinrich-Böll-Stiftung. https://www.boell.de/de/2022/01/04/pestizidatlas

Chiles, R. M., Broad, G., Gagnon, M., Negowetti, N., Glenna, L., Griffin, M. A. M., Tami-Barrera, L., Baker, S., & Beck, K. (2021). Democratizing ownership and participation in the 4th Industrial Revolution: challenges and opportunities in cellular agriculture. *Agriculture and Human Values*, *38*(4), 943–961. https://doi.org/10.1007/s10460-021-10237-7

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., Grimm, N. B., Grove, J. M., Harlan, S. L., Kaye, J. P., Knapp, A. K., Kofinas, G. P., Magnuson, J. J., McDowell, W. H., Melack, J. M., Ogden, L. A., Robertson, G. P., Smith, M. D., & Whitmer, A. C. (2011). An integrated conceptual framework for long-term social-ecological research. *Frontiers in Ecology and the Environment*, *9*(6), 351–357. https://doi.org/https://doi.org/10.1890/100068

Coroama, V. C., & Pargman, D. (2020). Skill rebound: On an unintended effect of digitalization. *ACM International Conference Proceeding Series*, 213–219. https://doi.org/10.1145/3401335.3401362

Cravotta, S., & Grottke, M. (2019). Digitalization in German family firms – some preliminary insights. *Journal of Evolutionary Studies in Business*, *4*(1), 1–25. https://doi.org/10.1344/jesb2019.1.j051

Crosson, P. R. (1992). Sustainable Agriculture. *Resources for the Future*, *106*, 14–17. https://www.cabidigitallibrary.org/doi/full/10.5555/19921800966

Cuadros-Casanova, I., Cristiano, A., Biancolini, D., Cimatti, M., Sessa, A. A., Mendez Angarita, V. Y., Dragonetti, C., Pacifici, M., Rondinini, C., & Di Marco, M. (2023). Opportunities and challenges for Common Agricultural Policy reform to support the European Green Deal. *Conservation Biology*, *37*(3), e14052. https://doi.org/10.1111/cobi.14052

da Silva, A. L. F., Plaza-Úbeda, J. A., & Souza Piao, R. (2024). Social innovation as a game changer in agriculture: A literature review. *Sustainable Development*, *32*(4), 4160-4171. https://doi.org/10.1002/sd.2898

Dara, R., Hazrati Fard, S. M., & Kaur, J. (2022). Recommendations for ethical and responsible use of artificial intelligence in digital agriculture. *Frontiers in Artificial Intelligence*, *5*, 884192. https://doi.org/10.3389/frai.2022.884192

Das Grüne Lexikon Hortipendium. (2021). *Gemüseanbau: Bio oder Konventionell*. Retrieved February 20, 2024, from https://hortipendium.de/Gemüseanbau:_Bio_oder_Konventionell

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly: Management Information Systems*, *13*(3), 319–339. https://doi.org/10.2307/249008

Davis, F. D. (1993). User acceptance of information technology: system characteristics, user perceptions and behavioral impacts. *International Journal of Man-Machine Studies*, 38(3), 475–487). https://doi.org/10.1006/imms.1993.1022

De Clerqu, M., Vats, A., & Biel, A. (2018). *Agriculture 4.0: The Future of Farming Technology*. World Government Summit. https://www.worldgovernmentsummit.org/api/publications/document?id=95df8ac4-e97c-6578-b2f8-ff0000a7ddb6%0Ahttps://www.oliverwyman.com/content/dam/oliver-wyman/v2/publications/2021/apr/agriculture-4-0-the-future-of-farming-technology.pdf

Degieter, M., De Steur, H., Tran, D., Gellynck, X., & Schouteten, J. J. (2023). Farmers' acceptance of robotics and unmanned aerial vehicles: A systematic review. *Agronomy Journal*, *115*(5), 2159–2173. https://doi.org/10.1002/agj2.21427

Deichmann, U., Goya, A., & Mishr, D. (2016). *Will digital technologies transform agriculture in developing countries?* (Working Paper No. 7669). World Bank Group. https://hvtc.edu.vn/Portals/0/files/636104758652860273WillDigitalTechnologiesTransformAgricultureinDevelopingCountries.pdf

Del Río Castro, G., González Fernández, M. C., & Uruburu Colsa, Á. (2021). Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review. *Journal of Cleaner Production*, *280*, 122204. https://doi.org/10.1016/j.jclepro.2020.122204

DESIRA. (2019). *About DESIRA*. https://desira2020.agr.unipi.it/the-project/

Deutsches Landwirtschafts-Gesellschaft, Mücke, M., & Kreikenbohm, C. (2022). *Mechanical weed control: practical concepts for root crops* (DLG Expert Knowledge Series No. 475). Deutsches Landwirtschafts-Gesellschaft. https://www.dlg.org/en/mediacenter/dlg-expert-knowledge/dlg-expert-knowledge-475-mechanical-weed-control-practical-concepts-for-root-crops

Dienstleistungszentrum Ländlicher Raum Rheinpfalz. (2016). *Ernährung der Obstgehölze.* Abteilung Gartenbau, Dienstleistungszentrum Ländlicher Raum Rheinpfalz. https://www.obstbau.rlp.de/Internet/global/Themen.nsf/7f97e4b4b5935b96c12582580050d7a5/4c6d17627bb7e036c1256f56004d5604/$FILE/Ern%C3%A4hrung%20Obst.pdf

Dierend, W. (2009). *Kulturschutzeinrichtungen im Obstbau*. Ulmer. https://www.ulmer.de/usd-1557230/kulturschutzeinrichtungen-im-obstbau-.html

Diesner, M.-O., Groß, R., Helbich, M., Blepp, M., Bäuerle, P., & Bunke, D. (2014). *Kupfer im Bio-Landbau: Hintergrund, Herausforderungen und Handlungsempfehlungen.* Öko-Institut e.V. https://www.oeko.de/publikation/kupfer-im-bio-landbau-hintergrund-herausforderungen-und-handlungsempfehlungen/

Dillon, A., & Morris, M. G. (1996). User acceptance of information technology: Theories and models. *Annual Review of Information Science and Technology*, *31*, 3–32. https://www.learntechlib.org/p/82513/

Dirksmeyer, W., & Garming, H. (2024, June 28). *Horticulture*. Johann Heinrich von Thünen Institute. https://www.thuenen.de/en/thuenen-topics/plant-production/horticulture

Dirksmeyer, W., & Garming, H.. (2022, June 17). *Cultivated areas for soft fruit and protected fruit growing are steadily increasing*. Johann Heinrich von Thünen Institute. https://www.thuenen.de/en/thuenen-topics/plant-production/horticulture/cultivated-areas-for-soft-fruit-and-protected-fruit-growing-are-steadily-increasing

DLG e.V., & Griepentrog, H. W. (2019). *Digitalisierung in der Landwirtschaft* (Report No. 447). Deutsche Landwirtschafts-Gesellschaft. https://www.dlg.org/mediacenter/dlg-merkblaetter/dlg-merkblatt-447-digitalisierung-in-der-landwirtschaft

Dubey, A. (2024, July 5). *Sustainable Agriculture*. The Encyclopedia Britannica. https://www.britannica.com/technology/sustainable-agriculture

Duncan, D. W., & Broyles, T. W. (2006). A comparison of student knowledge and perceptions toward agriculture before and after attending a Govenor's school for agriculture. *NACTA Journal, 50,* 16–21.

Eastwood, C. R., Chapman, D. F., & Paine, M. S. (2012). Networks of practice for co-construction of agricultural decision support systems: Case studies of precision dairy farms in Australia. *Agricultural Systems, 108*, 10-18. https://doi.org/10.1016/j.agsy.2011.12.005

Ebel, R. (2020). Are small farms sustainable by nature?- Review of an ongoing misunderstanding in agroecology. *Challenges in Sustainability*, *8*(1), 17–29. https://doi.org/10.12924/cis2020.08010017

Ebel, R., Méndez Aguilar, M. de J., & Putnam, H. (2018). Milpa: One sister got climate-sick. The impact of climate change on traditional maya farming systems. *International Journal of Sociology of Agriculture and Food*, *24*(2), 175–199.

Eben, A., & Herz, A. (2022). Online-Fachgespräch zum Thema „Biodiversität im Obstbau". *Journal Fur Kulturpflanzen*, *74*, 11–18. https://doi.org/10.5073/JfK.2022.01-02.02

El-Ramady, H. R., Domokos-Szabolcsy, É., Abdalla, N. A., Taha, H. S., & Fári, M. (2022). Postharvest management of fruits and vegetables storage. *Sustainable Agriculture Reviews*, *15,* 1–16. https://doi.org/10.1016/B978-0-12-822921-7.00001-5

Enders, J. C., & Groschke, A. (2017). Die Idee der Verantwortung als Voraussetzung für den Erfolg von BNE – Bildung für Nachhaltige Entwicklung im Spiegel von Verantwortungsethik und Handlungsfähigkeit bei Max Weber und Hans Jonas. In M. Brodowski (Ed.), *Bildung für Nachhaltige Entwicklung, Interdisziplinäre Perspektiven* (pp. 33–58). Logos Verlag Berlin.

Enders, J. C., & Groschke, A. (2018). Geschlechterverhältnisse im Digitalen: welche Denkanstöße, Kritiken und Potenziale ins Zentrum der Debatte gehören. In A. Höfner & V. Frick (Eds.), *Was Bits und Bäume verbindet: Digitalisierung nachhaltig gestalten* (pp. 94–96). oekom.

Eungoo, K., & Hwang, H.-J. (2021). Ethical conducts in qualitative research methodology: Participant observation and interview process. *Journal of Research and Publication Ethics*, *2*(2), 5–10. http://dx.doi.org/10.15722/jrpe.2.2.202109.5

European Parliament. (2012, September). *Sustainable Agriculture*. Directorate-General for Parliamentary Research Services, European Parliament. https://epthinktank.eu/2012/09/04/sustainable-agriculture/

FAO. (2019). *Agricultural Transformation: Policy and Institutional Experiences from Asia*. Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/server/api/core/bitstreams/3f2c4c5f-6b57-4f48-a391-6293817cc7a2/content

Ferrari, A., Bacco, M., Gaber, K., Jedlitschka, A., Hess, S., Kaipainen, J., Koltsida, P., Toli, E., & Brunori, G. (2022). Rethinking Sustainability Requirements: Drivers, Barriers and Impacts of Digitalisation in Rural Areas from the Viewpoint of Experts. *Information and Software Technology, 145*, 106816. https://doi.org/10.1016/j.infsof.2021.106816

Fishbein, M., & Azjen, I. (1975). *Belief, attitude, intention, and behaviour: an introduction to theory and research*. Addison-Wesley Publishing Co, Inc.

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach*. Pitman Publishing.

Gallardo, R. K., & Sauer, J. (2018). Adoption of Labor-Saving Technologies in Agriculture. *Annual Review of Resource Economics*, *10*, 185–206. https://doi.org/10.1146/annurev-resource-100517-023018

Gandorfer, M., Schleicher, S., Heuser, S., Pfeiffer, J., & Demmel, M. (2017). Landwirtschaft 4.0- Digitalisierung und ihre Herausforderungen. In G. Wendl (Ed.), *Ackerbau - technische Lösungen für die Zukunft. Landtechnische Jahrestagung am 21. November 2017 in Deggendorf* (pp. 9–19), Bayerische Landesanstalt für Landwirtschaft. https://www.lfl.bayern.de/mam/cms07/publikationen/daten/schriftenreihe/ackerbau-technische-loesungen-zukunft-landtechnische-jahrestagung-2017_lfl-schriftenreihe.pdf

Gardezi, M., Joshi, B., Rizzo, D. M., Ryan, M., Prutzer, E., Brugler, S., & Dadkhah, A. (2023). Artificial intelligence in farming: Challenges and opportunities for building trust. *Agronomy Journal*, 1-12. https://doi.org/10.1002/agj2.21353

Garming, H., Welling, M., & Rieck, K. (2024, June 28). *Trends in German fruit and vegetable cultivation*. Johann Heinrich von Thünen Institute. https://www.thuenen.de/en/thuenen-topics/plant-production/horticulture/trends-im-deutschen-obst-und-gemuesebau

Genuss Bayern. (2024). *Obst vom Bodensee*. Genuss Bayern. Retrieved April 12, 2024, from https://www.spezialitaetenland-bayern.de/spezialitaeten/obst-vom-bodensee/

German Federal Ministry for Food and Agriculture. (2020). *Corona-Paket der Bundesregierung: wichtige Hilfen für die Land- und Ernährungswirtschaft erreicht*. Pressemitteilungen. https://www.bmel.de/SharedDocs/Pressemitteilungen/2020/054-coronapaket-der-bundesregierung.html

Gkisakis, V., Lazzaro, M., Ortolani, L., & Sinoir, N. (2018, January 15). *Digital Revolution in Agriculture: Fitting for Agroecology?* Agricultural and Rural Convention. https://www.arc2020.eu/digital-revolution-agriculture-agroecological-approach/

Goldschmidt, E. E. (2013). The Evolution of Fruit Tree Productivity: A Review. *Economic Botany, 67*(1), 51–62. https://doi.org/10.1007/s12231-012-9219-y

Griepentrog, H. W. (2012). Zukünftige Entwicklungen im Precision Farming. *Landinfo,* 5, 11-14. https://www.researchgate.net/profile/Hans-W-Griepentrog/publication/251564790_Zukunftige_Entwicklungen_im_Precision_Farming/links/00b4952455954110c7000000/Zukuenftige-Entwicklungen-im-Precision-Farming.pdf

Griliches, Z. (1957). Hybrid corn: An exploration in the economics of technological change. *Econometrica, 25*(4), 501–522.

Grimminger, R., Krawutschke, M., & Berger, S. (2018). *Mehr Bio vom Bodensee durch Tradition und Innovation*. Landratsamt Bodenseekreis. https://www.bodenseekreis.de/fileadmin/03_umwelt_landnutzung/landwirtschaft/downloads/bio-musterregion/fb_musterregion_bodensee.pdf

Groher, T., Heitkämper, K., & Umstätter, C. (2020). Nutzung digitaler technologien in der schweizer landwirtschaft. *Agrarforschung Schweiz*, *11*(6), 59–67. https://doi.org/10.34776/afs11-59

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. (2011). *Global food losses and food waste- extent, causes, and prevention* (1st ed.). FAO. https://doi.org/10.4337/9781788975391

Haarlem, L. van. (2020). *The future of fruit farming- the impact of technological applications on work* (Thesis code YSS-81812)[Bachelor thesis, Waginengen University]. https://edepot.wur.nl/531601

Hackfort, S. (2021). Patterns of inequalities in digital agriculture: a systematic literature review. *Sustainability (Switzerland), 13*(22). https://doi.org/10.3390/su132212345

Hackfort, S. (2022). Digital technology and power in agriculture. Technology development, data valorization, and sustainability narratives in Germany. Conference paper for American Political Science Association (APSA) Annual Meeting and Exhibition in Montreal. https://preprints.apsanet.org/engage/api-gateway/apsa/assets/orp/resource/item/6347315b0322f3343048e25e/original/digital-technology-and-power-in-agriculture-technology-development-data-valorization-and-sustainability-narratives-in-germany.pdf

Hackfort, S. (2023). Unlocking sustainability? The power of corporate lock-ins and how they shape digital agriculture in Germany. *Journal of Rural Studies, 101*, 103065. https://doi.org/10.1016/j.jrurstud.2023.103065

Hammerl, M., & Trötschler, P. (2006). *Sustainable Agriculture at Lake Constance (Austria, Switzerland, Germany)*. Lake Constance Foundation. https://www.globalnature.org/bausteine.net/f/7967/SustainableagricultureatLakeConstance.pdf?f d=2

Harris, D. R., & Fuller, D. Q. (2014). Agriculture: Definition and overview. In C. Smith (Ed.), *Encyclopedia of Global Archaeology* (pp. 104-113). Springer. https://doi.org/10.1007/978-1-4419-0465-2

Herklots, G. & Perrott, B. (2024, July 20). *Horticulture.* The Encyclopedia Britannica. https://www.britannica.com/science/horticulture

Hicks, J. (1932). *The Theory of Wages* (1st ed.). Macmillan.

Hilbert, M. (2011). The end justifies the definition: the manifold outlooks on the digital divide and their practical usefulness for policy making. *Telecommunications Policy*, *35*, 715–736. https://doi.org/10.1016/j.telpol.2011.06.012

Hirsch-Kreinsen, H. (2016). Digitization of industrial work: development paths and prospects. *Journal for Labour Market Research*, *49*(1), 1–14. https://doi.org/10.1007/s12651-016-0200-6

Hirsch Hadorn, G., Bradley, D., Pohl, C., Rist, S., & Weismann, U. (2006). Implications of transdisciplinarity for sustainability research. *Ecological Economics*, *60*, 119–128. https://doi.org/10.1016/ j.ecolecon.2005. 12.002

Hoang, H. G. (2020). Determinants of the adoption of mobile phones for fruit marketing by Vietnamese farmers. *World Development Perspectives*, *17*, 100178. https://doi.org/10.1016/j.wdp.2020.100178

Horcea-Milcu, A. I., Abson, D. J., Apetrei, C. I., Duse, I. A., Freeth, R., Riechers, M., Lam, D. P. M., Dorninger, C., & Lang, D. J. (2019). Values in transformational sustainability science: four perspectives for change. *Sustainability Science*, *14*(5), 1425–1437. https://doi.org/10.1007/s11625-019-00656-1

Horcea-Milcu, A. I., Martín-López, B., Lam, D. P. M., & Lang, D. J. (2020). Research pathways to foster transformation: Linking sustainability science and social-ecological systems research. *Ecology and Society*, *25*(1), 13. https://doi.org/10.5751/ES-11332-250113

Huck, C., Gobrecht, A., Salou, T., Bellon-Maurel, V., & Loiseau, E. (2024). Environmental assessment of digitalisation in agriculture: a systematic review. *Journal of Cleaner Production*, *472*, 143369. https://doi.org/10.1016/j.jclepro.2024.143369

Hueppe, R., & Zander, K. (2024). Perfect apples or sustainable production?- Consumer perspectives from Germany. *Journal of Consumer Behaviour*, *23*(2), 698–710. https://doi.org/10.1002/cb.2236

Hyson, D. A. (2011). A comprehensive review of apples and apple components and their relationship to human health. *Advances in Nutrition*, *2*(5), 408–420. https://doi.org/10.3945/an.111.000513

Igo, C., Leising, J. G., & Frick, M. (1999). A case study assessment of standard benchmarks for implementing food and fiber systems literacy. In *Proceedings of the 18th Annual Western Region Agricultural Education Research Meeting: Volume 18 (pp.218-230). https://www.researchgate.net/profile/Martin-Frick-4/publication/237527103_a_case_study_assessment_of_standards_and_benchmarks_for_implementing_food_and_fiber_systems_literacy/links/004635304f0598cd6f000000/a-case-study-assessment-of-standards-and-benchmarks-for-implemeting-food-and-fiber-systems-literacy.pdf*

Industriegewerkschaft Bauen-Agrar-Umwelt Bundesvorstand, & Institut für nachhaltige Regionalentwicklung in Europa e.V. (2020). *Initiative Faire Landarbeit Bericht 2020: Saisonarbeit in der Landwirtschaft*. https://www.peco-ev.de/docs/InitiativeFaireLandarbeit_Bericht2020_IGBAU-neu.pdf

Jamieson, M. K., Govaart, G. H., & Pownall, M. (2023). Reflexivity in quantitative research: A rationale and beginner’s guide. *Social and Personality Psychology Compass*, *17*(4), 1–15.

https://doi.org/10.1111/spc3.12735

Janick, J. (2005). The origin of fruits, fruit growing and fruit breading. *Plant Breeding Reviews*, *25*, 255–320. https://doi.org/10.1002/9780470650301.ch8

Jithin Das V., Sharma, S., & Kaushik, A. (2019). Views of Irish farmers on smart farming technologies: An observational study. *AgriEngineering*, *1*(2), 164–187. https://doi.org/10.3390/agriengineering1020013

Kagermann, H., Wahlster, W., & Helbig, J. (2019). Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. In Hellinger, A. and Stumpf, V. (Eds.), *Final Report of the Industrie 4.0 Working Group*. Acatech. https://doi.org/10.1109/REM.2019.8744120

Kamrath, C., Wesana, J., Bröring, S., & De Steur, H. (2019). What do we know about chain actors' evaluation of new food technologies? A systematic review of consumer and farmer studies. *Comprehensive Reviews in Food Science and Food Safety*, *18*(3), 798–816. https://doi.org/10.1111/1541-4337.12442

Kernecker, M., Knierim, A., & Wurbs, A. (2016). *Report on farmers' needs, innovative ideas and interests* (Deliverable 2.2). Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF) e.V. https://www.smart-akis.com/wp-content/uploads/2017/02/D2.2.-Report-on-farmers-needs.pdf

Kernecker, M., Knierim, A., Wurbs, A., Kraus, T., & Borges, F. (2020). Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precision Agriculture*, *21*(1), 34–50. https://doi.org/10.1007/s11119-019-09651-z

Kienzle, J., Maisel, H., Krismann, A., Esenova, G., & Benduhn, B. (2016). *Förderung der Artenvielfalt in Öko-Erwerbsobstanlagen*. Universität Hohenheim. https://biodivobst.uni-hohenheim.de/Steckbriefe.pdf

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences*, *90–91*(1), 1-16. https://doi.org/10.1016/j.njas.2019.100315

Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? *Global Food Security*, *24*, 100347. https://doi.org/10.1016/j.gfs.2019.100347

Kliem, L., Krachunova, T., Lange, S., Wagner, J., & Bellingrath-Kimura, S. (2023). *Chancen und Risiken der Digitalisierung in der Landwirtschaft aus Sicht des Umwelt- und Naturschutzes*. Bundesamt für Naturschutz. https://www.ioew.de/en/publication/chancen_und_risiken_der_digitalisierung_in_der_landwirtschaft_aus_sicht_des_umwelt_und_naturschutzes

Knierim, A., Kernecker, M., Erdle, K., Kraus, T., Borges, F., & Wurbs, A. (2019). Smart farming technology innovations – Insights and reflections from the German Smart-AKIS hub. *NJAS - Wageningen Journal of Life Sciences*, *90–91*(1), 1-10. https://doi.org/10.1016/j.njas.2019.100314

Kodors, S., Lacis, G., Zhukov, V., & Bartulsons, T. (2020). Pear and apple recognition using deep learning and mobile. In *19th International Scientific Conference Engineering for Rural Development: Proceedings: Vol. 19,* (pp.1795–1800). Latvia University of Life Sciences and Technologies Faculty of Engineering. https://doi.org/10.22616/ERDev.2020.19.TF476

Köhler, D. H. (2018). Digitalisierung im Obstbau – Anwendungen und Aussichten. *Rheinhessischer Obstbautag*, 1–3. https://www.gb-profi.de/fileadmin/user_upload/GBP/Obstbautag_Rheinhessen_2018.pdf

Köhler, H., & Immik, E. (2012). *Bedarfsorientierte Bewässerung im Obstbau*. Dienstleistungszentrum Ländlicher Raum - Rheinpfalz. https://www.obstbau.rlp.de/Internet/global/Themen.nsf/7f97e4b4b5935b96c12582580050d7a5/1 f4479f6de8ce415c1257aaf0052006e/$FILE/Broschüre_Bedarfsorientierte Bewässerung Obstbau_ 06.11.2012.pdf

Kollmann, T. (1998). *Akzeptanz innovativer Nutzungsgüter und -systeme: Konsequenzen für die Einführung von Telekommunikations- und Multimediasystemen*. Gabler Verlag Wiesbaden. https://doi.org/https://doi.org/10.1007/978-3-663-09235-3

Kompetenzzentrum Obstbau Bodensee. (2023a, April 18). *Bedarfsgerechte Wasserversorgung*. Kompetenzzentrum Obstbau Bodensee. https://www.kob-bavendorf.de/projekt-archiv/interreg-vi-bedarfsgerechte-wasserversorgung-im-obstbau.html

Kompetenzzentrum Obstbau Bodensee. (2023b). *Jahreswetterverlauf*. Kompetenzzentrum Obstbau Bodensee. https://www.kob-bavendorf.de/aktuelle-nachricht/wetter-2020.html

Kösler, J. (2023). *Statistisches Monatsheft Baden-Württemberg: Der baden-württembergische Baumobstanbau*. Statistisches Landesamt Baden-Württemberg. https://www.statistik-bw.de/Service/Veroeff/Monatshefte/PDF/Beitrag23_04_04.pdf

Kraatz, S., Zare, M., Libra, J. A., Grundmann, P., Reyhani, M. N., Zamani, O., Hunstock, U., & Jacobs, H. (2021). *Transformation Strategies in Agriculture*. Project report "IWRM Zayandeh Rud", German Federal Ministry of Education and Research (BMBF) (Report No. 02WM1353AG), Bornimer Agartechnische Berichte, Heft 104, ISSN 0947-7314, Potsdam-Bornim. Leibniz Institute for Agricultural Engineering and Bioeconomy e.G. (ATB). https://www.researchgate.net/publication/329912633_Transformation_Strategies_in_Agriculture

Krölling, C. (2021). A*pfelanbau in Klimawandel: Optimierung ressourcenschonender Anbau-konzepte zur Qualitätssicherung bei Apfel unter Berücksichtigung des Klimawandels* (Issue 5). Landesamt für Umwelt, Landwirtschaft und Geologie. https://slub.qucosa.de/api/qucosa%3A74472/attachment/ATT-0/

Kvikliene, N., Kviklys, D., Valiuškaite, A., Viskelis, P., Uselis, N., Lanauskas, J., & Buskiene, L. (2011). Effect of harvest date on fruit maturity, quality and storability of "Lodel" apples. *Journal of Food, Agriculture and Environment*, *9*(3&4), 210–213. https://doi.org/10.1234/4.2011.2254

Laborde, D., Lallemant, T., McDougal, K., Smaller, C., & Traore, F. (2019). *Transforming Agriculture in Africa & Asia: What are the policy priorities?* International Institute for Sustainable Development and International Food Policy Research Institute. *I*http://www.jstor.org/stable/resrep22022

Lal, R., Hall, G. F., & Miller, F. P. (1989). Degradation: I. Basic processes. *Land Degradation & Rehabilitation*, *1*, 51–69. https://doi.org/10.1002/ldr.3400010106

Landesanstalt für Landwirtschaft Ernährung und Ländlichen Raum. (2023). *Strukturdaten 2021/2022 zur Landwirtschaft in Baden-Württemberg nach Stadt- und Landkreisen sowie Dienstbezirken der Unteren Landwirtschaftsbehörden*. Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg. https://lel.landwirtschaft-bw.de/,Lde/Startseite/Unsere+Themen/C_Strukturdaten

Landwirtschaftliches Technologiezentrum Augustenberg. (2023). *Integrierter Pflanzenschutz 2023: Erwerbsobstbau*. Ministerium für Ernährung, Ländlichen Raum und Verbraucherschutz Baden-Württemberg. https://ltz.landwirtschaft-bw.de/,Len/Service/Broschueren+zum+Pflanzenschutz

Lang, D. J., & Wiek, A. (2022). Structuring and advancing solution-oriented research for sustainability. *Ambio*, *51*(1), 31–35. https://doi.org/10.1007/s13280-021-01537-7

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., & Thomas, C. J. (2012). Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science*, *7*(1), 25–43. https://doi.org/10.1007/s11625-011-0149-x

Lange, S., & Santarius, T. (2022). *Digital reset: Redirecting technologies for the deep sustainability transformation*. Department of Socio-Ecological Transformation, Technische Universität Berlin.

http://dx.doi.org/10.14279/depositonce-16187

Langer, G., & Kühl, S. (2024). Perception and acceptance of robots in dairy farming—a cluster analysis of German citizens. *Agriculture and Human Values*, *41*(1), 249–267. https://doi.org/10.1007/s10460-023-10483-x

LaRue, J. H. (1989). Establishing the orchard. In LaRue, J.H. & Johnson, S.R. (Eds.), *Peaches, Plums, and Nectaries: Growing and Handling for Fresh Market*: Publication No. 3331, (pp.21-30). Division of Agriculture and Natural Resources, University of California.

Lehr- und Forschungszentrum für Wein- und Obstbau Klosterneuburg. (2013). Europom 2012: Die grosse Welt des Obstes. *Mitteilung Kosterneuberg*, 82. https://doi.org/10.28937/978-3-7873-2810-9

Linsner, S., Kuntke, F., Steinbrink, E., Franken, J., & Reuter, C. (2021). The Role of privacy in digitalization – Analyzing perspectives of German farmers. *Proceedings on Privacy Enhancing Technologies*, *2021*(3), 334–350. https://doi.org/10.2478/popets-2021-0050

Madushanki, A. A. R., Halgamuge, M. N., Wirasagoda, W. A. H. S., & Syed, A. (2019). Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: A review. *International Journal of Advanced Computer Science and Applications*, *10*(4), 11–28. https://doi.org/10.14569/ijacsa.2019.0100402

Maleki, M. R., Mouazen, A. M., De Ketelaere, B., Ramon, H., & De Baerdemaeker, J. (2008). On-the-go variable-rate phosphorus fertilisation based on a visible and near-infrared soil sensor. *Biosystems Engineering*, *99*(1), 35–46. https://doi.org/10.1016/j.biosystemseng.2007.09.007

Manfredo, M. J., Bruskotter, J. T., Teel, T. L., Fulton, D., Schwartz, S. H., Arlinghaus, R., Oishi, S., Uskul, A. K., Redford, K., Kitayama, S., & Sullivan, L. (2017). Why social values cannot be changed for the sake of conservation. *Conservation Biology*, *31*(4), 772–780. https://doi.org/10.1111/cobi.12855

Marshall, F., Dolley, J., & Priya, R. (2018). Transdisciplinary research as transformative space making for sustainability: Enhancing propoor transformative agency in Periurban contexts. *Ecology and Society*, *23*(3). https://doi.org/10.5751/ES-10249-230308

Martens, K., & Zscheischler, J. (2022). The digital transformation of the agricultural value chain: Discourses on opportunities, challenges and controversial perspectives on governance approaches. *Sustainability (Switzerland)*, *14*(7). https://doi.org/10.3390/su14073905

Mayring, P. (2000). Qualitative Content Analysis. *Forum: Qualitative Social Research*, *1*(2), 10. https://www.qualitative-research.net/index.php/fqs/article/view/1089/2384

Meijer, S. S., Catacutan, D., Ajayi, O. C., Sileshi, G. W., & Nieuwenhuis, M. (2015). The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *International Journal of Agricultural Sustainability*, *13*(1), 40–54. https://doi.org/10.1080/14735903.2014.912493

Michels, M., Fecke, W., Feil, J. H., Musshoff, O., Pigisch, J., & Krone, S. (2020a). Smartphone adoption and use in agriculture: empirical evidence from Germany. *Precision Agriculture*, *21*(2), 403–425. https://doi.org/10.1007/s11119-019-09675-5

Michels, M., Fecke, W., von Ahlefeld, P. J. W., Mußhoff, O., Heckmann, A., & Beneke, F. (2019). Farmers' willingness to pay for digitalization training courses. *Berichte Uber Landwirtschaft*, *97*(1). https://www.cabidigitallibrary.org/doi/full/10.5555/20193328556

Michels, M., von Hobe, C. F., & Musshoff, O. (2020b). A trans-theoretical model for the adoption of drones by large-scale German farmers. *Journal of Rural Studies*, *75*, 80–88. https://doi.org/10.1016/j.jrurstud.2020.01.005

Michels, M., von Hobe, C. F., Weller von Ahlefeld, P. J., & Musshoff, O. (2021). The adoption of drones in German agriculture: A structural equation model. *Precision Agriculture*, *22*(6), 1728–1748. https://doi.org/10.1007/s11119-021-09809-8

Michelsen, L. (2018). Agrarindustrie 4.0 Zukunftsfähige Landwirtschaft? In Höfner, A. & Frick, V. (Eds.), *Was Bits und Bäume verbindet. Digitalisierung nachhaltig gestalten* (pp. 82–85). Oekom. https://doi.org/10.14512/9783962386368

Miller, T. R., Wiek, A., Sarewitz, D., Robinson, J., Olsson, L., Kriebel, D., & Loorbach, D. (2014). The future of sustainability science: A solutions-oriented research agenda. *Sustainability Science*, *9*(2), 239–246. https://doi.org/10.1007/s11625-013-0224-6

Miranda, J. C., Gené-Mola, J., Zude-Sasse, M., Tsoulias, N., Escolà, A., Arnó, J., Rosell-Polo, J. R., Sanz-Cortiella, R., Martínez-Casasnovas, J. A., & Gregorio, E. (2023). Fruit sizing using AI: A review of methods and challenges. *Postharvest Biology and Technology*, *206*, 112587. https://doi.org/10.1016/j.postharvbio.2023.112587

Miranda, J., Ponce, P., Molina, A., & Wright, P. (2019). Sensing, smart and sustainable technologies for Agri-Food 4.0. *Computers in Industry*, *108*, 21–36. https://doi.org/10.1016/j.compind.2019.02.002

Mohr, S., & Kühl, R. (2021). Acceptance of artificial intelligence in German agriculture: an application of the technology acceptance model and the theory of planned behavior. *Precision Agriculture*, *22*, 1816–1844. https://doi.org/10.1007/s11119-021-09814-x

Mottram, T. (2022). Chapter 1: An introduction to digital agritechnology. In Mottram, T. (Ed.), *Digital Agritechnology: Robotics and Systems for Agriculture and Livestock Production* (pp. 1–9). Academic Press. https://doi.org/10.1016/B978-0-12-817634-4.00005-7

Muder, A., Garmin, H., Dreisiebner-Lanz, S., Kerngast, K., Rosner, F., Klicková, K., Kurthy, G., Cimer, K., Bertazzoli, A., Altamura, V., De Ros, G., Zmarlicki, K., de Belém Costa Freitas, M., Duarte, A., Bravin, E., Kambor, J., Karamürsel, D., Pinar Öztürk, F., & Kacal, E. (2022). Apple production and apple value chains in Europe. *European Journal of Horitcultural Science*, *22*. https://doi.org/10.17660/eJHS.2022/059

Munz, J., Gindele, N., & Doluschitz, R. (2020). Exploring the characteristics and utilisation of Farm Management Information Systems (FMIS) in Germany. *Computers and Electronics in Agriculture*, *170*, 105246. https://doi.org/10.1016/j.compag.2020.105246

Munz, J. R. (2021). *Akzeptanz, Status quo und Entwicklung der Digitalisierung entlang der genossenschaftlichen agro-food Wertschöpfungskette* [Doctoral dissertation, University of Hohenheim]. Hohpublica. https://hohpublica.uni-hohenheim.de/handle/123456789/6726

Naisbitt, J. (1982). *Megatrends: Ten new directions transforming our lives*. Warner Books, Inc.

Neuenfeldt, S., Gocht, A., Heckelei, T., & Ciaian, P. (2019). Explaining farm structural change in the European agriculture: A novel analytical framework. *European Review of Agricultural Economics*, *46*(5), 713–768. https://doi.org/10.1093/erae/jby037

Nordmark, L., Skjöldebrand, C., Johansson, C., Segerström, M., Tahir, I., Gilbertsson, M., Ellner, F., Oskarsson, M., Hydbom, O., & Jensen, J. (2021). Launch of IoT and artificial intelligence to increase the competitiveness in Swedish apple and grapevine production. *Acta Horticulturae*, *1314*, 235–240. https://doi.org/10.17660/ActaHortic.2021.1314.30

Novara, A., Cerda, A., Barone, E., & Gristina, L. (2021). Cover crop management and water conservation in vineyard and olive orchards. *Soil and Tillage Research*, *208*, 104896. https://doi.org/10.1016/j.still.2020.104896

Nowack, W., Popp, T. R., Schmid, J. C., & Grethe, H. (2023). Does agricultural structural change lead to a weakening of the sector's social functions? – A case study from north-west Germany. *Journal of Rural Studies*, *100*, 103034. https://doi.org/10.1016/j.jrurstud.2023.103034

Oliveira, D. (2017). *Gender und Digitalisierung: Wie Technik allein die Geschlechterfrage nicht lösen wird* (No. 037). Hans Böckler Stiftung. https://www.boeckler.de/fpdf/HBS-006640/p_fofoe_WP_037_2017.pdf

Olum, S., Gellynck, X., Juvinal, J., Ongeng, D., & De Steur, H. (2020). Farmers' adoption of agricultural innovations: A systematic review on willingness to pay studies. *Outlook on Agriculture*, *49*(3), 187–203. https://doi.org/10.1177/0030727019879453

Ossevoort, R., Verdouw, C., Frans De Jong, P., Hennen En, W., & Robbemond, R. (2016). *Fruit 4.0: De vruchten van meer technologie* (LEI Rapport 2016-004). University & Research Center, LEI Wagenigen UR. http://library.wur.nl/WebQuery/wurpubs/fulltext/385030

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

Oxford University Press. (2024). *Agriculture*. https://www.oxfordreference.com/display/10.1093/oi/authority.20110803095356555

Patnaik, E. (2013). Reflexivity: Situating the researcher in qualitative research. *Humanities and Social Science Studies*, *2*(2), 98–106. https://www.researchgate.net/publication/263916084

Paustian, M., & Theuvsen, L. (2017). Adoption of precision agriculture technologies by German crop farmers. *Precision Agriculture*, *18*(5), 701–716. https://doi.org/10.1007/s11119-016-9482-5

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P. H., Hagedorn, G., Hansjürgens, B., Herzon, I., Lomba, Â., Marquard, E., Moreira, F., Nitsch, H., Oppermann, R., Perino, A., Röder, N., Schleyer, C., Schindler, S., Wolf, C., Zinngrebe, Y., & Lakner, S. (2020). Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People and Nature*, *2*(2), 305–316. https://doi.org/10.1002/pan3.10080

Pereira, A. C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, *13*, 1206–1214. https://doi.org/10.1016/j.promfg.2017.09.032

Pfeiffer, J., Gabriel, A., & Gandorfer, M. (2021). Understanding the public attitudinal acceptance of digital farming technologies: a nationwide survey in Germany. *Agriculture and Human Values*, *38*(1), 107–128. https://doi.org/10.1007/s10460-020-10145-2

Philadelphia Orchard Project. (2021). *Summary of Orchard Care*. Philadelpha Orchard Project: Resources. https://www.phillyorchards.org/wp-content/uploads/2015/07/orchard_care.pdf

Phills, J. A., Deiglmeier, K., & Miller, D. T. (2008). Rediscovering social innovation. *Stanford Social Innovation Review*, *6*(4), 34–43. https://doi.org/10.48558/GBJY-GJ47

Pierpaoli, E. (2013). *Technology development and consumer acceptance of innovation in fruit production* (Publication No. AGR/03) [Doctoral dissertation, University of Bologna]. University of Bologna. http://amsdottorato.unibo.it/6623/1/Pierpaoli_Emauele_Tesi.pdf

Popescu, D., Ichim, L., & Stoican, F. (2023). Orchard monitoring based on unmanned aerial vehicles and image processing by artificial neural networks: a systematic review. *Frontiers in Plant Science*, *14*, 1–30. https://doi.org/10.3389/fpls.2023.1237695

Porter, M. E., & Heppelmann, J. E. (2014, November). How smart, connected products are transforming competition. *Harvard Business Review*. https://hbr.org/2014/11/how-smart-connected-products-are-transforming-competition

Prause, L. (2021). Digital agriculture and labor: A few challenges for social sustainability. *Sustainability 2021, 13*(11), 5980. https://doi.org/10.3390/SU13115980

Prause, L., & Egger, A. (2023). Digitalisation for a socio-econological transformation in agriculture. In J. Jankowski, P., Höfner, A., Hoffmann, M. L., Rohde, F., Rehak, R. & Graf, J. (Eds.), *Shaping Digital Transformation for a Sustainable Society. Contributions from Bits & Bäume.* Technische Universität Berlin. https://publication2023.bits-und-baeume.org/

Prause, L., Hackfort, S., & Lindgren, M. (2021). Digitalization and the third food regime. *Agriculture and Human Values*, *38*(3), 641–655. https://doi.org/10.1007/s10460-020-10161-2

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: In search of conceptual origins. *Sustainability Science, 14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Rama, M. V, & Narasimham, P. (2003). Controlled-atmosphere storage: Effects on fruit and vegetables. In B. Caballero (Ed.), *Encyclopedia of Food Sciences and Nutrition (Second Edition)* (pp. 1607–1615). Academic Press. https://doi.org/https://doi.org/10.1016/B0-12-227055-X/00292-3

Regan, Á. (2019). 'Smart farming' in Ireland: A risk perception study with key governance actors. *NJAS - Wageningen Journal of Life Sciences*, *90–91*, 100292. https://doi.org/10.1016/j.njas.2019.02.003

Regan, Á., Green, S., & Maher, P. (2018). Smart Farming in Ireland: Anticipating positive and negative impacts through a qualitative study of risk and benefit perceptions amongst expert actors in the Irish agri-food sector. *13th European IFSA Symposium: Theme 4-Smart Technologies in Farming and Food Systems, July 2018*, 1–18. http://ifsa.boku.ac.at/cms/fileadmin/Proceeding2018/Theme4_Regan.pdf

Reid, A., Rhonda-Perez, E., & Schenker, M. B. (2021). Migrant workers, essential work, and COVID-19. *American Journal of Industrial Medicine*, *64*(2), 73–77. https://doi.org/10.1002/ajim.23209

Rentenbank. (2018). *Geschäftsbericht 2018*. Landwirtschaftliche Rentenbank. https://cms.rentenbank.de/export/sites/rentenbank/dokumente/Geschaeftsbericht-2018-Deutsch.pdf

Richards, H. M., & Schwartz, L. J. (2002). Ethics of qualitative research: Are there special issues for health services research? *Family Practice*, *19*(2), 135–139. https://doi.org/10.1093/fampra/19.2.135

Rijswijk, K., Bulten, E., Klerkx, L., Dessein, J., Debruyne, L., Brunori, G., Scotta, I., Bacco, M., Currie, M., Bartolini, F., van der Velden, D., Rolandi, S., & Metta, M. (2020). *Digital transformation of agriculture, forestry and rural areas: Developing a tutureproof socio-cyber-physical system*. Wageningen University and Research. https://iris.cnr.it/retrieve/f553843e-0567-4764-a704-29e219de885c/prod_453667-doc_172533.pdf

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Dessein, J., Scotti, I., & Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. *Journal of Rural Studies*, *85,* 79–90. https://doi.org/10.1016/j.jrurstud.2021.05.003

Robert Koch Institut. (2024). *COVID-19*. Robert Koch Institute, Bundesministerium für Gesundheit. https://www.rki.de/DE/Content/Infekt/EpidBull/Merkblaetter/Ratgeber_COVID-19.html#doc16886050bodyText1

Rogers, E. M. (1995). Attributes of innovations and their rate of adoption. In Rogers, E. M. (Ed.), *Diffusion of innovations* (4th ed., pp. 204–251). The Free Press.

Rohleder, B., & Meinel, T. (2024). *So digital ist die Landwirtschaft*. Bitkom. https://www.bitkom.org/sites/main/files/2024-06/Bitkom-Charts-Pressekonferenz-Digitalisierung-der-Landwirtschaft.pdf

Rose, D. C., & Bhattacharya, M. (2023). Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK. *Smart Agricultural Technology, 3,* 100118. https://doi.org/10.1016/j.atech.2022.100118

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R., Neufeld, H. T., Nixon, A., Pant, L., Shalla, V., & Fraser, E. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *Journal of Rural Studies*, *68*, 112–122. https://doi.org/10.1016/j.jrurstud.2019.01.023

Rumble, J. N., & Irani, T. (2016). Opening the doors to agriculture: The effect of transparent communication on attitude. *Journal of Applied Communications*, *100*(2). https://doi.org/10.4148/1051-0834.1030

Ryan, M. (2023). The social and ethical impacts of artificial intelligence in agriculture: mapping the agricultural AI literature. *AI and Society*, *38*(6), 2473–2485. https://doi.org/10.1007/s00146-021-01377-9

Saldaña, J. (2013). *The Coding Manual for Qualitative Researchers* (2nd ed.). *Sage*.

Saleh, R., El Benni, N., Masson, S., & Ammann, J. (2024). Public acceptance and sustainability perceptions of food produced with chemical, digital and mechanical weed control measures. *Food Quality and Preference*, *113*, 105079. https://doi.org/10.1016/j.foodqual.2023.105079

Sarewitz, D., Clapp, R., Crumbley, C., Kriebel, D., & Tickner, J. (2012). The sustainability solutions agenda. *New Solutions: A Journal of Environmental and Occupational Health Policy*, *22*(2), 139–151. https://doi.org/10.2190/NS.22.2.c

Schleicher, S., & Gandorfer, M. (2018). Digitalisierung in der Landwirtschaft: Eine Analyse der Akzeptanzhemmnisse. In *Digitale Marktplätze und Plattformen* (pp. 203–206). Gesellschaft für Informatik. https://dl.gi.de/handle/20.500.12116/23158

Scholz, R. W., Bartelsman, E. J., Diefenbach, S., Franke, L., Grunwald, A., Helbing, D., Hill, R., Hilty, L., Höjer, M., Klauser, S., Montag, C., Parycek, P., Prote, J. P., Renn, O., Reichel, A., Schuh, G., Steiner, G., & Pereira, G. V. (2018). Unintended side effects of the digital transition: European scientists' messages from a proposition-based expert round table. *Sustainability (Switzerland)*, *10*(6). https://doi.org/10.3390/su10062001

Scholz, R. W., Beckedahl, M., Albrecht, E., & Marx, D. (2021). *DiDaT Weißbuch: Verantwortungsvoller Umgang mit digitalen Daten- Orientierungen eines transdisziplinären Prozesses*. Nomos Verlagsgesellschaft mbH & Co. KG. https://doi.org/10.5771/9783748924111

Schweizer, P.-J., & Renn, O. (2019). Systemische Risiken und Transformationsprozesse auf dem Weg zu einer nachhaltigen Wirtschafts- und Gesellschaftsentwicklung. In M. Englert & A. Ternès (Eds.), *Nachhaltiges Management: Nachhaltigkeit als exzellenten Managementansatz entwickeln* (pp. 211–227). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-57693-9_11

Smit, B., & Smithers, J. (1993). Sustainable Agriculture: Interpretations, analyses and prospects. *Canadian Journal of Regional Science*, *16*(3), 499–524. https://idjs.ca/images/rcsr/archives/V16N3-Smit-Smithers.pdf

Spiller, A., Gauly, M., Balmann, A., Bauhus, J., Birner, R., Bokelmann, W., Christen, O., Entenmann, S., Grethe, H., Knierim, U., Latacz-Lohmann, U., Matinez, J., Nieberg, Hiltrud, Qaim, M., Taube, F., Tenhagen, B.-A., & Weingarten, P. (2015). Agrarwissenschaft Forschung Praxis Wege zu einer gesellschaftlich akzeptierten. *Agrarwissenschaft Forschung Praxis*, *221*, 172. https://doi.org/https://doi.org/10.12767/buel.v0i221.82

Statistisches Bundesamt. (2023a). *Areas and quantities harvested (production for the market)*[Data set]. Statistisches Bundesamt (Destatis). https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Agriculture-Forestry-Fisheries/Fruit-Vegetables-Horticulture/Tables/2-4-areas-quantities-harvested.html

Statistisches Bundesamt. (2023b). *Organic farming: fruit* [Data set]. Statistisches Bundesamt (Destatis). https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Agriculture-Forestry-Fisheries/Fruit-Vegetables-Horticulture/Tables/1-2-organic-farming-fruit.html?view=main

Statistisches Bundesamt. (2023c). *Organic Farming* [Data set]. Statistisches Bundesamt (Destatis). https://www.destatis.de/Europa/EN/Topic/Agriculture-forestry-fisheries/OrganicFarming.html

Statistisches Bundesamt. (2024). *Landwirtschaftliche Betriebe insgesamt und Betriebe mit ökologischem Landbau 2023* [Data set]. Statistisches Bundesamt (Destatis). https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/LandForstwirtschaftFischerei/LandwirtschaftlicheBetriebe/Tabellen/LandwirtschaftlicheBetriebeOekologischerLandbauBundeslaender.html

Statistisches Landesamt Baden-Württemberg. (2018). *Gartenbau in Baden-Württemberg: Vielfalt von Apfel bis Zuckermais* [Data set]. Statistisches Landesamt Baden-Württemberg.

Statistisches Landesamt Baden-Württemberg. (2020a). *Anbauflächen von Erdbeeren seit 2008: Landkreis Bodenseekreis* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05023060.tab?R=KR435

Statistisches Landesamt Baden-Württemberg. (2020b). *Anbauflächen von Erdbeeren seit 2008: Landkreis Konstan* [Data set]z. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05023060.tab?R=KR335

Statistisches Landesamt Baden-Württemberg. (2020c). *Anbauflächen von Erdbeeren seit 2008: Landkreis Ravensburg* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05023060.tab?R=KR436

Statistisches Landesamt Baden-Württemberg. (2020d). *Landwirtschaftlich genutzte Fläche seit 1979 nach Hauptnutzungsarten: Bodenseekreis* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05025033.tab?R=KR435

Statistisches Landesamt Baden-Württemberg. (2020e). *Landwirtschaftlich genutzte Fläche seit 1979 nach Hauptnutzungsarten: Landkreis Konstanz* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05025033.tab?R=KR335

Statistisches Landesamt Baden-Württemberg. (2020f). *Landwirtschaftlich genutzte Fläche seit 1979 nach Hauptnutzungsarten: Landkreis Ravensburg* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/05025033.tab?R=KR436

Statistisches Landesamt Baden-Württemberg. (2022a). *Baumobstfläche nach Obstart: Landkreis Bodenseekreis* [Data set]. Statistisches Landesamt Baden-Württemberg

Statistisches Landesamt Baden-Württemberg. (2022b). *Baumobstfläche nach Obstart: Landkreis Landkreis Konstanz* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502308x.tab?R=KR335

Statistisches Landesamt Baden-Württemberg. (2022c). *Baumobstfläche nach Obstart: Landkreis Landkreis Ravensburg* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502308x.tab?R=KR436

Statistisches Landesamt Baden-Württemberg. (2022d). *Pressemitteilung 2015/2022: Äpfel dominieren den Obstanbau in Baden-Württemberg. Größstes Anbaugebiet am Bodensee*. http://www.statistik-bw.de/Presse/Pressemitteilungen/2022205

Statistisches Landesamt Baden-Württemberg. (2023a). *Strauchbeerenanbau und -ernte: Landkreis Bodenseekreis* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502307x.tab?R=KR435

Statistisches Landesamt Baden-Württemberg. (2023b). *Strauchbeerenanbau und -ernte: Landkreis Konstanz* [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502307x.tab?R=KR335

Statistisches Landesamt Baden-Württemberg. (2023c). *Strauchbeerenanbau und -ernte: Landkreis*

Ravensburg [Data set]. https://www.statistik-bw.de/Landwirtschaft/Bodennutzung/0502307x.tab?R=KR436

Stefas, N., Bayram, H., & Isler, V. (2016). Vision-Based UAV Navigation in Orchards. *International Federation of Automatic Control (IFAC)- Papers Online*, *49*(16), 10–15. https://doi.org/10.1016/j.ifacol.2016.10.003

Stöckle, C. O., Marsal, J., & Villar, J. M. (2011). Impact of climate change on irrigated tree fruit production. *Acta Horticulturae*, *889,* 41–52. https://doi.org/10.17660/ActaHortic.2011.889.2

Sullivan, T. P., Sullivan, D. S., & Granatstein, D. M. (2018). Influence of living mulches on vole populations and feeding damage to apple trees. *Crop Protection*, *108*, 78–86. https://doi.org/10.1016/j.cropro.2018.02.007

Taherdoost, H. (2018). A review of technology acceptance and adoption models and theories. *Procedia Manufacturing*, *22*, 960–967. https://doi.org/10.1016/j.promfg.2018.03.137

Talavera, J. M., Tobón, L. E., Gómez, J. A., Culman, M. A., Aranda, J. M., Parra, D. T., Quiroz, L. A., Hoyos, A., & Garreta, L. E. (2017). Review of IoT applications in agro-industrial and environmental fields. *Computers and Electronics in Agriculture*, *142*(118), 283–297. https://doi.org/10.1016/j.compag.2017.09.015

Tamirat, T. W., Pedersen, S. M., & Lind, K. M. (2018). Farm and operator characteristics affecting adoption of precision agriculture in Denmark and Germany. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, *68*(4), 349–357. https://doi.org/10.1080/09064710.2017.1402949

Tey, Y. S., & Brindal, M. (2012). Factors influencing the adoption of precision agricultural technologies: A review for policy implications. *Precision Agriculture*, *13*(6), 713–730. https://doi.org/10.1007/s11119-012-9273-6

The European Commission. (2019a). *The European Green Deal: Annex* (Com. no. 640, final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640#document2

The European Commission. (2019b). *The European Green Deal: Communcation from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions*(Com. no. 640, final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640

The European Commission. (2023). *Digitalisation of agriculture and rural areas in the EU*. Agriculture and Rural Development, The European Commission. https://agriculture.ec.europa.eu/sustainability/digitalisation_en

The European Commission. (2024a). *An Environmentally Sustainable CAP*. Agriculture and Rural Development, The European Commission. https://agriculture.ec.europa.eu/sustainability/environmental-sustainability/cap-and-environment_en

The European Commission. (2024b). *Sustainable Agriculture in the EU*. Agriculture and Rural Development, The European Commission. https://agriculture.ec.europa.eu/sustainability_en

The European Commission. (2024c). *The CAP and social sustainability*. Agriculture and Rural Development, The European Commission. https://agriculture.ec.europa.eu/sustainability/socially-sustainable-cap_en

Townsend, R., Lampietti, J., Treguer, D., Schroeder, K., Haile, M., Juergenliemk, A., Hasiner, E., Horst, A., & Hakobyan, A. (2019). *Future of food: Harnessing digital technologies to improve food systems outcome.* World Bank Group. http://elibrary.worldbank.org/doi/book/10.1596/31565

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., Hemerik, L., de Vries, F. T., Bardgett, R. D., Brady, M. V., Bjornlund, L., Jørgensen, H. B., Christensen, S., Hertefeldt, T. D., Hotes, S., Gera Hol, W. H., Frouz, J., Liiri, M., Mortimer, S. R., Heikki, S., Tzanopoulos, J., Uteseny, K., Pizl, V., Stary, J., Wolters, V., & Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology*, *21*, 973–985. https://doi.org/10.1111/gcb.12752

Turner, B. L., Kasperson, R. E., Matsone, P. A., McCarthy, J. J., Corell, R. W., Christensene, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(14), 8074–8079. https://doi.org/10.1073/pnas.1231335100

Ullah, A., & Perret, S. R. (2014). Technical- and environmental-efficiency analysis of irrigated cotton-cropping systems in Punjab, Pakistan using data envelopment analysis. *Environmental Management*, *54*(2), 288–300. https://doi.org/10.1007/s00267-014-0300-4

UNESCO. (2012). Education for sustainable development in action: Learning & training tools. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000216383

van der Burg, S., Giesbers, E., Bogaardt, M. J., Ouweltjes, W., & Lokhorst, K. (2024). Ethical aspects of AI robots for agri-food; a relational approach based on four case studies. *AI and Society*, *39*(2), 541–555. https://doi.org/10.1007/s00146-022-01429-8

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly: Management Information Systems*, *27*(3), 425–478. https://doi.org/10.2307/30036540

Verbraucherzentrale Niedersachsen e.V., & Bundesministerium für Ernährung Landwirtschaft und Verbraucherschutz. (2022). *Obst und Gemüse im Einzelhandel*. Verbraucherzentrale Niedersachsen e. V. https://www.verbraucherzentrale.de/sites/default/files/2022-01/verbraucherzentrale-marktcheck-obst-und-gemuese-2022.pdf

Vik, J., Melås, A. M., Stræte, E. P., & Søraa, R. A. (2021). Balanced readiness level assessment (BRLa): A tool for exploring new and emerging technologies. *Technological Forecasting and Social Change*, *169*. https://doi.org/10.1016/j.techfore.2021.120854

Voerste, A. (2008). *Lebensmittelsicherheit und Wettbewerb in der Distribution: Rahmenbedingungen, Marktprozesse und Gestaltungsansätze, dargestellt am Beispiel der BSE-Krise*. Josef Eul Verlag. https://www.fernuni-hagen.de/marketing/docs/pub/waschzettel-voerste.pdf

von Veltheim, F. R., & Heise, H. (2021). German farmers' attitudes on adopting autonomous Field robots: An empirical survey. *Agriculture 2021*, *11*(3), 216. https://doi.org/10.3390/AGRICULTURE11030216

von Veltheim, F. R., Theuvsen, L., & Heise, H. (2019). Akzeptanz autonomer Feldroboter im Ackerbaueinsatz: Status quo und Forschungsbedarf. *Berichte Über Landwirtschaft, 97*(3), 1-18. https://doi.org/10.12767/buel.v97i3.248

Wacker, S. (2023). *Bodensee-Obst-Museum*. https://www.bodensee-linzgau.de/de/poi/museum/bodensee-obst-museum/1691429/#caml=a14,1j79yk,7wonqj,0,0

Walter, A. I., Helgenberger, S., Wiek, A., & Scholz, R. W. (2007). Measuring societal effects of transdisciplinary research projects: Design and application of an evaluation method. *Evaluation and Program Planning*, *30*(4), 325–338. https://doi.org/10.1016/j.evalprogplan.2007.08.002

Werth, J., Kittemann, D., Beck, M., Kuster, T., Bravin, E., Buchleither, S., Zoth, M., & Scheer, C. (2020). Entwicklung nachhaltiger Strategien zur Beikrautregulierung. *Obstbau, 9, 534-538*. https://www.kob-bavendorf.de/files/bereiche/%C3%96kologischer%20Obstbau/Publikationen/Besseres%20Obst/Werth%20et%20al%20-%20Beikrautregulierung%20Teil%201%20%2B%20BO.PDF

Wiek, A., Harlow, J., Melnick, R., van der Leeuw, S., Fukushi, K., Takeuchi, K., Farioli, F., Yamba, F., Blake, A., Geiger, C., & Kutter, R. (2015). Sustainability science in action: a review of the state of the field through case studies on disaster recovery, bioenergy, and precautionary purchasing. *Sustainability Science*, *10*(1), 17–31. https://doi.org/10.1007/s11625-014-0261-9

Wiek, A., & Lang, D. J. (2016). Transformational Sustainability Research Methodology. In Heinrichs, H., Martens, P., Michelsen, G., & Wiek, A. (Eds.), *Sustainability Science* (pp. 31–41). Springer. https://doi.org/10.1007/978-94-017-7242-6

Wiek, A., Talwar, S., O'Shea, M., & Robinson, J. (2014). Toward a methodological scheme for capturing societal effects of participatory sustainability research. *Research Evaluation*, *23*(2), 117–132. https://doi.org/10.1093/reseval/rvt031

Wiggins, S., Kirsten, J., & Llambí, L. (2010). The future of small farms. *World Development*, *38*(10), 1341–1348. https://doi.org/10.1016/J.WORLDDEV.2009.06.013

Wiman, M. R., Kirby, E. M., Granatstein, D. M., & Sullivan, T. P. (2009). Cover crops influence meadow vole presence in organic orchards. *HortTechnology*, *19*(3), 558–562. https://doi.org/10.21273/hortsci.19.3.558

World Bank Group. (2016). *Metadata Glossary: Agricultural land*. https://databank.worldbank.org/metadataglossary/africa-development-indicators/series/AG.LND.AGRI.K2#:~:text=Arable land includes land defined,of shifting cultivation is excluded.

World Health Organization. (2023, August 9). *Increasing fruit and vegetable consumption to reduce the risk of noncommunicable diseases*. World Health Organization. https://www.who.int/tools/elena/interventions/fruit-vegetables-ncds

Yap, T. L., Nayak, R., Vu, N. T. H., Bui, D. T., Pham, T. T. T., & Allen, D. W. E. (2023). Adopting blockchain-based traceability in the fruit supply chain in a developing economy: facilitators and barriers. *Information Technology and People*, *38*(1), 419-441. https://doi.org/10.1108/ITP-02-2023-0168

Yue, M., Li, W., Jin, S., Chen, J., Chang, Q., Jones, G., Cao, Y.-Y., Yang, G., Li, Z., & Frewer, L. J. (2023). Farmers' precision pesticide technology adoption and its influencing factors: Evidence from apple production areas in China. *Journal of Integrative Agriculture*, *22*(1), 292–305. https://doi.org/10.1016/j.jia.2022.11.002

Zambon, I., Cecchini, M., Egidi, G., Saporito, M. G., & Colantoni, A. (2019). Revolution 4.0: Industry vs. agriculture in a future development for SMEs. *Processes*, *7*(1), 1–16. https://doi.org/10.3390/pr7010036

Zhang, C., Valente, J., Kooistra, L., Guo, L., & Wang, W. (2021). Orchard management with small unmanned aerial vehicles: a survey of sensing and analysis approaches. *Precision Agriculture*, 22, 2007-2052. Springer. https://doi.org/10.1007/s11119-021-09813-y

Zhang, C., Valente, J., Kooistra, L., Guo, L., & Wang, W. (2019). Opportunities of uavs in orchard management. In *The international archives of the photogrammetry, remote sensing and spatial information sciences: Vol. XLII-2/W13* (pp. 673–680). https://doi.org/10.5194/isprs-archives-XLII-2-W13-673-2019

Zhang, J., Kang, N., Qu, Q., Zhou, L., & Zhang, H. (2024). Automatic fruit picking technology: a comprehensive review of research advances. *Artificial Intelligence Review*, *57*(3). Springer Netherlands. https://doi.org/10.1007/s10462-023-10674-2

Zhang, Q., Karkee, M., & Tabb, A. (2019). The use of agricultural robots in orchard management. In J. Billingsley (Ed.), *Robotics and automation for improving agriculture* (pp. 187–214). Burleigh Dodds Science Publishing. https://doi.org/10.19103/as.2019.0056.14

Zhang, Z., Heinemann, P. H., Liu, J., Baugher, T. A., & Schupp, J. R. (2016). The development of mechanical apple harvesting technology: A review. *Transactions of the ASABE*, *59*(5), 1165–1180. https://doi.org/10.13031/trans.59.11737

Zimbelman, R. G., Wilson, L. L., Bennett, M. B., & Curtis, S. E. (1995). Public image of animal agriculture in the United States. *Livestock Production Science*, *43*(2), 153–159. https://doi.org/10.1016/0301-6226(95)00040-R

Zohary, D., & Spiegel-Roy, P. (1972). Beginnings of Fruit Growing in the Old World. *Science*, 319–327.

Zscheischler, J., Brunsch, R., Griepentrog, H. W., Tölle-nolting, C., Rogga, S., Berger, G., Lehmann, B., Strobel-unbehaun, T., Reichel, C., Ober, S., & Scholz, R. W. (2024). Landwirtschaft, Digitalisierung und digitale Daten. In *Digitale Daten als Gegenstand eines transdisziplinären Prozesses (DiDaT)* [White paper chapter VR 04]. https://didat.eu/files/pdf/vernehm/WBK04/WB_Kapitel_VR04_Landwirtschaft.pdf

Zscheischler, J., Brunsch, R., Rogga, S., & Scholz, R. W. (2022). Perceived risks and vulnerabilities of employing digitalization and digital data in agriculture – Socially robust orientations from a transdisciplinary process. *Journal of Cleaner Production*, *358*, 132034. https://doi.org/10.1016/j.jclepro.2022.132034

Zscheischler, J., & Rogga, S. (2015). Transdisciplinarity in land use science - A review of concepts, empirical findings and current practices. *Futures*, *65*, 28–44. https://doi.org/10.1016/j.futures.2014.11.005

Zu, L. (2013). Social Innovation. In S. O. Idowu, N. Capaldi, L. Zu, & A. Das Gupta (Eds.), *Encyclopedia of Corporate Social Responsibility* (pp. 2213–2223). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-28036-8_252

12. Appendix

Interview Guideline (translated to English)

1. How old are you?
    a) < 30
    b) 30-40
    c) 41-50
    d) 51-60
    e) 61-70
    f) >70
    g) No answer
2. What gender do you identify as?
    a) female
    b) male
    c) diverse
    d) no answer
3. Which county do you live in?
4. How would you describe the area you live in?
    a) Mostly rural
    b) Mixed
    c) Mostly urban
    d) No answer
5. What is your highest level of completed education?
    a) Primary school
    b) Secondary school
    c) Post-secondary at a university or technical college (e.g. Diplom, Magister, Bachelor, Master, PhD)
    d) Other (please specify)
    e) No answer
6. Do you have a specific training in one of these topics?
    a) Agriculture
    b) Food science
    c) Forestry
    d) Sustainability
    e) Digital technologies (e.g. IT, electrician, engineering, etc.)
    f) Other (please specify)
    g) No answer
7. Where do you get your information about digitalization in fruit production or in your professional field? (multiple responses are possible)
    a) Magazines, newspapers
    b) Social media
    c) Colleagues and neighbours
    d) Agricultural fairs or conferences
    e) Training courses
    f) Other (please specify)
    g) No answer
    h) I do not have any information on digitalization in fruit production or my professional field
8. Please self-grade your knowledge on digitalization in fruit production
    a) High
    b) Rather high

   c) Medium
   d) Rather low
   e) Low
   f) No answer
9. Which role do you play in the digitalization of agriculture? (multiple responses are possible)
   a) Agricultural production
   b) Agricultural advising
   c) Agricultural organization or association
   d) Mechanical engineering
   e) PPP manufacturer
   f) Fruit storage and/or processing
   g) Wholesaler and/or marketing
   h) IT- and digital sector
   i) Administration
   j) Research
   k) Education
   l) Technology development
   m) Local community initiatives or groups
   n) Community service/charitable foundations
   o) No professional/institutional area
10. Which sector do you work in? (multiple responses are possible)
   a) Private
   b) Public
   c) Non-profit
   d) Civil society
   e) Other (please specify)
   f) No answer

Questions only for owners or leasers of farming enterprises

11. Which production system do you use on your farm? (multiple responses are possible)
   a) Integrated production (IP)
   b) Organic production
   c) Certified organic production
   d) Demeter production
   e) No answer
12. How large is your farming enterprise? (answer in hectares)
13. Please provide the main products of your farming enterprise (multiple responses are possible)
   a) Plant products
      1. Stone fruits
      2. Soft fruits/berries
      3. Other fruits
      4. Cereals
      5. Other
   b) Animal products
      1. Eggs
      2. Milk
      3. Other
   c) Services
      1. Lodging
      2. Vacation apartments
      3. Maintenance work for the community
      4. Other
   d) No answer
14. Please describe the ownership of your farming enterprise (multiple responses are possible)
   a) Own property
   b) Lease

   c) Community of joint heirs/civil law association/community of farms/cooperative/Ltd
   d) Other form (please specify)
   e) No answer
15. Do you use digital tools or technologies on your farming enterprise?
   a) If yes, which ones? Or rather for which purposes do you use the tools?
   b) If no, why not?
   c) No answer
16. How do you store your products? (multiple responses are possible)
   a) On-site storage
   b) Off-site storage
   c) Storage in communal storage facility
   d) Storage in commercial storage facility
   e) Other (please specify)
   f) No answer
17. How do you market your products? (multiple options are possible)
   a) Direct marketing
      1. Farm shop
      2. Delivery service
      3. Shipping
   b) Intermediary trade
   c) Wholesaler
   d) Communal marketing over e.g. farming cooperative
   e) Export
   f) Other form (please specify)
   g) No answer

Challenges in fruit production (your farming enterprise/the Lake Constance region)

18. Describe the most important environmental challenges of fruit production in the Lake Constance region
   a) Do these differ from those in organic fruit production?
      1. If yes, which challenges differ, and what are the reasons for these differences?
   b) Are there differences based on farm size?
      1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
19. Describe the most important socioeconomic and social challenges of fruit production in the Lake Constance region
   a) Do these differ from those in organic fruit production?
      1. If yes, which challenges differ, and what are the reasons for these differences?
   b) Are there differences based on farm size?
      1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
20. What do you understand by the term “digitalization in fruit production”? Please give examples.
21. Do you believe that digitalization can help mitigate the previously mentioned ecological challenges? If yes, which challenges and how?
22. Do you believe that digitalization can help mitigate the previously mentioned socio-economical and social challenges? If yes, which challenges and how?
23. What are the advantages of digitalization in fruit production?
   a) Do these differ from those in organic fruit production?
      1. If yes, which challenges differ, and what are the reasons for these differences?
   b) Are there differences based on farm size?
      1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
24. What are the disadvantages of digitalization in fruit production?

   a) Do these differ from those in organic fruit production?
      1. If yes, which challenges differ, and what are the reasons for these differences?
   b) Are there differences based on farm size?
      1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.

25. What barriers do you see to the introduction/use of digital technologies and innovations in fruit production?
   a) Do these differ from those in organic fruit production?
      1. If yes, which challenges differ, and what are the reasons for these differences?
   b) Are there differences based on farm size?
      1. If yes, which challenges differ, and what are the reasons for these differences? Please name the farm sizes in hectare for small/large.
26. In your opinion, would the use of digitalized technologies in fruit production change public opinion about the products or production methods? (Yes, no and what reasons play a role here)
   a) Does your answer differ when we speak about the use of digitalized technologies in **organic** fruit production? (if yes, how and what are the reasons for these differences)
27. Please indicate which of the following groups of people or organizations you think would benefit (winners), not benefit (losers) or neither benefit nor lose (neutral) from the digitization of fruit growing, and add if any should be missing from your point of view (your farm/region).
   a) Organic fruit producers
   b) Conventional or integrated fruit producers
   c) Small to medium sized farms
   d) Larger farms
   e) Fruit wholesalers and marketers
   f) Production cooperatives/associations
   g) Agricultural researchers
   h) Manufacturers of agricultural technologies
   i) Companies in the field of digitalization/digital technologies in agriculture
   j) Consultant for fruit production
   k) Consultant for digitalization
   l) Crop protection manufacturers
   m) Consumers

Table 5: Selection of stakeholder group characteristics

		Stakeholder groups					
		Fruit farmers (n=8)	*Cultivation consultants (n=5)*	*Fruit wholesalers or marketers (n=5)*	*Technology developers (n=5)*	*Nature, agriculture, and consumer associations (n=6)*	*Researchers (n=5)*
Age	>30	0	0	0	0	0	0
	30-40	3	1	1	4	1	0
	41-50	3	2	2	1	2	1
	51-60	2	1	1	0	3	4
	61-70	0	1	1	0	0	0
	>70	0	0	0	0	0	0
	Prefer not to answer	0	0	0	0	0	0
Self-identified gender	Female	2	0	2	1	2	0
	Male	6	5	3	4	4	5
	Diverse	0	0	0	0	0	0
	Prefer not to answer	0	0	0	0	0	0
Region	Lake Constance	8	4	5	0	4	2
	Outside Lake Constance	0	1	0	5	2	3
Description of living region	Mostly rural	6	3	2	3	1	1
	Mixed	2	2	3	0	5	1
	Mostly urban	0	0	0	2	0	1
	Prefer not to answer	0	0	0	0	0	2
Education	Primary school	0	0	0	0	0	0
	Secondary school	2	0	0	0	0	0
	Post-secondary school	6	5	5	5	6	5
	Other	0	0	0	0	0	0
	Prefer not to answer	0	0	0	0	0	0
Knowledge of digitalization	High	1	0	0	0	0	1
	Rather high	2	0	1	2	1	0
	Medium	2	4	2	1	0	1
	Rather low	3	1	2	2	4	1
	Low	0	0	0	0	1	0
	Prefer not to answer	0	0	0	0	0	2