

**SOWING SUSTAINABLE AGRICULTURE: INVESTIGATING "SUSTAINABILITY"
IN THE ACADEMIC DISCOURSE ON PRECISION AGRICULTURE**

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Abstract

The academic literature suggests that precision agriculture (PA) is revolutionizing the agricultural sector, with claims that it can enhance sustainability through technological advancements such as tractors with automated guidance, sensor suites, satellites, and drones. The literature on PA widely asserts PA has sustainability benefits claiming that these emerging agricultural technologies will address food system challenges. These challenges include improving the state of food security in the face of a growing global population and the ongoing threats of climate change and environmental degradation caused by agriculture by enhancing agricultural efficiency, productivity, and profits for farmers. Despite this pervasive notion of an inherent link between PA and sustainability, questions persist regarding the substantiation of these “sustainability” benefits, particularly in the promotion of these technologies.

To investigate this link between PA and sustainability, this thesis considers the following research questions: What are the key factors and influences that have contributed to the enduring connection between PA and sustainability within the academic literature and how is the concept of sustainability conceptualized and operationalized within the academic discourse on PA? Employing an inductive constructivist perspective, this research examines academic literature collected through systematic literature review and interview transcripts from semi-structured interviews with key informants from academia, to explore the dominant models of sustainability present in the literature and the factors that have contributed to the formation of this inherent link. Drawing on this constructivist perspective, the research demonstrates that sustainability is not an inherent aspect of PA but rather a construct shaped by the various actors responsible for the promotion of PA. This implies that those actively advocating for or endorsing PA, construct the understanding and portrayal of sustainability in relation to PA, leading to a convergence of sustainability conceptualizations reflective of existing productivist paradigms in agriculture. Considering these findings, this thesis contributes to the greater literature which asserts that PA, although full of promise, may reinforce the issues created by contemporary agriculture.

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Chapter 1 Introduction

1.1 Overview

The Intergovernmental Panel on Climate Change report number six states that climate change is a considerable threat to the global food supply (Pörtner et al., 2022). Climate science indicates that increasing temperatures, changing precipitation patterns, and the increasing frequency and intensity of extreme weather events create uncertainty for the future of agriculture (Bezner Kerr et al., 2022). Loss of arable land and modern agriculture practices reliant on intense agrochemical use have further detrimental effects on our environment, leading to declines in biodiversity (Dudley & Alexander, 2017), water pollution (Parris, 2011), air pollution (Cloy et al., 2012), soil pollution and soil erosion (Sakrabani et al., 2012), and unsustainable water consumption (Horrigan et al., 2002). The agricultural industry also contributes significantly to climate change, as the agriculture industry is the 5th largest emitter of greenhouse gas (GHG) emissions in Canada, accounting for 10% of the country's total GHG emissions in 2021 (Environment and Climate Change Canada, 2022). These challenges, coupled with the fact that the global population is likely to reach 9 billion people by 2050 (United Nations, 2021), create a need to change the way we produce our food to foster sustainability within our agricultural system (Baldos & Hertel, 2014; Grafton et al., 2015).

In light of this uncertain future, many believe that various digital technologies will help mitigate the impacts of climate change and reduce environmental degradation across many sectors of industry including the transportation, manufacturing, and energy sectors (Bagloee et al., 2016; Kätelhön et al., 2019; R. Zhang & Fujimori, 2020). These digital technologies encompass a wide range of innovations such as automation, artificial intelligence (AI), and the

Internet of Things, which are, as some believe, positioned to revolutionize the way we approach sustainability (Khakurel et al., 2018; Mukherjee et al., 2022). The agriculture sector is not exempt from the application of these technological interventions. Optimism surrounds the application of emerging agricultural technologies in food production, where many believe that these technologies not only promise to help mitigate agricultural climate emissions but also have the potential to boost agricultural output, helping meet the needs of growing populations while simultaneously minimizing the environmental impact of agriculture (E. D. G. Fraser, 2020; Gebbers & Adamchuk, 2010). The advent of new digital tools for food production has led some academics to argue that agriculture is undergoing a fourth revolution, a digital revolution, as farmers begin to adopt high-tech methods of production, incorporate the use of big data and machine learning on farms, and turn to automation to conduct regular farm activities (Bronson, 2020; Lowenberg-DeBoer, 2015; Sharma et al., 2022). This integration of digital technologies on farms is known as precision agriculture (PA). PA encompasses a range of technologies that involve sensors, information systems, enhanced machinery, and informed management (Bronson, 2019a). Its goal, as many scholars claim, is “to optimize production by accounting for variability and uncertainties within agriculture systems” (Gebbers & Adamchuk, 2010, p. 828).

By integrating various on-farm implements including internet and mobile devices, automatic guidance systems and global positioning systems (GPS), variable rate application systems and unmanned aerial vehicles to collect data and monitor field conditions and relying on aggregated data, farmers can make data-driven decisions that are intended to optimize the use of inputs like water and pesticides (Bacenetti et al., 2020; Franco et al., 2017; Kiran Kumara et al., 2020) and reduce GHG emissions (R. M. Brown et al., 2016; Sehy et al., 2003). Environmental benefits drive adoption, along with the belief that PA will increase agricultural productivity

(Abdullahi et al., 2015; Kayad et al., 2021) and has been shown to increase yield stability year over year (Yost et al., 2017). These outcomes not only reduce uncertainty surrounding future food supply but also deliver benefits to farmers all while contributing to a more sustainable agricultural system through more judicious use of scarce or harmful inputs (Gebbers & Adamchuk, 2010; Pierce & Nowak, 1999). Integrating these emerging technologies is said to not only benefit the environment but also promote long-term viability for farmers and society. PA is thought to have the potential to reduce labour hours (de Koning, 2010), and input costs (Finco et al., 2023), and contribute to local economies through emerging job markets (Mulla, 2013). The technical literature widely asserts PA will help deliver on these promises, helping farmers mitigate the environmental impact of industrial agriculture practices and meet future production needs (Hatfield & Kitchen, 2013; Oliver, 2013). This notion of increased sustainability is a significant selling point for PA as it is a claim that is used to sell PA to farmers and garner investments in PA at the national and supra-national levels (Bronson, 2022).

Despite this widely promoted belief that PA will bring about sustainability within the modern agricultural system, the literature lacks consensus on what sustainability means in the context of PA. While this research is not advocating that scholars should establish a single definition of sustainability to explain the potential environmental, economic, and social benefits associated with the introduction of PA, there exists a scholarly gap. There is a need for focused attention toward improving our understanding of the diverse conceptualizations of sustainability in relation to PA that scholars are using to assess and report on the benefits of these technologies. A comprehensive analysis is needed to understand the context under which sustainability is used and how it is being measured. Additionally, there is a need to assess the economic, political, and social forces that have influenced the development of these scholarly understandings and uses of

sustainability. Without such a synthesis, the understanding of sustainability in PA remains ambiguous which means that any real, technical assessment of PA's benefits remains incomplete.

Again, the aim of this research is not to establish a master narrative on sustainability as it relates to PA but rather help to uncover the underlying assumptions and power dynamics that influence the connection of PA with sustainability. Through an analysis of literature collected via systematic review combined with interviews with key informants from PA scholarship and practice, this research investigates the relationship between sustainability and PA. In doing so, I ultimately elucidate how existing paradigms in agriculture (i.e., productivism) are infiltrating the way sustainability is being conceptualized by scholars and how various actors shape the connection between PA and sustainability. My main arguments reveal a prevailing hierarchical model prioritizing economic then environmental sustainability over social sustainability in the literature, measured in terms of productivity gains, and optimization of resource use. The emphasis on productivity and efficiency aligns with productivist paradigms, reinforcing their dominance and raising concerns about potential "greenwashing" in the sustainability claims of emerging agricultural technologies.

1.2 Previous Research

Some academics have questioned the prevalence of the widely asserted link between PA and sustainability and they have sought empirical evidence to support these claims of sustainability benefits. Brown et al. (2016), Balafoutis et al. (2017), and El Chami et al. (2019) all identify a lack of concrete evidence to support the claim that PA has greater environmental benefits than conventional agriculture production. To respond to these articles, I worked in a research group led by Dr. Kelly Bronson, a critical social scientist, to further investigate the

presence or absence of evidence in the literature which supports sustainability claims surrounding PA.

Our research group conducted a meta-review of the English-language literature and found a lack of robust evidence, which we considered field trial evidence, to substantiate the claimed sustainability benefits of PA. Among the 145 papers reviewed, a total of 26 contained robust empirical evidence linking PA technologies to specific environmental gains that equate to environmental sustainability. Some evidence did exist, with these papers often focusing on automated chemical sprayers, and variable rate application technologies, showing their contribution to enhancing the efficiency of specific tasks (e.g., applying pesticides) when compared to conventional, non-precision technologies. For example, PA equipment demonstrated the ability to facilitate more accurate application of agricultural chemicals, which allows for a reduction of inputs along with downstream benefits such as reduced leeching of agricultural chemicals into nearby watersheds and decreasing the likelihood of major chemical drift events (see Chen et al., 2020; Timmermann et al., 2003).

Despite the presence of some evidence supporting sustainability claims for PA, this meta-review additionally revealed that the majority of articles in the reviewed dataset which appeared (by title or abstract) to report on the sustainability benefits of PA actually failed to explicitly measure sustainability or lacked detailed empirical analysis. From the literature reviewed, several patterns emerged. One, it was found that the research investigating PA and sustainability often evaluates the environmental gains of PA indirectly, by assuming a reduction in agrochemical and water use and GHG emissions correlates to overall environmental sustainability (Bronson, 2020). Two, in the dataset of collected papers, a large proportion of articles fall into one of two categories: adoption studies, which document implementation, or

feasibility analyses, which report on the development and testing of novel, non-proprietary PA technologies. Both types of papers claim to discuss the sustainability benefits of PA as they almost always begin with the presupposition that using PA increases sustainability, which is presented without direct evidence or citing work that provides critical empirical evidence (see Nicol & Nicol, 2018). Three, articles often support claims with irrelevant evidence (see Schimmelpfennig, 2018) or evidence which may be considered hearsay. For example, in the case of Lassoued et al. (2021), scholars presented evidence in the form of testimonials from “international biotechnology experts” largely drawn from industry who were asked about the perceived benefits of PA, rather than using direct, verifiable data or research. Four, a concern emerged from the dataset regarding the use of analytical modelling, a technique often employed to illustrate the potential benefits of PA in the literature. Several of the examined papers use models, employing proprietary models, whose internal mechanisms and operations remain undisclosed (see Bacenetti et al., 2020; Saleem et al., 2014). This lack of transparency hinders the ability to validate or replicate the findings presented in these papers.

In sum, while there is a prevalent *belief* among academics which appears as a dominant academic discourse that PA has sustainability benefits, there seems to be a lack of empirical evidence to support this claim. This meta-review thus raises questions about the validity of such assertions as well as questions around where the basis of such claims originates and what the literature on PA truly means when discussing sustainability. My research aims to provide answers to these questions which emerged from this meta-review.

1.3 Research Problem

Both grey and academic literature on PA maintains there is a link between PA and sustainability. Despite researchers widely asserting and frequently emphasizing this connection

in the literature, the aforementioned research (Bronson et al., forthcoming) found, through a systematic review, that authors often do not substantiate this claim with strong empirical evidence. These findings form the basis for the research presented in this thesis, suggesting that the widespread promotion of PA, grounded in the assumption that these technologies contribute to increased sustainability, warrants further investigation. Notably, this project focuses on the need to understand the forces which have shaped the assumed connection between PA and sustainability.

This research is important, as the blind promotion of PA may exacerbate existing issues within the food system and create additional social, economic, political, and ecosystem or environmental challenges. PA has the potential to create issues of unethical data governance (Bronson & Knezevic, 2016; Carolan, 2018), increase corporate concentration within the agriculture system (Clapp, 2021; Rotz, Duncan, et al., 2019) and exacerbate undesired consequences to environmental health (Gardezi & Arbuckle, 2020; Soma & Nuckchady, 2021). Furthermore, multiple levels of government and farmers themselves are making significant investments into these technologies under the promise of improved sustainability and thus the basis of these investments is worthy of attention (Agriculture and Agri-Food Canada, 2022; Jochinke et al., 2007).

The research is also embedded in a scholarly debate which remains lively about the interpretive flexibility and problematic ambiguity of the term sustainability in general (i.e., not just in the context of PA); this body of research reveals that sustainability, even in academia, remains a collection of loosely defined concepts with various definitions that vary by context, purpose, and application (Allen et al., 1991; Rosen, 2018; Vos, 2007). My project is warranted because sustainability itself is a multifaceted and context-dependent term, often bearing diverse

interpretations (Allen et al., 1991; Rosen, 2018; Vos, 2007). I investigate this apparent ambiguity of the term sustainability as it appears in the literature on PA through my research. Gaining insight into the contextual factors which have shaped the relationship between PA and sustainability is crucial to understand how sustainability is conceptualized and operationalized. Furthermore, to ensure that we build a resilient agricultural system capable of providing for future generations, we must understand how sustainability facilitated by PA is positioned and imagined within the literature. As technology becomes increasingly integrated within the agricultural sector, and its role in enhancing sustainability remains a selling point, it becomes essential to examine the nuanced ways in which the literature examines sustainability.

1.4 Research Questions

This research aims to shed light on how sustainability is understood in relation to PA within the academic literature. To accomplish this goal, my research asks the specific questions of:

1. What are the key factors and influences that have contributed to the enduring connection between PA and sustainability within the academic literature?
2. How is the concept of sustainability conceptualized and operationalized within the academic discourse on PA?

1.5 Research Objectives

To answer each respective research question, two research objectives were pursued:

1. Identify the contextual factors that have contributed to the emergence of the idea that PA and sustainability are inextricably linked and understand the role these factors play in shaping the narrative around PA and sustainability.

2. Develop a comprehensive understanding of the various working models of sustainability present in the literature on PA.

1.6 Thesis Outline

This thesis employs a monograph structure and is comprised of the following six chapters. Following the introduction, the literature review begins with an overview of PA, defining it as a concept and situating it within the bigger context of digital agriculture. It then provides insight into the dominant areas of research relating to PA and introduces the sociological perspective on the topic. Subsequently, this literature review chapter explores the technical, rather than social science literature, suggesting a connection between PA and sustainability, shedding light on how PA is being conceptualized therein. This second chapter also introduces the conceptual framework guiding this project. Within this section, I present the complexities associated with defining sustainability, emphasising how a social constructivist approach can help understand the multiplicity of sustainability concepts and the actors responsible for shaping them. Chapter three then provides a detailed account of the research methods and sampling strategies employed in data collection and analysis. Following this section, chapter four, presents the main findings or themes uncovered in this research, focusing on how the literature conceptualizes sustainability and the actors responsible for shaping the link between PA and sustainability. Chapter Five forms the core of this thesis, as it discusses these findings and addresses the two research questions posed in this study. This discussion chapter presents the argument that existing sustainability models tend to favour economic and environmental sustainability over social sustainability, reflecting a hierarchical model of sustainability that prioritizes productivity and efficiency in agriculture. Such a conception of sustainability aligns with the dominant productivist paradigm of modern agriculture. This raises

concerns about greenwashing and the genuine pursuit of sustainability through PA. The concluding chapter serves to succinctly summarize the research contributions, offer recommendations, and provide an overarching conclusion to this research project.

Chapter 2 Literature Review

Scholars have directed significant research attention toward understanding how Precision Agriculture (PA) can be integrated into agricultural operations. This chapter presents the relevant literature on PA. It begins by outlining the primary focus of current research in this field, which centres on technology development and technology adoption on farms, and then presents the sociological literature. While the social science research on PA is less voluminous and less prevalent than technical work in the sciences, engineering or economics, critical social science scholarship provides an examination of how emerging technologies impact the social dimensions of agriculture. Collectively, this literature review situates PA within the greater concept of sustainability and begins to highlight the multiplicity of definitions surrounding sustainability within the PA literature.

2.1 What is Precision Agriculture?

The agricultural industry is an evolving landscape where technologies for collecting, storing, analysing, and sharing agricultural data are said to be transforming the future of the industry (Lowenberg-DeBoer, 2015; Robert, 1999; Ryder, 2014; Sonka & Cheng, 2015). Beyond widely implemented technologies such as personal computers and GPS, farmers are further integrating computer-based technologies, machine learning and advanced data analytics to optimize agricultural efficiency and drive decision-making on the farm and beyond (Nowak, 2021; Statistics Canada, 2022; Sundmaeker et al., 2016). This integration of technology on farms, within agricultural operations has become known as PA. PA is one element of digital agriculture which goes beyond the farm to incorporate technology and data along the entire food supply chain (Klerkx et al., 2019).

Advocates of PA view the integration of technology into food production as a potential fourth agricultural revolution, with the belief that innovative practices can effectively address challenges to food system sustainability (Bongiovanni & Lowenberg-Deboer, 2004; E. D. G. Fraser, 2020; Gebbers & Adamchuk, 2010; Hatfield & Kitchen, 2013; Ryder, 2014; Sonka & Cheng, 2015; Weersink et al., 2018). Throughout the history of agriculture, the introduction of novel technologies has demonstrated the potential to improve food production methods (Clapp, 2020, pp. 37–42; Evenson & Gollin, 2003; McClelland, 1997). From the first seed drill to high-yield genetically modified seed varieties, significant increases in agricultural productivity have been achieved through the integration of novel technologies, supporting both a greater world population and population density (Sarkadi, 2019). Many scholars view PA as a comparable transformative force in modern agriculture, given its potential to contribute to sustainable and productive farming practices (Gebbers & Adamchuk, 2010; Pretty & Bharucha, 2014; Ryder, 2014; Sonka & Cheng, 2015).

Unlike traditional agriculture, the collection and use of vast amounts of data lies at the core of PA (Bronson, 2020). The collection of this data, often referred to as agricultural *big data*, occurs through the use of various technologies from digital sensing components embedded within farm machinery to cell phones and tablets used by farm workers (Bronson, 2020). The data collected through these implements is then stored in databases where insights are generated using algorithms or AI (Bronson & Knezevic, 2016). Often using commercially available AI systems (called “decision support platforms”), AI-generated advice is used to create ‘prescriptions’ that can guide farmers and equipment to apply the right input, at the right rate, at the right time, in the right place, with the right tool (Zhai et al., 2020). The intention is that with AI, farmers can make data-informed decisions to more precisely manage operations and

decisions associated with production, market variability, and climate variability (Tey & Brindal, 2012), using geospatial, environmental, population and biological data on topics ranging from field characteristics, including soil pH and seed types, to on-farm weather and broader climate patterns (Bronson, 2020). The core function of PA is thus to facilitate the precise collection of relevant data through specialized equipment, and it is this reliance on data collection and use of big data that separates PA from traditional agriculture.

When defining PA, it is common to explain it in terms of its ability to improve efficiency and optimize agricultural processes. One of the formative definitions put forth by Pierce and Nowak (1999) encapsulates this optimization-centric perspective. These scholars define PA as a suite of technologies employed to “optimize agricultural production and food system processes by informing decisions to help decrease variability and uncertainty associated with all aspects of agricultural production” (Pierce & Nowak, 1999), focusing on its ability to enhance various aspects of an agricultural operation. Other definitions place technology at the centre of PA, focusing on the type of technologies used in the collection of data (Bauer et al., 2019; Boursianis et al., 2021; Yue et al., 2012). One example of this comes from the work of Yang (2020) who, in their evaluation of the application of variable rate and remote sensing technologies for disease detection in crops, referred to remote sensing as the core of PA. This work, situated in agricultural engineering, places the role of technology at the forefront when defining PA.

Some scholars perceive PA not merely as technology but rather as an approach to farm management. This approach incorporates a range of technologies and practices, enabling farmers to make more informed decisions and optimize processes throughout their entire operation (see Hedley, 2015; Robert, 2002; Whelan & McBratney, 2000). Placing PA within an administrative role, Fountas et al. (2020) imagine PA as a management system which allows farmers to collect

data to “observe, comprehend and manage” variability within their operations. Within this vision of PA, scholars view technology as an element that enables improved farm management which, through the data gathered using technologies, allows farmers to make more informed decisions about planting, applying treatments (e.g., pesticides and herbicides), and harvesting. Despite these different definitions, the overall goal of PA, shared across the literature, remains the same: to improve agricultural productivity and “sustainability” (though this is ill-defined) using advanced technologies and data-driven decision-making. Whether stakeholders view it as a management strategy or a suite of technologies, the lack of a universally accepted definition allows PA to be shaped by specific contexts, technologies, practices, and proponents themselves.

In my research, I define PA using the definition provided by Bronson (2019a), who defines PA as a “suite of artifacts” which facilitate “monitoring and measuring of inter and intra-field variability in crops in order to drive on-farm decisions” (p. 583). This suite of artifacts includes sensors capable of soil sensing and yield evaluation, GPS units for mapping and automated guidance, and other equipment which may not collect data but rather uses data in its operation such as variable rate application systems used to apply pesticides, fertilizer, and seeds (Bronson, 2019a; Schimmelpfennig, 2016; Shannon et al., 2018) The data collected by precision equipment is aggregated and coupled with additional data sets and algorithms to deliver data-driven insights to farmers on field conditions and inform actions for future seasons (Bronson, 2019a). This view on PA is non-normative and serves as a foundation for my research, guiding the exploration of the connection between PA and sustainability.

2.2 Current Research on PA

In the existing body of research on PA, scholarly attention centres around two key areas of research: the first being the development and evaluation of novel technologies and the second

being the assessment of adoption decisions made around well-established PA technologies. Research on the advancement of precision technologies encompasses a broad spectrum of studies focused on developing and assessing the effectiveness of various PA techniques and technologies. These investigations explore the development of novel technologies like remote sensing (Yue et al., 2012), drones (Srivastava et al., 2019), robots (Wu et al., 2020) and data analytics or AI (Shadrin et al., 2019) or examine outcomes of non-proprietary PA techniques and technologies by evaluating their comparative performance against commercial products. This sort of research does not evaluate sustainability per se but rather tests that novel technologies can perform as expected (i.e. can a computer algorithm accurately detect nitrogen fertilizer requirements from satellite imagery (see Paleari et al., 2019)). Another example of this kind of investigation comes from the research conducted by Shen et al. (2017). In their research, the authors analysed a laser-guided, air-assisted precision sprayer to assess its ability to identify weeds and spray them. The authors then compared the performance of this non-proprietary application system to a commercially available variable rate application system to determine if it performed better, worse, or comparatively to the commercially available technology. This research, among others (see Chen et al., 2020; Dammer & Wartenberg, 2007; Fabbri et al., 2020), often takes a software, electrical or mechanical engineering perspective to developing and evaluating new technologies. Research in this area seeks to contribute to the advancement of PA technologies and assesses the ability of novel technologies to perform in a manner which is competitive with commercially available solutions. By evaluating these emerging technologies, researchers aim to identify their strengths and weaknesses to improve the development of PA.

The other prominent area of research in the literature focuses on assessing the adoption of PA technologies, often looking to identify determinants of adoption and barriers that hinder the

widespread uptake of PA technologies. Articles in this area explore various aspects of adoption such as farmers' attitudes and perception of PA (D'Antoni et al., 2012; Gallardo et al., 2019; Thompson et al., 2019) and their decision-making processes leading to the adoption of PA technologies within their agricultural operations (Aubert et al., 2012; Khanal et al., 2019). These articles also investigate the role of demographic, and socioeconomic factors and field characteristics in adoption (Bucci et al., 2018; Butts et al., 2021; Gardezi & Bronson, 2020), often seeking to identify the groups who are eager to adopt or those who show hesitancy towards these new technologies (Nowak, 2021) and investigate techniques to overcome adoption barriers (Paustian & Theuvsen, 2017; Thompson et al., 2019). Understanding the barriers and the reasons behind the slower adoption rates is a critical aspect of PA research, as adoption rates have stalled in recent years (Lowenberg-DeBoer & Erickson, 2019). Considering a Canadian context, Mitchell et al. (2021) surveyed Ontario agriculture service providers, primarily equipment and input suppliers, to assess the barriers hindering the adoption of PA by Ontario farmers. This research identified income pressures, initial equipment costs and farmer confidence as the primary barriers to adoption (Mitchell et al., 2021). Contrasting research investigates enabling factors that drive farmers to adopt PA technologies in their agricultural operations. These determinants include the perceived utility of the technology, the state of relationships between farmers' agriculture consultants and service providers, incentives to adopt particular precision technologies, and self-perceived skill and knowledge level (see Pathak et al., 2019; Yatribi, 2020). Additionally, articles such as those written by Aubert et al. (2012), Barnes et al. (2019), and Bolfé et al. (2020) look to assess the value of PA through farmers' perceptions in an attempt to evaluate the environmental, economic, and social benefits of using these technologies. This type of research relies on the self-reported benefits farmers perceive from using these

technologies. For example, in the study conducted by Bolfé et al. (2020), scholars sought to investigate the application, challenges and future potential of PA technologies across Brazilian agricultural operations. In this work, the authors concluded PA has the potential to increase the sustainable management of natural resources, mainly soil and water, based on their finding that approximately 60% of farmers surveyed perceived the use of PA to reduce environmental impact (Bolfé et al., 2020). Although the particular focus of this paper is on adoption, other papers that examine adoption tend to arrive at similar conclusions (Aubert et al., 2012; Barnes et al., 2019). Scholars often attribute the perceived benefits of adopting a technology or practice with realized benefits, suggesting that people are more likely to adopt something when they believe it will be beneficial. Research investigating the adoption of PA relies on surveys and interviews to gauge farmers' attitudes and perceptions towards these technologies; the goal is to understand the reasons for adopting these technologies and to uncover the underlying factors contributing to the slow rates of precision technology uptake.

2.3 Sociological Literature on PA

Sociologists, economists, political scientists, and geographers also do work on PA, though this is a relatively much smaller collection of scholars. These researchers critically examine the role of PA in modern agriculture and explore a range of social considerations that are often overlooked in the above literature. Unlike the technology-focused literature, research on the social considerations offers a critical reflection on technology adoption in the agricultural sector, investigating the intersection between PA adoption and farm data management, farmer well-being, and rural livelihood and economies. Academics within this sub-field of research often present views that are critical or cautiously optimistic.

A key theme in the social science literature focuses on researching issues around data, seeking to understand the issues and politics around data used in the application of and generated by PA technologies. Academics investigate the ownership, access, and control of the extensive data generated by PA technologies, including the mechanisms of data sharing (Bronson, 2019b, 2020; Bronson & Knezevic, 2016; Carolan, 2015, 2018; Duncan et al., 2021; A. Fraser, 2019; Rotz, Duncan, et al., 2019). It also examines the implications of data sharing, including its effects on farmers, equipment manufacturers, software providers, and data analytic firms, especially in situations where multiple parties engage in data acquisition and distribution. Anidu and Dara (2021) highlight a central concern regarding data ownership, access and usage, which has become a large concern among farmers. This anxiety stems from concerns related to data-sharing practices, the lack of transparency regarding the terms of data licensing agreements, and disparities in negotiating power between farmers and those who gain access to their data (Anidu & Dara, 2021). Often, farmers believe they have full ownership of their data, even though this may not align with the legal realities (Anidu & Dara, 2021; Wiseman et al., 2019). Adding to the complexity, private contracts and data use agreements often govern agricultural data, giving rise to additional apprehensions regarding data privacy and security (Anidu & Dara, 2021). Farmers express legitimate worries about the potential misuse or unauthorized access to their data (Anidu & Dara, 2021). These issues have been identified by other academics (C. Brown et al., 2023) and public agencies such as the *Organization for Economic Cooperation and Development (OECD)* (Jouanjean et al., 2020). Challenges around data governance have created a need to introduce regulatory frameworks aimed at safeguarding farmers and enhancing transparency in data-sharing agreements, creating an area of research concerned with making recommendations to protect farmers (C. Brown et al., 2023). By looking at legal frameworks, licensing agreements,

and existing data protection regulations and engaging in discourse with farmers, academics in this area of research seek to understand the intricate intersection of data ownership, privacy laws, ethical considerations, and policy gaps to provide insights that balance technological innovation with legal and societal concerns (Bronson, 2022; Jakku et al., 2019; Wiseman et al., 2019).

Another area of focus in the social science literature centres on understanding the role PA plays in reinforcing existing power dynamics in the agricultural sector. Currently, a small number of large corporations control key aspects of the food system, including seed and agrochemical production, equipment manufacturing, and retail (Clapp, 2021; Hackfort, 2021; Howard, 2023). This concentration of power can limit competition, restrict independent innovation, and affect prices and availability of inputs (e.g., fuel and fertilizer) and commodities themselves (Clapp, 2021; Hackfort, 2021). Concentrating technology and data in the hands of large agribusinesses, on top of their existing monopolies, can potentially further exacerbate inequalities and concentrate power, impacting smaller farmers and rural communities (Carolan, 2021, pp. 26–39). Because large players in the agricultural industry are the predominant marketers of PA, PA technologies and their associated data have become grounds for biased technological development (Bronson, 2022). In their work, Rotz et al. (2019) discuss this issue, identifying the potential undesirable outcomes associated with increasing corporate concentration within the agri-food sector as agriculture and the broader food system becomes increasingly digitized. PA relies heavily on collecting massive amounts of data and large agricultural corporations such as Bayer (formerly Monsanto) and John Deere, are positioned to gain access to massive amounts of farm data (Bronson & Knezevic, 2016), creating potential issues with data governance and technology development in favour of corporate entities (Rotz, Duncan, et al., 2019). In her work, Bronson (2019) also discusses this idea: how a narrow set of

values around agriculture, agribusiness, and the role of technology in agriculture, held by the actors responsible for innovation and development in agriculture tend to favour large-scale and commodity crop farmers. This literature exposes the need to integrate new values around diversity and the accessibility to develop technologies and use data in a way that fosters equitable precision farming (Bronson, 2019b; Goodman, 2023).

Social science researchers also explore the socioeconomic ramifications of PA, often investigating the socio-technological transformations catalysed by emerging agricultural technologies. This exploration involves the analysis of labour dynamics shifts, alterations in social networks, and the evolving fabric of community structures all driven by the increasing adoption of and reliance on precision technologies within farming operations (Rotz, Gravely, et al., 2019; Shaji & Hovan, 2020). The socio-technological transitions ushered in by the introduction of PA, as noted by Gardezi et al. (2022), involve “reconfiguring farmers’ social practices, such as knowledge, meanings, work tasks, and social identities” (p.3). As precision technologies become more integrated into agriculture, they are not only replacing mechanized farm work but are also capable of performing tasks that once relied on human intuition and cognition (Gardezi et al., 2022). This restructuring of agricultural practices is reflective of the evolving relationships between farmers and their fields, as “smart” farming integration reshapes traditional farm roles and creates new roles where the knowledge of existing systems is changing. Research on the disruptive forces of PA in rural communities and economies further describes how not only the requisite knowledge required to operate advanced farm equipment is changing but the very nature of farm labour is also undergoing a transformation (Rotz, Gravely, et al., 2019). PA has the potential to both alleviate and increase workloads due to rising technical requirements (Gardezi et al., 2022). The literature suggests farmers may benefit from reduced

labour hours from using GPS-assisted guidance, which decreases the number of field passes required (Jensen et al., 2012), or from using robotic milking systems which, through automated milking of dairy cows, leads to reductions in the work hours of farmers (Molfino et al., 2014). Contrary to the expectation of easing workloads, research assessing the perceived benefits of using PA also reports an increased labour burden of farming (Erickson et al., 2018; Kitchen et al., 2002). The integration of technology has introduced additional complications to farming such as increased time spent troubleshooting advanced technologies (Ofori & El-Gayar, 2021). Furthermore, the literature emphasizes the central role of PA in transforming rural economies. PA is catalysing changes in the labour markets as technological change is reshaping traditional employment patterns and roles in farming communities (Rotz, Gravely, et al., 2019). As PA gains prominence, the demand for specialized skills related to data analysis, geographic information systems, remote sensing and technology maintenance is expanding (Bucci et al., 2018). This trend is altering the composition of the rural workforce, emphasising a need for expertise beyond traditional farming practices (Bucci et al., 2018). Research in this area looks at the implications this shift in labour markets has on the potential displacement of existing agricultural workers (Rotz, Gravely, et al., 2019), the need for training and education to equip farmers with the knowledge required to understand increasingly advanced machinery (Pogorelskaia & Várallyai, 2020), and the potential economic impact of emerging industries associated with technology development, data analysis and equipment servicing (Duncan et al., 2022; A. Fraser, 2019). The evolving relationship between farmers and their fields, coupled with the reconfiguration of traditional roles, reflects the socio-technological transitions driven by PA, emphasising the growing demand for specialized skills and adaptation beyond traditional farming practices. Overall, the social science literature highlights the profound shifts in

agriculture and rural communities resulting from the application of emerging agricultural technologies.

2.4 Linking Sustainability with PA

Since the creation of the first modern PA technologies in the 1980s (Mulla & Khosla, 2015), academics appear to have published on the topic of PA and its prospective ability to contribute to sustainable agriculture. It is likely that an early article titled “Improving fertilizer and chemical efficiency through ‘high precision farming’”, published in 1990, may have set a foundation for what would become the vast collection of literature on the topic linking PA with sustainability (Munson & Runge, 1990). This article which makes a series of recommendations to optimize the use of fertilizers and herbicides using precision equipment, begins to suggest there is a link between PA and sustainability through the perceived ability for precision technologies to reduce harmful agricultural inputs and optimize agricultural processes. This belief, widely expressed and well-established in academic literature, posits that PA can contribute to sustainability. In a 2004 paper titled “Precision Agriculture and Sustainability”, published in the journal *Precision Agriculture*, academics Bongiovanni and Lowenberg-Deboer open with the bold claim, “The concepts of precision agriculture and sustainability are inextricably linked.” (p.359). Their paper claims to investigate the sustainability benefit of variable rate application for nutrient management through a systematic literature review and a small-scale field study, asserting PA can foster both environmental and economic sustainability within the agriculture system (Bongiovanni & Lowenberg-Deboer, 2004). Scholars argue PA technologies play a role in creating a sustainable agricultural system by minimizing some of the impacts of the current industrial agricultural system, specifically through reductions in fertilizer, pesticides, water usage and GHG emissions, while simultaneously increasing productivity and

improving farmers' bottom line (Pierce & Nowak, 1999). Across the literature, there is a dominant claim around PA suggesting a strong link between these emerging agriculture technologies and sustainability.

In the context of PA, there appear to be diverse perspectives on what agricultural sustainability looks like and how to facilitate its operationalization. Within the literature, there exists a body of research on PA suggesting that precision technologies hold promise for decreasing input use and mitigating GHG emissions (Bacenetti et al., 2020; R. M. Brown et al., 2016; Franco et al., 2017; Kiran Kumara et al., 2020). This literature collectively suggests PA can contribute to environmental sustainability, defined as meeting human needs without compromising the health of the ecosystem (Morelli, 2011). An example from the work of Balafoutis et al. (2017) illustrates this idea. The authors speculate that PA holds promise to both indirectly and directly mitigate greenhouse gas emissions produced by the agriculture industry through, “(i) the enhancement of the ability to operate as carbon stock...(ii) the reduction of fuel consumption...and (iii) the reduction of inputs... (p.2)”. Primarily building upon the insights of others, these researchers emphasize PA’s likely capacity to reduce overall agricultural inputs, including fertilizer and fuel, and increase rates of carbon fixation to reduce GHG emissions and mitigate the impact of climate change. Together these improvements are believed to serve to mitigate the GHG emissions of the agriculture sector along with reducing amounts of other harmful inputs. This article, among the others, mentioned (see Bacenetti et al., 2020; R. M. Brown et al., 2016; Franco et al., 2017; Kiran Kumara et al., 2020), suggests the literature often frames sustainability in the context of PA in alignment with environmental sustainability, achieved through input reduction with the goal of increasing agricultural efficiency.

In addition to the discussion around environmental sustainability, the literature hints at PA's potential contribution to economic sustainability, referring to the ability to maintain economic viability over the long term (Basiago, 1995). Many proponents of PA expect that the application of technology will enhance many aspects of the agriculture industry including increasing yields (McKinion et al., 2001; Yost et al., 2017) and improving economic well-being (Bewley, 2010). The potential for more stable income and higher, less variable profits is one area of discussion central to the narrative on economic sustainability brought about by PA (N. Zhang et al., 2002). As seen in many works of academic research, academics are interested in quantifying the cost savings associated with using various PA technologies such as variable rate application systems and GPS-assisted guidance (Knight & Malcolm, 2007; Schieffer & Dillon, 2015; Van Evert et al., 2017). An example of such research can be seen in the work of Schimmelpfennig and Ebel (2016), where through a series of models and adoption scenarios the authors demonstrate that PA has the potential to decrease input costs through more precise application, facilitated by variable rate technologies. Much research on this topic is done through the use of modelling (Bazzi et al., 2015; Math & Dharwadkar, 2020) or by assessing farmers' perceptions of their financial state following the integration of PA within their agricultural operations (Bolfe et al., 2020; Gallardo et al., 2019). Through studies primarily focused on adoption research and farmer perceptions, it is evident that the perceived economic benefits often lead to the belief that these gains contribute to long-term economic sustainability.

Some of the literature also emphasizes the role of PA in strengthening certain facets of social sustainability. Social sustainability in the context of PA encompasses various aspects, including the role PA plays in enhancing the well-being of farmers and rural communities (Janker & Mann, 2020). One area in which this social narrative is dominant is in the application

of PA within the dairy industry. Through the application of various sensors that report on animal well-being and the use of robotic milkers to reduce manual intervention, farmers report increased well-being of both themselves and their livestock (Veissier et al., 2019). Within the literature on PA, academics also frequently position PA as a potential solution to address broader social issues, such as enhancing food security and mitigating world hunger, by leveraging promises around its capacity to improve agricultural output (Erickson & Fausti, 2021; E. D. G. Fraser, 2020; Hatfield & Kitchen, 2013; Philips, 2014). However, it is worth noting that while the literature highlights the potential of PA to address certain aspects of social sustainability, it may not consistently or comprehensively consider the broader social narrative surrounding these emerging technologies. Social sustainability appears to take a back seat in the literature and requires further investigation.

In the literature on PA, another concept of sustainability is sustainable intensification. In simple terms, sustainable intensification implies producing more output on less land and with fewer inputs (Pretty & Bharucha, 2014; T. Garnett et al., 2013). This model for sustainability combines efficient resource use, minimal environmental impact, economic viability, and equitable benefits for local communities into a balanced approach to agriculture development (Pretty & Bharucha, 2014; T. Garnett et al., 2013). By merging these dimensions, sustainable intensification aims to enhance multiple dimensions of sustainability which, by some imaginings of sustainability by academics, is the intended and realized definition of PA (Cassman, 1999; Lindblom et al., 2017). For example, Gebbers and Adamchuck (2010) state “[Precision Agriculture] will contribute to the main goal of achieving food security in a constantly changing world” (p.830), as they highlight the ability of PA to apply the right treatment in the right place at the right time to improve input efficiency in intensive crop production. These authors believe

that the primary role of PA is as an intervention to combat food insecurity by boosting the productivity of the agricultural system which can be facilitated through the improved application of various inputs thus resulting in positive returns in production (Gebbers & Adamchuk, 2010). By enabling data-informed decisions, academics believe this approach aims to reduce farmer error and optimize output, thereby boosting agricultural productivity while also contributing to reducing the environmental impact of agriculture and enhancing rural livelihood.

In summary, the literature on PA and sustainability appears to reflect a multitude of interpretations regarding how PA may lead to a more sustainable agriculture system. Further exploration is necessary to understand precisely how scholars writing on PA conceptualize sustainability as well as unpack the values inherent to these conceptualizations.

2.5 Research Gap

Many academics who write on the topic of PA assert or simply assume a link between PA and sustainability; however, questions remain around how academics define sustainability within what we might call the discourse on PA. Specifically within the social science literature, there is little consideration given towards sustainability and evaluating the seemingly inherent link between PA and sustainability. The literature on PA suggests a link between PA and sustainability, but no academic work has synthesized what is meant by “sustainability” in this context. Previous research has not yet attempted to trace the origins of these sustainability claims or uncover the historical, social, economic, and political forces that might have shaped this association. This lack of research leaves a gap in our understanding of how the link between PA and sustainability has formed and how it is understood within the literature.

To enhance our understanding of the link between sustainability and PA, in my research, I review the literature to identify existing models of sustainability and understand how the

literature defines (or does not define) sustainability. In addition to improving our understanding of what is meant by sustainability when discussing PA, I explore the question as to where this seemingly inherent link between PA and sustainability originates and explore the factors that may have contributed to its proliferation, especially in the absence of empirical evidence.

2.6 Conceptual Framework

These diverse interpretations of sustainability in the PA literature underscore its interdisciplinary and multidimensional nature. This chapter aims to provide an overview of the challenges associated with defining sustainability, emphasizing the relevance of social constructivism as a valuable framework for comprehending how actors have shaped the various interpretations of sustainability. It also explores how those interpretations have come to bear on how the definition of sustainability connects with the ways in which scholars define it in the literature. In this chapter, I introduce the theory of social constructivism, which offers a lens through which to better comprehend the multitude of conceptualizations of sustainability present in the discourse on PA.

2.6.1 The Plural Definitions of Sustainability

Coming from the forestry industry, Hans Carl von Carlowitz, a Saxon tax accountant and mining administrator, first formally used the idea of sustainability in his work “*Sylvicultura Oeconomica*” (or as translated “The Economic News and Instructions for the Natural Growing of Wild Trees”) (Spindler, 2013, p. 11). In this work, he explores the sustainable use of forests as he imagines sustainability as the continued, responsible use of a natural resource (Spindler, 2013, p. 11). However, despite the common attribution of sustainability to one wealthy white man, the reality is people have practised sustainability for generations, and it cannot be credited to any

single person. The challenge of sustainability is not only a contemporary one; it was, at the very least, an underlying goal for early civilizations (Rosen, 2018). During the Neolithic age, when humans shifted from mobile hunter-gatherers to living in agrarian settlements in what we now call the agricultural revolution, sustainability became a critical factor in determining the success or failure of societies (Altieri, 2004; Hughes, 1992; Rosen, 2018). These societies inherently understood the importance of utilizing natural resources in a manner that ensured their preservation and availability for future generations (Altieri, 2004; Hughes, 1992; Rosen, 2018).

Today, the term sustainability has undoubtedly gained prominence, permeating various disciplines, from business and politics to everyday conversations as climate change and other environmental issues continue to be a significant threat to humanity. We continue to develop ways to allow for economic growth and societal well-being while simultaneously attempting to consider and mitigate environmental impacts. As the term sustainability has become democratized, we come to question what sustainability means and how to define it. Frequently, the terms sustainability and sustainable development are used interchangeably, stemming from the initial widespread use of the term in the late 1980s with the publication of *Our Common Future* by the Brundtland Commission. This influential report presents a widely accepted definition of sustainable development as, “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (Brundtland, 1987). Building upon this early definition, other organizations including the *United Nations Food and Agriculture Organization (FAO)*, *World Bank* and *The Organization for Economic Cooperation and Development (OECD)* have drawn on inspiration from the Brundtland Commission to frame sustainability as the imperative to meet the needs of the present without compromising the ability of future generations to fulfil their own needs (FAO, 2023; OECD,

n.d.; The World Bank, 2015). These definitions often highlight a desire to preserve human, environmental and economic well-being.

Originally rooted in ecological preservation, sustainability has gradually expanded in scope and the word is used to encompass social, economic, and cultural dimensions (Basiago, 1995). Together, these elements of environmental stewardship, economic viability, and social responsibility form the dominant and widely accepted model of sustainability (Purvis et al., 2019; Todorov & Marinova, 2009). Often seen as the three-pillar model of sustainability (Figure 1 A), sustainability is viewed as a balance between the three interdependent dimensions, that can only remain standing if all dimensions are fulfilled (Rosen, 2018; Todorov & Marinova, 2009). Sustainability also manifests as the intersection point between three circles (Figure 1 B), where the circles represent each of the three dimensions (Rosen, 2018; Todorov & Marinova, 2009). Another variation of this exists where sustainability is modelled in terms of three concentric circles (Figure 1 C), where each dimension is a subset of the other (Rosen, 2018; Todorov & Marinova, 2009). A final model presents sustainability as a hierarchy (Figure 1 D), where the environment forms the foundation upon which social and economic sustainability are built (Rosen, 2018). Despite the ubiquity of these models, the origins of this conceptualization remain somewhat elusive (Purvis et al., 2019). Ultimately, these various models of sustainability emphasize the need to address ecological integrity, social welfare, and economic prosperity simultaneously to achieve an agricultural system that is productive now and will remain productive in the future (Purvis et al., 2019; Todorov & Marinova, 2009) and they provide a framework under which we can begin to understand sustainability.

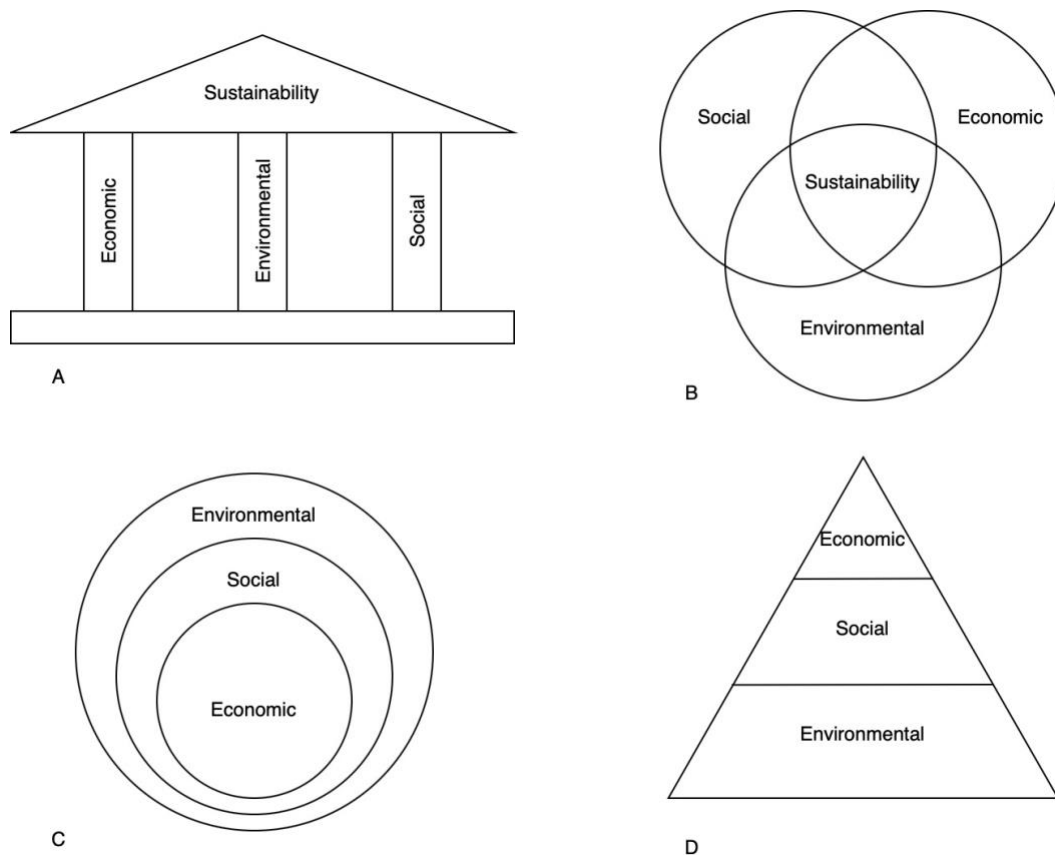


Figure 1 Models of sustainability. A) 3-Pillar Model B) Venn Diagram Model C) Concentric Circle D) Hierarchical or Pyramid Model. Adapted from Purvis et al. (2019) and Todorov & Marinova (2009).

This idea of sustainability as a means of economic and social progress with consideration for the ecological health of the planet is widely accepted, but with over 300 definitions of the term sustainability (Johnston et al., 2007), the concept has interpretations that conflict and the word itself is thus highly contested and is often considered to be vague and unmeasurable (Johnston et al., 2007). While some scholars promote a broad and thus holistic understanding of sustainability, such a conceptualization has also opened the door to diverse interpretations and applications. Indeed sustainability has been labelled a wicked problem (Rittel & Webber, 1973), meaning that it is often poorly defined, and poorly measured and action to achieve sustainability requires the engagement of multiple stakeholders operating at different scales (Struik & Kuyper,

2017). Moreover, sustainability interpretations are normative concepts, in that each is rooted in particular value systems (Ramsey, 2015). This means that different people or communities may have different understandings of what sustainability entails and how to measure and act on these definitions. Due to its diverse usage across various contexts, sustainability has evolved into an umbrella term encompassing a wide range of activities and initiatives, often unrelated to its core principles. This ambiguity in its usage has diminished the clarity of the term, making it increasingly challenging to distinguish genuine sustainable practices from superficial attempts and to provide a meaningful and somewhat universal definition. A significant body of literature attempts to conceptualize the term (see Purvis et al., 2019; Vos, 2007), but the consensus around defining sustainability lies with the idea that as a standalone term, sustainability is a challenge to define (Ramsey, 2015). The multifaceted nature of sustainability and its diverse interpretations underscore the ongoing challenge of providing a concise and universally accepted definition.

2.6.2 Social Constructivism and Sustainability

The sociologist Peter L. Berger and the philosopher Thomas Luckmann published their seminal work, “The Social Construction of Reality,” in 1966, which argued that reality is not a fixed or objective phenomenon, but rather a product of social consensus or collective meaning-making. They claim that individuals create and maintain a shared social reality through their everyday interactions and that this reality is not inherent in the physical world but is rather constructed through social processes (Berger & Luckmann, 1966). Under a social constructivist framework, our knowledge of the world and the ways we intervene in it, or our reality, is shaped by cultural and social factors. According to social constructivism, knowledge and understanding are not objective or independent of human perception, but rather are constructed through social interaction and cultural practices (Berger & Luckmann, 1966). With this perspective, we

understand that each person holds their own knowledge and understanding of a particular idea, and they actively create these ideas through social relationships and interactions (Charmaz, 2014, p. 240; Lynch, 2019). Unlike the positivist assumption that claims the existence of a single universal truth, social constructivism asserts no singular truth exists (Charmaz, 2014, pp. 229, 239–241), but rather there exists a multitude of truths rooted and informed by unique contexts.

The relevance of social constructivism to the discussion of sustainability and PA lies in its acknowledgement that social and cultural factors shape our understanding of the single term or concept of “sustainability.” Constructivism emphasizes that sustainability is not merely an objective reality that exists independently of human perception. The concept of sustainability assumes the existence of a set of social structures under which it can be defined (Ramsey, 2015). Therefore, any discussion or evaluation of sustainability must consider the specific social, economic, and environmental contexts in which it is applied. Diverse people define sustainability based on their particular sets of values and assumptions, which are not objective or universally agreed upon. It is additionally important to acknowledge the bidirectionality of the constructivist perspective, meaning the resulting construct created when we define sustainability holds significant power in mobilizing particular directions for our actions. Said differently: social realities (like values) help shape our usage of the term sustainability and in turn particular usages or models of sustainability help to direct our action in shaping the environmental and social world. The ‘construct’ of sustainability, as shaped by social, political, and economic values, becomes a critical catalyst that guides and influences the ways we intervene in the world to address sustainability challenges. Different interpretations of sustainability, grounded in particular sets of values and assumptions, can lead to diverse actions and strategies aimed at

achieving sustainability goals. Within the discourse on PA, people's conceptualizations of sustainability can influence how sustainability is operationalized.

As discussed previously, ambiguity exists around the concept of sustainability. The term sustainability has become intertwined in numerous disciplines, leading to the proliferation of various imaginings of the concept; each unique to the context in which it was created (Vos, 2007). This central premise, that the concept of sustainability has various meanings which are themselves rooted in various contexts, informs my intention to take a social constructivist approach in my research. Considering sustainability as it relates to PA under social constructivism, it becomes evident how cultural, economic, and political factors influence diverse understandings of sustainability. These contextual variations result in differing viewpoints among various proponents. A multitude of different actors including industry, government agencies, international development agencies and academia, have researched, promoted, and funded digital innovation in agriculture (Bronson, 2022), which should lead to the integration of various conceptualizations of sustainability as it relates to PA. Moreover, this constructivist approach can be applied to understanding the origins of such sustainability claims. Different proponents, including farmers, researchers, policymakers, and environmental advocates, have contributed to the creation of distinct visions of sustainability within this agricultural paradigm (see Bewley, 2010; de Koning, 2010; Finco et al., 2023; Franco et al., 2017; Kiran Kumara et al., 2020; Math & Dharwadkar, 2020; McKinion et al., 2001). These visions are not static but rather social interactions, cultural contexts, and evolving technological possibilities shape various conceptualizations of sustainability. In essence, PA becomes a dynamic arena where proponents construct and reconstruct the meaning of sustainability through social interactions and the convergence of different values, interests, and ideologies.

From within a constructivist framework, I will explore sustainability as a diversely framed concept, one which is shaped by perspectives and values. By acknowledging the plurality of perspectives and values that shape our understanding of sustainability, this framework can help me uncover the underlying assumptions and power dynamics that may influence definitions of sustainability in PA research. This framework can also facilitate a more critical examination of the dominant narratives and discourses surrounding sustainability and promote more reflexive and context-specific approaches to agriculture's sustainability challenges. Through this lens, we can gain a more nuanced and multifaceted understanding of sustainability and develop more effective and equitable strategies for achieving goals for how we humans wish to intervene in the natural world via food production.

Chapter 3 Research Design and Methods

This chapter outlines the methods used to answer the central research questions which all employed a qualitative research design to explore the relationship between PA and sustainability. The approach encompassed a multi-step strategy to data collection, combining a systematic literature review with in-depth semi-structured interviews with key informants from various academic backgrounds, which were then analysed using qualitative inductive coding. The following chapter will further outline these methods and provide rationale for these methodological choices.

3.1 Research Design

This research employed a qualitative methodology to investigate the connection between PA and the concept of environmental sustainability in scholarship on PA. Qualitative methods offer ways to analyse perceptions and socially constructed realities (James A. Holstein & Gubrium, 2021). Data collection occurred in two parts. First, an analysis of the peer-reviewed literature was undertaken to comprehend the framing of sustainability claims made in the technical literature on PA. Following that, key informants from academia, those who have published on and been cited for their publications on PA, participated in semi-structured interviews to further investigate how they conceptualize sustainability and to help identify various factors and influences that have played a role in linking PA with the concept of sustainability in their scholarship and the scholarship more broadly. The resulting data collected from these two activities was then analysed using inductive coding and qualitative content analysis. This analysis involved identifying recurring themes and relationships within the data to

provide a nuanced understanding of the connection between PA and environmental sustainability.

3.2 Data Collection

3.2.1 Systematic Literature Review

Previous articles collected through a systematic literature review conducted by myself, Dr. Bronson, and colleagues from the University of Ottawa and the University of California Berkley formed my first data set. Academic literature from the databases Greenfile, Scopus, and Web of Science was collected using a standardized search string – “Precision agriculture” OR “Precision farming” AND ((reduction OR reduce*) W/4 (pesticide* OR herbicide* OR water OR greenhouse)). Because our data collection sought to facilitate the assessment of the evidence to support sustainability claims, we used this search string as an indication of various metrics of environmental gain, where environmental gain was defined in terms of a reduction of pesticide, herbicide, water, or fertilizer use or a reduction in GHG emissions. While the search string primarily targeted articles related to environmental sustainability, some articles on other dimensions of sustainability, such as economic or social sustainability benefits, and sustainable intensification, were incidentally included due to the multidimensional nature of sustainability. The inclusion of other dimensions was evident during the analysis conducted in the previous research, (Bronson et al., Forthcoming), where many articles were found to focus on dimensions of sustainability that extend beyond the environmental aspect. Articles were then gathered and using the features available through these databases, citations were extracted and compiled in Microsoft Excel under standardized criteria. After the articles were identified and collected, they were evaluated to find and remove duplicates and the articles were screened on the basis that they were academic articles or full-length conference submissions published in English. The

resulting collection of articles, comprising 145 articles published between 1997 and 2021, served as the dataset for my analysis.

3.2.2 Participants Selection and Recruitment

Key informants from academia who published on PA and its relationship with sustainability served as the participants for the interviews. The choice of conducting key informant interviews lies with the objective of understanding the factors that have shaped the link between PA and sustainability, where key informants served as subject matter experts who could provide important knowledge on the topic. A large portion of the existing research on PA focuses on farmers and other food system actors and not academics (see Abeni et al., 2019; Barnes et al., 2019; Erickson et al., 2018; Mitchell et al., 2021; Paustian & Theuvsen, 2017; Sanders et al., 2022; Yost et al., 2019).

Selection of these key informants was purposive following a set methodology which sought to identify participants based on their contribution to the field of PA. To identify academics who published in the field of PA, Google Scholar was used to create a list of eligible academics. Using the search string “Precision Agriculture” AND “Sustainability,” a list of the top 100 most cited peer-reviewed articles was created. Only articles on PA were included to align with the research objectives focused on the on-farm implements. This criterion led to the omission of other technologies often classified as DA, such as blockchain, which are implemented beyond the farm and further down the food supply chain. The list of articles generated in this search was then reviewed to ensure the articles were peer-reviewed and that their abstracts referred to sustainability to some degree. Articles that did not discuss sustainability in their abstracts were omitted. Following this review, information for each article was collected including the names of the first and last authors. And using intuitional webpages,

Google Scholar, and Scopus's author search functionality, I reviewed each author's most recent publications to ensure they had published at least three articles on the topic of PA within the last five years. This criterion ensured that the participants had up-to-date knowledge and expertise related to PA and sustainability and had likely conducted recent research in the field. The decision to omit authors who had only one or two publications on PA was based on the need to ensure that the selected authors had a demonstrated interest and active engagement in the field of PA. After reviewing the articles according to the established criteria, a list of key informants was compiled, and academics were contacted via email to solicit participation. It can be noted that snowball sampling was used as well to identify participants, as there were some instances where academics who were unable to participate, provided contacts to colleagues who could participate or following interviews participants made recommendations of colleagues who would be an asset to be interviewed. From the list of authors contacted, five interviews were conducted. Two participants were affiliated with institutions in the United States, two worked out of Canadian institutions and one was located in the United Kingdom (Table 1).

Table 1 Complete list of interview participants.

Assigned ID	Discipline	Country of Institution	Gender
Key Informant A	Agricultural Science	United States	Male
Key Informant B	Economics and Agronomy	United Kingdom	Male
Key Informant C	Geography	Canada	Female
Key Informant D	Sociology	United States	Male
Key Informant E	Sustainability and Business	Canada	Female

3.2.3 *Semi-Structured Interviews*

Following recruitment, a total of 5 interviews took place during June, July, and August 2023. Interview questions were prepared beforehand (see **Error! Reference source not found.**) and made use of open-ended questions to allow the participants to guide the conversation and provide as much insight into their perspective on sustainability while also maintaining consistency across interviews. The interview questions were prepared following the literature review, informed by some of the initial findings, and consequently, reflected the insights gained from the analysis of the literature. This approach taken in the preparation for the interviews also aligns with the constructivist perspective informing this research and considers the multitude of perspectives and opinions held on sustainability as it relates to PA.

The interviews were conducted virtually and recorded using the teleconferencing platform Zoom, which allowed academics from various locations in the United States, Canada, and the United Kingdom to participate in this research. The interviews lasted between 45 and 65 minutes. Following the interviews, the audio recordings were transcribed making use of both the automated transcription provided through Zoom and the qualitative data analysis software Nvivo (Version 1.7.1). Participants were given a copy of the transcript to review and modify following their interviews. All transcripts were accepted as is, without any additional modification. The final transcripts, not including introductory & concluding remarks ranged from 17 to 28 pages.

3.3 Data Analysis

Data analysis occurred in two parts, seeking to analyse both the collection of articles obtained through the systematic literature review and the transcripts obtained through interviews. Analysis was conducted in a stepwise fashion so that results from the literature review could be brought into and inform the interviews. The analysis made use of inductive qualitative coding

through content analysis which aligned with the constructivist perspective because inductive coding aims to develop theories to understand the link between PA and sustainability from the texts themselves in the absence of preconceived notions (Charmaz, 2014, p. 240). The qualitative data analysis software Nvivo facilitated the analysis.

3.3.1 Qualitative Coding

Analysis began with the collection of articles obtained through the systematic literature review and then a separate coding followed which used the transcripts acquired through interviews. To analyse the first dataset – the articles collected through a systematic literature review – I employed an inductive approach for qualitative and thematic coding. Specifically, the analysis focused on coding only the introductions of each article since this section typically defined the concept of sustainability. The primary goal of this portion of the analysis was to gain insight into how the academic literature on PA conceptualized sustainability and understand how sustainability was operationalized in the study. To achieve this, I began the inductive coding process by first reading five articles and establishing codes from each article. This formed my first sample. This initial sample was revisited, and the established codes were applied. The process continued by analysing additional samples (i.e. groups of five articles), enabling the creation of new codes, as required. These codes were then refined and aggregated. This iterative procedure continued with new samples until all articles had been read and codes were applied. To ensure consistency within the analysis, the codes generated through this iterative approach were then used in a final round of reading and coding for all the articles. In this analysis of the literature and the creation of the qualitative codes I focused on themes regarding the definition and context of sustainability, the presentation of sustainability in alignment with particular models of sustainability, if there was emphasis placed on certain dimensions of sustainability,

and how sustainability was measured or operationalized. The resulting comprehensive codebook is available in Appendix B: Coding Schemas.

A similar inductive approach to qualitative coding was applied to analyse the dataset comprising the interview transcripts. In this analysis, each interview transcript was treated as an individual sample. Initially, the sample was read, and codes were assigned to text passages. Upon subsequent rounds of coding, these established codes were then applied to the same sample. This process was repeated for additional samples, and new codes were introduced as needed. The codes were continually refined and consolidated. This iterative process was replicated with each new sample until all the interview transcripts had been read and codes were applied. When coding the interview transcripts, I focussed on identifying underlying values present in the context of sustainability, the actors discussed as responsible for the link with sustainability and discussions around the inherent link between PA and sustainability, in addition to the themes about models of sustainability. Ultimately, the codes developed through this iterative method were used in a final round of reading and coding to ensure consistency within the analysis. The comprehensive codebook resulting from this process can be found in Appendix B: Coding Schemas.

Following the independent coding of both the articles and the interview transcripts, the findings from the systematic literature review and the interviews were triangulated to gain a more comprehensive understanding of sustainability in the context of the research question. Codes from each data source were compared to identify themes consistent between the two and to identify codes that could be applied across both data sources.

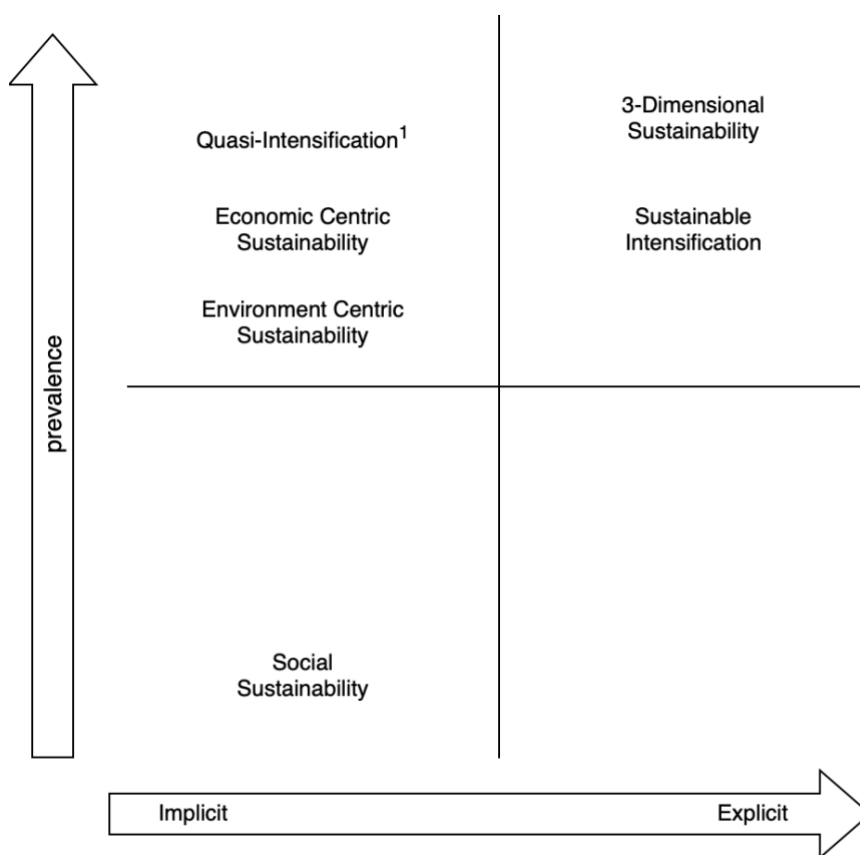
Chapter 4 Findings

The objective of this chapter is to present the seemingly multifaceted conceptual landscape of sustainability within the context of PA. In doing so, I help to uncover the intricate web of sustainability conceptualizations, models, and interpretations found in the literature on PA. The imaginings of sustainability present in the literature include economic, environmental, and social aspects, with articles often emphasizing specific performance indicators such as profitability and productivity. As I explore this relationship surrounding PA and sustainability, it becomes apparent that sustainability is a term frequently invoked but in some instances is left conceptually undefined or ill-defined by scholars in the literature where sustainability is implicitly interpreted. In this section, I also present a finding which emerged through my analysis regarding how scholars in the literature commonly frame sustainability in alignment with a predominant bias or inclination that associates sustainability with the existing productivist paradigm in agriculture.

After presenting findings from the analysis of academic literature for models of sustainability, this chapter then puts forth findings from the interviews held with key informants from academia. This analysis focused on tracing the origins and evolution of sustainability claims around PA. In this findings chapter, I reveal one way we might comprehend the roots of sustainability claims associated with PA by identifying the specific actors and factors that appear to have played pivotal roles in reinforcing the dominant understandings of sustainability in the PA literature and the assumed link between PA and sustainability.

4.1 Imaginings of Sustainability

The literature and academic interviews reveal diverse perspectives on sustainability (Table 2). Scholars associate PA with sustainability, often drawing on explicit definitions linking it to economic, environmental, or social well-being, often under a 3-dimensional model. However, the literature most often, lacks explicit sustainability models. Academics emphasize specific economic or environmental aspects, presenting benefits implicitly as sustainability. Figure 2 provides a qualitative overview of these findings, representing sustainability models based on prevalence and definitions in the literature. The subsequent sections further discuss these findings.



¹ Quasi-sustainability is representative of the combination of environmental and economic sustainability

Figure 2 Representation of sustainability models based on their prevalence and specificity in the literature.

Table 2 Summary of findings regarding sustainability models in the literature and interviews, listed in order of prevalence.

Model of sustainability	Method	Source	Key ideas around sustainability
Three Pillar	Literature Review	McBratney et al. (2015) Diacono et al. (2014) Gallardo et al. (2019) Liu et al. (2018) Rotz et al. (2019) Sanches et al. (2021)	Balancing profit, environment, and society Holistic Approach Efficiency and optimization Intergenerational Responsibility
	Interviews	Informant A Informant B Informant E	
Intensification	Literature Review	Huttel et al. (2022) Blaine et al. (2020) Fabiani et al. (2020) Lindblom et al. (2017)	Yield enhancement Resource efficiency Emphasis on economic aspect Explicit consideration for environmental stewardship Comprehensive – inclusion of the social
Economic Sustainability	Literature Review	Kolady et al. (2020) Bora et al. (2012) Ashworth et al. (2018) Lassoued et al. (2021) Takácsné György et al. (2018) Fountas et al. (2016)	Efficiency improvements without output compromises Optimization of resource use Profitability enhancements Cost reduction
	Interviews	Key informant C	

Table 2 continued

Model of sustainability	Method	Source	Key ideas around sustainability
Environmental Sustainability	Literature Review	Bongiovanni & Lowenberg-DeBoer (2004)	Optimizing resource use Reductions in chemicals, water, ghg emissions Enhanced crop yield and quality Environmental and climate impact reduction
		Knierim	
		Andretta et al. (2017)	
		Balafoutis et al. (2017)	
		Lang et al. (2021)	
		Kayad et al. (2021)	
Carballido et al. (2013)			
Complementary Benefits	Literature Review	Chami et al. (2019)	Resource Efficiency and Financial Gains Environmental impact reduction Yield and Quality enhancement Economic priority Environmental benefits as secondary
		Van Evert et al. (2017)	
		Biao et al. (2017)	
		Abouva et al. (2020)	
		Aleixandre-Tudo et al. (2018)	
		Colaço et al. (2020),	
	Jensen et al. (2012)		
	Pallottino et al. (2019)		
Schieffer and Dillon (2015)			
Interviews	Key informant E		
	Key informant B		
Social Dimension	Literature Review	Thompson et al. (2019)	Labour efficiency and improvements Need for comprehensive social sustainability.
		Yanes et al. (2020)	
		Morgan-Davis et al. (2018)	
		Khanna (2021)	
	Interviews	Key Informant B	
Key Informant C			

1. The prevalence of combined economic and environmental benefits, referred to as 'commentary benefits,' is more prominent than in instances where economic and environmental benefits are considered independently.

4.1.1 Holistic Models of Sustainability

3 Dimensions of Sustainability. The analysis of literature, conducted in part one of my research, when combined with the analysis of interview transcripts, reveals that the only coherent definition of sustainability to emerge across the literature is one which draws on the three-dimensional model of sustainability, academics present sustainability as a balance between social, economic, and environmental well-being. This model emerged as the most common explicit conceptualization of sustainability among academics. McBratney et al. (2005), define sustainability under the triple-bottom line model of sustainability. In their article, these authors discuss the benefits of PA and state:

In simple terms—a concomitant increase in quantity and/or quality of production and/or the environment along with the same or decreased inputs...This will indeed involve a triple-bottom line kind of definition focusing on sustainable development and taking into account traditional profitability along with environmental and social benefits.

In this example, McBratney et al. echo the understanding that sustainability encompasses a broad set of goals and underscores the idea that sustainable agriculture under PA should be ecologically responsible, socially equitable, and economically viable. Other authors including Gallardo et al.(2019), Liu et al. (2018), Rotz et al. (2019), and Sanches et al.(2021) reiterate this sentiment in their research. These papers all view the application of precision technologies as a means of increasing profits and productivity, improving the livelihoods of farmers, enhancing the health and well-being of livestock, and reducing the environmental impact of the agriculture industry by aligning sustainability with the various interpretations of the three-dimensional model, to some degree.

Among those papers that present this three-dimensional model, scholars also often reference well-known definitions to conceptualize sustainability. In their paper “An approach for assessing the effects of site-specific fertilization on crop growth and yield of durum wheat in organic agriculture”, authors Diacono et al. (2014) open their article by defining sustainability before linking the concept to PA. In this paper, they define sustainability as per the definition provided by the *FAO*, stating, “Sustainability refers to agricultural practices technically appropriate, economically and environmentally viable that meet society needs for food, feed, ecosystem services and human health for present and future generations” (p. 480). This way of conceptualizing sustainability aligns with the three-dimensional model; it recognizes the interdependence between economic, environmental, social, and technical dimensions of sustainability while also having consideration for the responsibility to meet present needs while safeguarding resources and opportunities for future generations. It also recognizes an alignment with the goals of PA with greater societal goals put forth by international development organizations such as the *FAO* and emphasizes the need for comprehensive agricultural practices that extend beyond mere economic or environmental considerations.

When asked how they would define sustainability in interviews, all five key informants provided a definition that aligned with the 3-dimensional model, highlighting the idea that PA should contribute to economic, environmental, and social well-being, for present and future generations. They drew on definitions provided by the Brundtland Commission and the *FAO* to illustrate how sustainability aims to, as key informant C says, “produce a desirable future”. This informant went on to state:

My reaction is to like, go to the pillars of sustainability like social, economic, and environmental...If PA is sustainable, it doesn't reproduce kind of negative social patterns.

It has economic sustainability; you know there's a return on investment over time. And there's environmental sustainability and it's not degrading our landscape.

Another key informant (A), when asked how they define sustainability under the context of PA, called upon the *FAO* definition of sustainability saying:

I think to me, I agree with, think it's the *FAO* definition of it. Basically, the idea that sustainability in the agricultural context, is that we are providing production of food, fuel fibre, and feed for livestock without degrading our natural resource base that is being used to produce those products. So, in a way, it's, meeting our needs, along with not degrading, what is providing for those needs.

Key informant B defined sustainability in terms of the definition outlined by the Brundtland Commission:

So, you know, probably the most widely quoted definition of sustainability is from the Brundtland Report, which I'm sure you're familiar with, is about being able to satisfy current needs without impinging on the ability of future generations to also produce.... I think it's important to point out that this sustainability has an important human and especially economic component as well. If you had a system that was quite ecologically sustainable, but didn't sustain the human in that, that system, it's not sustainable.

Even when defining sustainability from the perspective of business and entrepreneurship in agriculture, key informant D defined sustainability as a comprehensive concept with social, economic, and environmental dimensions:

So, from the viewpoint of being a business owner is how I typically try to define sustainability. And to me, that is an entrepreneur or business owner that knows the social,

environmental, and economic input of *all* the decisions they make in the production of their product or creation of their service.

Defining sustainability as a balance between social, economic, and environmental well-being brings attention to the importance of meeting societal needs while preserving the health of our planet and pursuing economic prosperity in a way that supports the well-being of all people. In this context, these works from the academic literature and words from key informants serve as an illustration of how the three dimensions of sustainability are operationalized in the field of PA. It highlights the notion that emerging agricultural technologies can lead to positive outcomes in multiple dimensions, thus contributing to a more comprehensive and balanced form of sustainability facilitated by PA technology and practices.

Sustainable Intensification. Alongside the three-dimensional model, the literature revealed one other model, or more appropriately considered as a framework, known as sustainable intensification. Although still common to see sustainability presented under this conceptualization, when considering the coherent models of sustainability, intensification is *less* prevalent than 3-dimensional models. Many articles, including the works of Balaine et al. (2020), Fabiani et al. (2020), and Lindblom et al.(2017), conceptualize sustainability in terms of intensification. In the work by Hüttel et al.(2020), a paper included in my analysis, sustainable intensification is defined as, "...sustainability that implies producing more commodities from less land and water, which in turn requires increasing yields and sustainability of the production system." (p.79). Under this conceptualization, the focus is on enhancing agricultural productivity without expanding the agricultural land base or using excess resources. This approach aims to optimize resource use, including the use of land, water, and chemicals, to achieve higher yields

while minimizing negative environmental impact and preserving biodiversity – two common core principles of sustainability. In the context of intensification, as demonstrated by Blaine et al. (2020), authors also explore the potential benefits for social sustainability arising from the use of PA, especially within the dairy industry, integrating intensification within the three-dimensional model:

When applied to livestock production, sustainable intensification relies on diluting the environmental costs of animal maintenance (environmental pillar) through production efficiency gains (economic pillar) with socially acceptable standards of animal welfare (social pillar) (p.1)

The explicit inclusion of this social dimension recognizes the consideration for social well-being in the framework of sustainable intensification. It emphasises the need to not only improve economic and environmental aspects but also ensure the well-being of farmers and animals involved in agricultural operations when using emerging technologies, reflecting the belief the PA is beneficial for productivity, the environment and society.

Lack of Definitions. It is important to note that, although the above two models of sustainability were prevalent in the literature, a significant number of articles I analysed do not explicitly provide a clear definition of sustainability when discussing PA. This pattern was especially evident in the literature that focussed on the technical aspects of PA such as sensor technologies, data analytics, and automation (Jawad et al., 2017; Pallottino et al., 2019; Scharf et al., 2011; Shen et al., 2017). A key informant (A) discussed this issue in our interview, noting that academics often fail to provide context when discussing sustainability, especially when the focus is on technical elements. This participant went further to say:

So, I think that when researchers aren't providing a definition or a context, they're relying on this, this kind of agreed upon definition, this general definition that when you dig into it, there's a lot of nuances to it. And so, I guess you could say that if, if researchers are talking about sustainability, but they're not really defining it, are they really focused on promoting sustainability?

These remarks about relying on an "agreed-upon definition" suggests that scholars may be assuming a shared understanding of sustainability. The absence of explicit definitions given by scholars writing on sustainability and PA may reflect a gap in the collective understanding of what constitutes sustainable practices in PA. Overall, in many cases, authors neglected to provide clear definitions or context surrounding what they meant by sustainability in their articles. Additionally, despite definitions being present in the literature, there is a common absence of consideration for sustainability defined in broad terms (e.g., three pillars). Instead, authors often mention sustainability superficially without further defining the concept or explaining how to measure it, which raises questions about the intention of using the term.

4.1.2 Implicit Models of Sustainability

In the academic discourse surrounding PA, a large portion of the literature does not present discrete models of sustainability or articulate sustainability in explicit terms. While some researchers adhere to comprehensive sustainability models, others tend to value isolated aspects, presenting economic-centric and environmental-centric models, or combining the two in a model representative of what I call quasi-intensification. Scholars often depict these models implicitly as in many cases, academics do not overtly label or define their findings as sustainability. Instead, I as an analyst had to infer their definition of sustainability by the ways, for example, they describe how precision technologies in agriculture have positive effects on the environment,

increase economic efficiency, or achieve a balance between these two factors. These implicit conceptualizations are common across the literature, with the biggest focus often directed towards economic benefits presented in conjunction with environmental gains. Said differently, my results show no one common framework, revealing scholars often leverage ideas of sustainability without explicitly defining it.

Environment-Centric Models. Beginning with the ecological perspective, the literature on PA and sustainability underscores the environmental benefits achieved through precision technologies. These benefits include reductions in scarce or harmful agricultural chemicals (Shang et al., 2021; Wu et al., 2020)14/02/2024 16:18:00, water usage (González Perea et al., 2018; Neupane & Guo, 2019), or GHG emissions (R. M. Brown et al., 2016; D’Antoni et al., 2012) and improvements in tillage to reduce soil erosion (Li et al., 2016). Bongiovanni and Lowenberg-DeBoer exemplify this idea in their 2004 paper titled “Precision Agriculture and Sustainability”. In this article, the author's primary objective was to evaluate the sustainability of PA technologies, with a particular focus on variable rate application. In the article, the authors write, “From the first time a GPS was used on agricultural equipment the potential for environmental benefits has been discussed. Intuitively, applying fertilizers and pesticides only where and when they are needed, should reduce environmental loading.” (p.359). In this example, the author’s statements reflect a strong emphasis on environmental good as being a key benefit of PA. Such benefits are intrinsically linked to the broader concept of sustainability, or more specifically, are a hallmark of an environment-centric model of sustainability. In this case, scholars regard PA as a means to achieve environmental goals through the precise and efficient application of agricultural inputs, a core principle of PA. This site-specific approach minimizes

the overuse of chemicals, decreases runoff, and mitigates the risk of environmental pollution, underscoring the significant focus on environmental benefits. Other articles such as Andretta et al. (2018), Balafoutis et al. (2017) and, Lang et al. (2021), identify PA's ability to contribute to climate change mitigation, in addition to the other ecological benefits previously discussed. One of these articles is the work by, Knierim et al. (2019), where scholars explore farmers' and other stakeholders' perceptions and attitudes towards PA across Germany. When discussing the application of PA technologies, they state: "This broad range of technologies is supposed to contribute to a "smarter" way of farming that benefits cultivation practices, crop yield and quality, and farm work, so that "it reduces the environmental and climate impact of farming" (p.2). PA's potential capacity to address the pervasive challenge of climate change not only highlights its environmental merits but also extends the environment-centric model of sustainability. One common theme across the literature that examines the environmental advantages of PA, is the close association between environmental improvements and the broader concept of sustainability. This pervasive idea underscores the belief that environmental benefits achieved through PA practices, such as reduced resource usage, minimized environmental impacts, and enhanced ecological well-being, are not just isolated successes but integral components of a more sustainable and responsible approach to agriculture. By aligning environmental gains with sustainability, the literature presents a conceptualization of sustainability with a central focus on fostering environmental good.

Researchers commonly evaluate these environment-centric conceptualizations of sustainability, often associated with the reduction of harmful or scarce inputs, through the lens of input optimization and efficiency improvements. Kayad et al. (2021) discuss resource optimization within an environmental context in their decade-long field study of site-specific

application. Addressing nitrogen application, the authors write, “Site-specific application of nitrogen is a PA approach to optimize nitrogen fertilizer use efficiency and to reduce nitrogen leaching. This approach aims to adjust nitrogen fertilizer application to match crop requirements at different spatial and temporal extents.” (p. 2). Here, these scholars show how the optimization of nitrogen application, a practice facilitated by PA, mirrors a broader trend within PA, where sustainability is frequently articulated in terms of resource optimization and efficiency enhancements. Carballido et al. (2013), add to this discussion by discussing the benefits of precise herbicide application, outright highlighting its perceived ability to make operations more efficient:

The current objective of precise herbicide application is to make operating input more efficient by minimizing overlap and skip incidents and eliminating application on non-crop areas. As this objective is achieved, fewer herbicides can be used compared to conventional application, resulting in lower cost and risk for the environment (p. 642).

This focus on operational efficiency aligns seamlessly with the broader theme that efficiency is an integral component of sustainability within PA. It underscores the idea that by optimizing resource use and minimizing waste, PA can not only increase efficiency but also contribute to more sustainable agricultural practices. The core premise is to do more with less, ensuring that agricultural practices not only meet the current needs but also safeguard the capacity of ecosystems to support future generations.

Economic-Centric Models. In addition to the ecological benefits of PA framed as sustainability, there is a *more notable* emphasis placed on the economic benefits of using PA on farms. While the literature commonly equates ecological benefits with sustainability, directing

attention to economic advantages reveals a different dimension of the way the literature conceptualizes sustainability. By enabling better decision-making and precise input usage, academics associate PA with improved economic performance of the farm and associate this benefit with sustainability. Kolady et al. (2021), exemplify this belief in their research on the determinants of PA adoption when they state, “[PA] technology allows producers to conserve inputs, and this improves efficiencies while maintaining or even improving output, and ultimately enhancing profitability” (p.960). This article emphasizes the belief that PA enhances profitability by optimizing input use, without negatively affecting crop yields, thus contributing to economic viability. This economic dimension of sustainability is essential because it directly impacts the livelihoods of farmers. Economic sustainability addresses the immediate needs and concerns of agricultural stakeholders, making it a compelling and tangible selling point for adopting PA technologies. A key informant’s observation about the prioritization of economic benefits in the promotion of PA also aligns with this perspective. When discussing the promotion of PA under the premise of sustainability, key informant C discussed that PA’s capacity to boost productivity and profitability takes centre stage in PA promotion efforts aimed at encouraging farmers to adopt these technologies. They state:

To get people to buy into [PA] there has to be some kind of benefit for the farmer that's been articulated, and the number one seller is always going to be enhanced productivity and profitability. And so, I think that's been promoted more than the sustainability piece.

These perspectives underscore dominant paradigms of agriculture, where proponents often prioritize economic sustainability due to its direct and tangible impact on farmers' livelihoods and well-being. Considering this reality, where production holds significance, sustainability is

frequently equated to some economic benefits or gains, often in the form of increases in productivity.

Within the framework of economic benefits, throughout the literature, when evaluating sustainability, it is common to observe the practice of equating metrics related to input reduction with enhancements in resource utilization efficiency, resulting in cost savings. For instance, in their 2012 paper, which investigated the energy savings incurred following the adoption of PA in various rural communities across the United States, Bora et al. write, “[PA] involves the development and adoption of knowledge-based technical management systems with the goal of optimizing application of fertilizer, chemicals, seeds, and irrigation resources to reduce input costs and maximize production.”. By making this statement, highlighting the ability of PA to reduce inputs and maximize productivity, these authors emphasize the ability of PA to deliver the economic promise of improving financial viability and operational productivity. Furthermore, considering site-specific management, a subset of variable rate application, Fountas et al. (2016) describe the benefits of using such a system when they state, “PA can assist crop producers, as it permits the use of precise and optimized inputs leading to reduced costs and environmental impact...” (p.42). In conjunction with this article and others (Ashworth et al., 2018; Lassoued et al., 2021; Takácsné György et al., 2018), the literature displays a recurring theme where sustainability is operationalized through optimization and efficiency enhancements. This emphasis on the economic gains achieved through the operational efficiencies of PA aligns with the broader economic theme in the literature, which frequently equates sustainability with improved economic outcomes.

Complementary Benefits? Indeed, it is significant that, in the analysed articles, the largest portion of the articles discuss both environmental *and* economic benefits to some degree, emphasising the intended role of PA in achieving both at the same time, without trade-off, in some form of quasi-intensification. These articles frequently assert a connection between economic and environmental good in a manner that supposes that PA can deliver on both, or that in delivering on one (typically economic) there is a delivery on the other (environment). In their 2019 paper, Chami et al., authors who sought to investigate the financial and environmental benefits of using precision irrigation via modelled scenarios based in Southern England, illustrate both the cost savings and environmental stewardship capacity of PA; “The potential benefits of managing crops using variable rate irrigation techniques include financial and environmental benefits obtained as a result of higher water use efficiency, energy savings and increased marketable yield and/or crop quality.” (p.43). This sustainability construction or framing also appeared in the works of Abouva et al.(2020), Aleixandre-Tudo et al. (2018), Colaço et al.(2020), Jensen et al. (2012), Pallottino et al.(2019) and Schieffer and Dillon (2015). Emphasising both benefits through PA, this approach to sustainability highlights how PA frequently promotes the promise of economic and environmental benefits, which scholars often perceive as mutually reinforcing.

Despite the finding that scholars often present sustainability as a complementary relationship between economic and environmental gains, some obscure trends emerged from the literature. These trends suggest that even when the literature presents sustainability as quasi-intensification, there is continued attention directed towards the economic dimension. When discussing the relationship between economic gain and environmental benefits, authors draw distinct boundaries around the two concepts. While this trend is present in the literature and

should be noted, it is not necessarily a negative occurrence. Rather, it prompts a consideration of how academics perceive the relationship between economic and environmental-centric sustainability. This phenomenon is a subset of the greater trend of the presentation of economic and environmental benefits as integral components of the overarching concept of "sustainability". Often, profitability can be considered as one element of sustainability, particularly within its economic dimension, yet authors often separate the two concepts, delineating between sustainability and profitability. For instance, in the work by Van Evert et al. (2017), when defining PA, these authors highlight the expected economic and environmental benefits of PA for farmers and society:

[PA] is the scientific domain that deals with management of spatial and temporal variability to improve economic returns and reduce environmental impact. For farmers, PA is expected to lead to an increase in profitability; for society, PA is expected to lead to increased sustainability. (p.1)

The distinction drawn between profitability and sustainability, as illustrated by these authors reflects a nuanced understanding of these concepts within the PA literature. In this example, the authors draw a clear line between profitability and sustainability; for farmers, the primary expectation is increased profitability, indicating a strong economic focus but in contrast, the expectation for society is increased sustainability, with the emphasis shifting toward broader environmental and societal benefits. This separation indicates that when considering sustainability in the context of PA, economic gain and environmental benefits are not necessarily synonymous. It emphasizes the idea that, although profitability is a crucial component of economic sustainability, it should not be equated with overall sustainability. By making this separation, academics draw additional attention to economic benefits. Biao et al. (2017) also

express the notion that profitability and sustainability are not mutually exclusive concepts. In this example, the authors distinguish not only between profitability and sustainability, but introduce the concept of environmental stewardship as separate as well, drawing a distinction between all three. Biao et al., state, “PA technique is a management system based on the spatial variability of the factors inherent to the productivities obtained in the areas, aiming at optimizing profit, sustainability and environmental protection.” (p.938). How these authors distinguish between profitability, sustainability, and environmental stewardship, while emphasising their individual significance, may inadvertently create some ambiguity around these concepts and foster a disconnect between them. By isolating these concepts in the discourse, there is a risk of overlooking their inherent interdependencies. Profitability, sustainability, and environmental stewardship are, in practice, deeply intertwined and separating these dimensions may not fully capture the interactions that can exist between them.

The distinct separation of interrelated sustainability concepts also raises questions about what is really being achieved. Considering the interviews with key informants, one critical finding suggests that the potential environmental good achieved using PA is as the key informant (B) states a “side benefit” to the more prominent economic component. When asked about the benefits PA has for farmers, key informant B responded by providing an example of GPS guidance.

The way a lot of precision agriculture has been sold has been sold based on the economic benefits for farmers, so if you look at...well how has GPS guidance for spray or boom control or other kinds of application technology been sold? Well, it's been sold as you know, it saves you money...Oh, and, by the way, it has an environmental benefit because

you're reducing the total amount of pesticide that you're applying, and you're not, you're applying it on the right place. But that's a side benefit.

PA technologies consistently present economic benefits as the primary selling point, framing environmental benefits as secondary or side benefits. This observation demonstrates the dominance of profitability in the discourse and the way it often eclipses the broader environmental objectives. Key informant E responded to a similarly framed question in the same way, highlighting how although both economic and environmental benefits are present in the promotion of PA, the economic benefits take precedence.

The number one seller is always going to be enhanced productivity and profitability. And so, I think that's been promoted more than the sustainability piece, because that's what farmers care about that a hundred times more than sustainability. Farming is a business, and that's at the bottom line.

The conflation of profitability and sustainability raises questions about the true nature of the achievements within PA. It is evident that economic benefits are frequently prioritized and framed as the primary driver, with environmental benefits often relegated to the status of "side benefits".

In the instances mentioned earlier, whether in an ecological or economic context, or a combination of the two, what is observed is not all-encompassing models of sustainability. Instead, we see fragments of sustainability, each focusing on specific benefits that have become the prevailing frameworks for promoting the concept of PA. These fragmented perspectives, whether they are primarily environment-centric, economic-centric, or a blend of both, exemplify models that emphasize specific dimensions of sustainability.

4.1.3 *Lack of a Social Dimension*

As previously stated, the prevailing conceptualizations or framing of sustainability presented within the literature centres on the economic and environmental dimensions of sustainability, often with the implicit assumptions the two are linked. The academic literature less commonly addresses the social dimension of the traditional three-dimensional model of sustainability, which encompasses improved labour conditions, support for rural communities, and increased overall farmer well-being. My analysis illustrates that the literature partially addresses social sustainability, primarily from the perspective that PA can “reduce operator fatigue and increase the ability to multitask”, as described by Thompson et al.(2019), in their research on PA adoption. This sentiment is echoed by Yanes et al. (2020), Morgan-Davies et al. (2018), Khanna (2021), and Fabiani et al (2020), all of whom attribute certain enhancements in labour conditions on farms to the implementation of PA.

My analysis revealed an additional trend: those articles which do discuss social sustainability or social benefits often present these benefits with economic gains. An example of this comes from Bora et al.’s (2012) paper on energy savings achieved following the adoption of PA. Within their writing, these authors discuss the benefits of using variable rate technologies where they make mention of the reduction in labour achieved through the use of PA: “Adoption of [variable rate technologies] can reduce fuel use, since [variable rate technologies] coupled with GPS guidance systems reduces implement overlap during input applications, thus *saving labour* [emphasis mine] and machine hours.” (p.1). This statement is then followed directly by a discussion on the cost savings associated with GPS guidance and variable rate technologies which according to a United States Department of Agriculture study “saves about US\$13, 000 in variable costs annually” (p.2). Despite these authors identifying labour savings, attention shifts to

the economic benefits. This transition reflects the overarching emphasis on efficiency and profitability in the PA and sustainability literature. These articles often include any social benefits under the umbrella of economic sustainability benefits, considering social sustainability a by-product of larger economic gains such as in the case of labour “savings”. This tendency to link social benefits to economic outcomes is common within the literature and it underscores the relative neglect of the social dimension in discussions of the sustainability of PA.

Furthering this discussion of the relative neglect of the social dimension, while there is some discussion which considers a social dimension when conceptualizing sustainability in the literature on PA, many of the articles I examined either do not address the social benefits of PA or neglect social sustainability in favour of directing attention towards economic or environmental gains. This sentiment finds resonance in the words of key informant B which arose during our discussions around the prevailing framing of sustainability in the discourse on PA. Key informant B spoke about how industry and academics have consistently discussed the economic and environmental benefits of PA but frequently neglect the social dimension:

The social part of it really in PA has not been very present. It's there, but it's been much more economic and environmental focused. Now, the social part of it on, say, the milking robot example, the social part of it was there from the very beginning with *Lely* and when the other milking machine companies started developing milking robots the discussion of the social aspects have been important in that context, but that hasn't been the case for all PA.

Key informant C also expressed a belief that the social dimension of sustainability is often lacking from discussions, emphasising the potential for PA to undermine any attempt at social sustainability: “In terms of kind of the social sustainability of farming, I think [PA] actually in a

lot of ways undermines that potential... and so that's to me, that's not sustainable.”. In alignment with key informant B and C's concerns, it is evident that the current discourse on PA may not adequately address the critical social sustainability aspects, creating a gap in the broader understanding of its impacts. The prevailing sentiment in the literature focuses on quantifiable and easily measurable aspects, such as economic and environmental benefits, which marginalizes or omits the social dimension of sustainability in the literature on PA. While there are some instances where social sustainability is emphasised in scholarly articles on PA, overall, this dimension of sustainability remains either underexplored or omitted from the discourse.

4.2 Origins of Sustainability

Through the analysis of my interviews, I identified various factors that influence the connection between PA and sustainability and shape its various conceptualizations (Table 3). To provide an overview, the concept web below (Figure 3) presents these factors and key ideas, illustrating how each factor contributes to the creating and reinforcing the link between PA and sustainability.

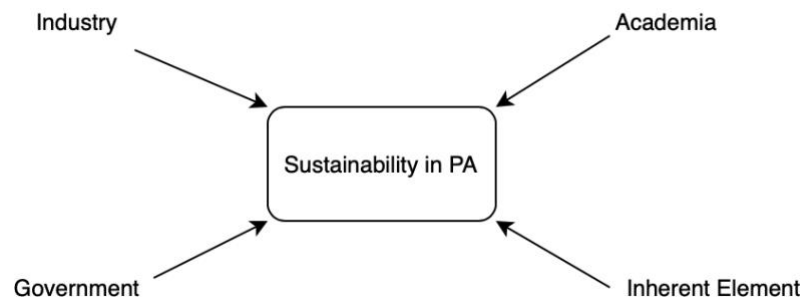


Figure 3 Concept web representing the factors responsible for shaping the link between PA and sustainability, highlighting the three factors identified and the inherent connection PA has with sustainability.

Table 3 Summary of findings of influential actors responsible for shaping the link between PA and sustainability.

Influence/ Actor	Source	Key themes and values
Inherent element		Sustainability has been a part of PA from the outset
	Key informant B	Sustainability is an inherent element of technology development
	Key informant C	Historical connection between technology advancement in agriculture and sustainability
	Key informant D	Enduring commitment to environmental stewardship rooted in PA
		Link between technological progress with sustainable agriculture practices
Academics	Key informant B	High impact academic works assert a connection
	Key Informant C	Key players assert a connection (i.e., Pierre Robert)
	Key informant E	Interdisciplinary interest in PA and sustainability
	Key informant D	Academics play a role in introducing ambiguity by promoting narrative uncritically
Industry	Key informant E	Industry promotes the economic and environmental benefits of PA
	Key informant D	Emerging markets are key areas to promote sustainability
	Key informant A	Economic emphasis in the presentation of sustainability
	Key informant C	Values profitability and productivity for farmers
Government		Governments support PA to combat environmental issues
	Key informant C	Sustainability goals promoted by government primarily concern climate change mitigation
	Key informant D	Promotion is often done without presence of Evidence
	Key informant B	Government promotion of PA has led to a hole that is filled by industry
		Sustainability promoted by government done primarily through subsidies and regulations

4.2.1 Sustainability as an Intrinsic Element?

From my interviews, it appears that the concept of sustainability, primarily the principles of environmental stewardship and resource conservation, has been intertwined with PA since its inception, but the framing of sustainability within the context of PA often centres on productivity, profitability, efficiency, and optimization. When asked about the potential origins of this link, some participants explained that sustainability has always been a fundamental element of PA. Key informant B, for instance, highlighted its historical importance by stating: “I think that this was part of the discussion from the beginnings of precision agriculture.”. This key informant further explained the idea that, even if the notion of sustainability in its contemporary form did not exist, the element of environmental conservation has always been present in the discourse on PA:

When I started becoming involved in [the International Society of Precision Agriculture] reading about precision agriculture there was always the issue, and whether it was called sustainability or not, that’s another matter, that that maybe it’s the word that, that became common later. But the idea that this would improve the environmental footprint, or the environmental performance of agriculture was part of [PA] from the very beginning. This perspective from key informant B presents the notion that sustainability is deeply rooted in the formative stages of PA development. It is evident that PA, perhaps even before the term “sustainability” gained widespread recognition, had always held the intention of delivering on promises of improved environmental performance and responsible resource management. This enduring commitment to environmental betterment illustrates the innate connection between PA and the promise of sustainable farming practices, emphasising the longstanding tradition of promoting PA as a contributor to sustainability.

My interviewees also brought up the evolution of agriculture, revealing a historical dedication to advancing agriculture by reducing inputs and minimizing environmental impact through technological innovation. Recalling the era of the Green Revolution, key informant D underscored,

The green revolution comes to mind...it's not necessarily PA, but through the idea that they were able to make crops more efficient in their fertilizer use efficiency. So, I mean, historically there has always been a connection between the advancement of technology and sustainability in agriculture.

This perspective reinforces the long-standing correlation made by scholars and technology proponents between technological progress and sustainable agricultural practices. Framed in this broader context of ideas, proponents view PA as another agricultural innovation rooted in this foundational belief of improving resource use via technology. The historical parallels between the Green Revolution and the emergence of PA serve as a testament to the consistent quest for sustainable farming practices through technological means. Key informant C further elaborated on this sentiment, shedding light on the origins of the connection between PA and sustainability. In our conversations, they explored the notion that it may be intrinsic to 21st-century technology development, which in this context, the promotion of technology often centres around advancing sustainability goals. They stated, "So, it's the idea that you know, it's new, is part of this kind of narrative of the hype around like there's this new technology out there that you should adopt for sustainability.". The initial excitement surrounding technology often comes with the promise of sustainability benefits, shaping a narrative that centres on the appeal of embracing new technologies to achieve sustainability gains. This trend emphasizes the ongoing commitment to progress and technological solutions in agriculture, as it consistently promotes advancements in

technology to align with sustainability promises. Throughout my conversations with these academics, the belief that sustainability has been an inherent, albeit sometimes underplayed, element of PA since its inception emerged. This idea of embracing new technologies for sustainability gains echoes a longstanding tradition in agriculture, emphasizing that sustainability is a foundational principle guiding PA research, development, and promotion, rather than being a recent phenomenon. PA serves as a contemporary embodiment of agriculture's enduring commitment to sustainable resource management, and it aligns with the historical narrative of using technology to optimize resource use.

4.2.2 Influence of Academics

Despite the assumption made in the literature on PA that there is an inherent connection between PA and sustainability, key informants revealed in interviews that academics themselves are a primary influence in both creating and perpetuating these claims around PA and sustainability. Certain academics, recognized as “thought leaders” in the field of PA, are perceived by their peers as actively responsible for not only conceptualizing PA but also initiating discussions around sustainability. In conversation with key informant B, a discussion around who conceptualized these technologies and perpetuated this narrative of sustainability began, they stated:

So, you can look back, well... there's a great study in the mid-1920s at Purdue on variable rate lime application on Indiana soils. This is done by Purdue agronomists.... and then you had researchers like Pierre Robert at the University of Minnesota and others that were thought leaders in this area.

Key informant C made mention of more recent academic works that have further solidified the link between PA and sustainability. These works, published in high-impact journals have played a

pivotal role in promoting the idea of PA as a driver of sustainability. Key informant C cited additional examples:

The one that like came out that like when I first started this research that had been published in *Nature* or *Science* is from Gebbers and Adamchuk...this was like a paper that was published in 2010, and it has been cited a lot and I think the title is maybe “Precision Agriculture and Food Security”, but like it definitely promotes this idea that precision agriculture will promote sustainability and food security...there's another one that came out, I think, in *Nature* by Basso and Antel...and that was more recent, maybe 2019, and again, like, kind of these big think pieces that draw these connections without, like, very concrete examples about how these things are being done.

Academics such as Dr. Pierre Robert appear to have led the way in PA research. Other influential articles such as “Precision Agriculture and Sustainability” by Bongiovanni and Lowenberg-DeBoer, “Precision Agriculture and Food Security” by Gebbers and Adamchuk, and “Digital Agriculture to Design Sustainable Agricultural Systems” by Basso and Antle, published in *Precision Agriculture*, *Science*, and *Nature* respectively, also shape the narrative on sustainability. These highly cited articles are frequently acknowledged for playing a role in further disseminating the narrative around sustainability.

Conversations that did not explicitly mention specific academics or papers still underscored the influence of academics in shaping the connection between PA and sustainability. Notably, key informants emphasised the role of academics in downplaying the actual sustainability benefits realized through PA. PA is an interdisciplinary topic where social scientists, engineers, and economists, among other disciplines, coalesce to form a unique body of academics who all publish on the same topic from different academic backgrounds. This

multiplicity of academic backgrounds has, according to interviewees, led to some issues around the promotion of sustainability from an uncritical lens says key informant E, “because PA is a really interdisciplinary topic, there's a lot of academics who come from perhaps less critical backgrounds, who might promote these narratives very uncritically.”. This perspective is reflected by a key informant D who brought attention to the role engineers play in introducing ambiguity into the discussion around PA and sustainability, explaining how engineers, primarily focused on the technical aspects of PA, may struggle to grasp various nuanced aspects when attaching unsubstantiated beliefs to novel technologies: “that makes it a little bit challenging like for engineers, because then they're in a kind of in a murky area where it's not, well there's no black and white, it's all grey...”. The interdisciplinary nature of PA often means that some academics involved in its research may direct focus on other aspects of PA, such as technology development, without considering the impacts of their assertions. Such an observation highlights the potential for differing perspectives across disciplinary boundaries in the discourse surrounding PA and sustainability. It also demonstrates how values can influence the definition and promotion of sustainability. Different motivating factors within various disciplines can lead to the inclusion of sustainability as a peripheral aspect, sometimes without a deep examination of its relevance or implications.

4.2.3 Take-Over by Industry

Moving beyond the role of academics, a key recurring theme that emerged during my conversations revolves around the influential role that industry has played and continues to play in shaping and perpetuating the sustainability claims within PA. Despite the sustainability claims potentially beginning with academics conducting and publishing research on PA, interviewees mentioned that the industry has played a significant role in reinforcing a link between emerging

agricultural technologies and sustainability. As well, as PA continues to be of interest to industry, the prevailing model of sustainability shifts to revolve around economic values. Key informant E explained that the agricultural technology industry has invested capital into the development of technologies and thus has played a role in shaping this narrative:

I think it begins with the industry side and the development of ag-tech and the investment as well...And so, having industry investors alongside is important. And these technology companies lead with, well they should lead with economic benefit and efficiencies to the farmer, first and foremost, and then a secondary benefit would be environmental benefit.

This perspective highlights how industry stakeholders are not only influencing the direction of innovation but also placing a strong emphasis on the “sustainability” benefits these technologies can deliver. It is important to recognize that industry stakeholders often prioritize economic benefits and operational efficiencies for farmers, with environmental benefits as a complementary aspect. This strategic alignment reinforces the close association between PA and sustainability while reflecting the influential role that the industry has played in promoting and perpetuating this narrative.

Furthermore, as made evident through my analysis, many interviewees highlighted that because of the potential for PA technologies to create new business opportunities, the agricultural technology industry has grown to be one of the primary actors responsible for spreading the sustainability narrative. This is not merely coincidental; rather, it reflects the potential that PA technologies hold for creating novel business opportunities. This potential has not only attracted traditional players but has also enticed new actors in the tech sector who were previously uninvolved in agriculture. These actors use these sustainability claims to promote these emerging technologies. Key informant D pointed out that in the context of using

technology for carbon capture in agriculture, the private sector envisions sustainability as a strategy to support emerging markets, capitalizing on the environmental benefit for profit: “The private sector is imagining sustainability, at least from the environment point of view as a way to bolster some of these new markets.” During our conversations, this key informant elaborated on how technology companies prioritize promoting the economic outcomes of these technologies as their primary benefit:

The number one seller is always going to be enhanced productivity and profitability. And so, I think that's been promoted more than the sustainability piece, because that's what farmers care about a hundred times more than sustainability. It's, farming is a business, and that's at the bottom line.

The agricultural technology industry strategically and fundamentally concentrates on enhancing the productivity of a farmer's agricultural operation, recognizing that farmers prioritize increasing productivity and profitability as key concerns. As a result, industry stakeholders, particularly technology companies, consistently emphasize the economic benefits of their innovations. Technology companies' unwavering emphasis on promoting the economic outcomes of their innovations serves as a means of ensuring that sustainability claims remain relevant and attractive to a broader audience. Key informant A discussed this when they said that in the adoption of PA economics have played a dominant role. They state, “So clearly in in the adoption of PA, the economics have played the dominant role because it's been primarily an industry-led technology...”. This industry-led technology promotion has firmly placed economic-centric sustainability at the forefront. However, it is noteworthy that the industry’s promotion of PA goes beyond economic-centric sustainability claims. As the initial economic benefit gains traction, industry stakeholders also proactively promote the environment-centric

sustainability associated with PA technologies. Key informant C explains this idea, discussing how the environmental sustainability piece takes a back seat in the promotion of PA, but is still present:

Also, to some extent promoted the [environmental] sustainability piece, and whether the sustainability piece is true or not doesn't really matter to them, because they're, they're trying to make a profit off this kind of software data new source of capital on the farm.

The acknowledgement among interviewees that the environmental sustainability component may take a back seat in the marketing and promotion of PA, yet is still present to some extent, underscores the nuanced approach taken by the industry. This duality reflects a strategic balancing act, where industry stakeholders recognize the importance of environmental sustainability but often prioritize economic considerations to remain competitive in a profit-driven market. Yet, ultimately, these conversations shed light on the role industry has played in shaping the sustainability narrative within PA. While academics may have initiated this discourse, it is the agricultural technology industry that has assumed a prominent role in perpetuating it. As the industry integrates PA into its operations, the prevailing model of sustainability has gradually shifted, increasingly emphasising economic values over a more balanced approach.

4.2.4 The Role of Government

In my conversations with academics, a recurring theme emerged that underscores the pivotal role government agencies have also played in shaping the connection between PA and sustainability. Some key informants elucidate the role government bodies play in influencing how PA is framed as a contributor to broader sustainability efforts. As explained by key

informant C, in a Canadian context, both Federal and Provincial government agencies position PA in a role to help achieve environmental sustainability goals:

The government as both federal and provincial regulating bodies have, have a duty to protect the public good, to protect our water sources and to protect, reduce greenhouse gas emissions and, and to promote sustainability...and instead of regulating these things...it's a lot easier to say, well, this technology does this we should adopt it, and we'll help you adopt it through funding or incentives or grants or something like that.

The sentiment among some of my interviewees that government agencies actively promote sustainability in PA coexisted with concerns they have about the lack of empirical evidence to substantiate the benefits claimed by these policies. Key informant C noted that governments have embraced sustainability initiatives without conducting comprehensive assessments of the empirical evidence supporting these claims. They emphasised, "So, I think, to some extent governments like broadly, have gotten on board with this kind of sustainability piece around PA without like looking in to, to find that empirical evidence.". The statements made by key informant C demonstrate how governments actively promote the sustainability aspect of PA. This promotion, however, occurs despite the need for a more rigorous evaluation of its true impact on environmental and other sustainability goals. This lack of evaluation may contribute to the ongoing perpetuation of the belief that PA has proven sustainability benefits.

In conversation with key informant D, they shared a similar idea, discussing investments made by policymakers in the United States. This academic talked about the investments made by the United States Department of Agriculture into precision and climate-smart technologies, emphasising the government's focus on the role of technology in mitigating climate change:

Now the role that I see the government is playing, and other than [data sharing] is like, of course, there's a lot of investment in PA and climate-smart agriculture... So I mean there's a huge emphasis on, I don't know if that's necessarily really sustainability but that's how they're defining sustainability, but certainly getting farmers to use like more efficient technology, that in some ways can be improved.

Key informant D's insights highlight the significance of efficiency and technology adoption within the government's definition of sustainability. As governments incorporate PA into policy initiatives to enhance agricultural sustainability through precision technologies, they not only legitimize these sustainability claims but also further solidify the role of efficiency and technology adoption as key components of their conceptualization of sustainability.

Key informant B further emphasises this point, discussing the idea that, despite the relatively negligible amount of public funding directed towards agriculture, governments still play a role in constructing the link between PA and sustainability. According to this key informant, government agencies often rely on regulations and subsidies to promote the environmental advantages of technology, but with limited success. They state, "Sometimes there's often a secondary role in terms of environmental regulation that supports the use of the technology due to its public and environmental benefits. There have been attempts at subsidies, which, in general, have not yielded significant results." They went on to explain how the lack of public sector funding has created an opportunity for the industry to step in, saying,

"There's this environment of lower overall funding, in many places. And there just haven't been a lot of money left over [for agriculture] and it hasn't been a priority, because there was a thinking that oh, industry will take care of that. Well, Industry has

taken care of certain aspects of it, very well. They have taken care of the parts that will make money.”

Government initiatives appear to influence the conceptualization of sustainability; It is evident that the government's emphasis on efficiency and technology adoption as part of their sustainability definition has led to a legitimization of these elements in the broader literature.

4.3 Interviews Corroborate: Lack of evidence

Throughout my interviews, key informants mention that while the promise of PA to improve sustainability is a recurring theme in the literature, there is a lack of concrete evidence and metrics for assessing it. Multiple key informants candidly acknowledged that, despite the widespread acknowledgement of there being a link between PA and sustainability, there remains a notable lack of robust empirical evidence within the literature on PA. In response to a question about the sustainability implications of using PA, key informant C talked about how PA holds a lot of promise in terms of environmental sustainability but ultimately the evidence is not present to support this claim. They state,

And there's not a lot of empirical evidence that those technologies are sustainable at this current time, given the data that's available. So, I think that in in terms of like that kind of environmental sustainability piece, it holds a lot of promise, but it's definitely not there.

Key informant B corroborated the promise of PA in terms of environmental sustainability but also identified the lack of absence of empirical evidence to substantiate this assertion. They said, “In terms of evidence, I would say no.... that's the case that there’s been very, very, very few cases of where overall there's been careful measurement.”. This conversation around evidence continued and this key informant began discussing how research most often measures the sustainability of PA in terms of inputs:

Most studies, in terms of sustainability, well most variable rate fertilizer studies will base their claim of sustainability on somehow reducing inputs. You know that if you do variable rate nitrogen, you will use much less fertilizer overall. So, there's been a focus on the input side. What is very rare in that literature is something that actually measures the outcomes.

Informants indicated that much research on the sustainability of PA often hinges on claims of sustainability on the reduction of inputs. For instance, the informant above points out that using variable-rate nitrogen application results in overall reduced fertilizer usage. This approach, which centres on input reduction, has been dominant in the literature. What remains uncommon, according to this key informant, is a concerted effort to measure the actual outputs or outcomes resulting from these input reductions. While there is the pervasive assumption that a reduction in inputs equates to a more sustainable system, empirical evidence does not inherently validate this assumption.

Key informant A contributes to this discussion by addressing the lack of empirical evidence to support the sustainability claims related to PA technologies. Key informant A asserts that, in theory, PA technologies have the potential to reduce runoff, enhance nutrient efficiency, and mitigate GHG emissions associated with nitrogen fertilizer use, all of which are key aspects of sustainability, stating:

We're reducing runoff, we're overall like making really efficient use of nutrients, especially nitrogen fertilizer which comes with a lot of greenhouse gas emissions. So, in theory, that's a good sustainable, sustainability implication. But the way that, the technology isn't quite there, and there's not a lot of empirical evidence that those technologies are able to do that at this current time, given the data that's available.

Collectively, these insights highlight a critical gap between the theoretical potential of PA in sustainability and the current state of empirical evidence.

4.4 Summary

My findings reveal how academics conceptualize sustainability, both in their written words found throughout the literature and in what they express during interviews. These conceptualizations paint an interesting picture of how the literature presents the connection between sustainability and PA. Scholars use a variety of models of sustainability in their work, but most of the literature does not explicitly define the model being used; instead, it leverages the model implicitly. Moreover, these working models often simplify sustainability by concentrating on one or two dimensions, and do not necessarily define sustainability in a broader three-dimensional way to reflect current thinking. Last, academics frequently frame economic *and* environmental combined benefits as the primary model or definition in a kind of quasi-intensification model.

In interviews, the perspectives of academics indicate that behind these conceptualizations of sustainability in PA, there are specific actors and interests at play in formulating or propagating these ideas. These actors include academics, industry members, and government entities, each of whom plays a role in shaping the connection between PA and the interpretation of sustainability (as intensification). The contributions, values, and motivations of these key social groups all appear to converge to craft a framing of sustainability that is shaping the direction and perception of sustainability brought about by PA. Key informants further illuminated a significant revelation that aligns with the previous findings (Bronson et al., forthcoming) underlying my research, where academics themselves acknowledged a notable

absence of robust empirical evidence to substantiate the assertion that PA yields measurable benefits, especially around environmental gains.

Chapter 5 Discussion

To better understand the complex relationship between PA and sustainability, this research set out to investigate the models of sustainability present in academic discourse. Using academic literature obtained through systematic review combined with qualitative interviews, I explored the definitions of sustainability present in the literature and the origins behind the relationship that emerges from the literature – one that draws an inherent link between PA and environmental, economic, and societal benefits. In this discussion chapter, I talk about the significance of the various conceptualizations of sustainability in the literature on PA. I establish a connection between the actors responsible for linking PA and sustainability, examining their values and the role they play in shaping the dominant models of sustainability prevalent in the literature.

The main argument I make is twofold. First, while there are multiple conceptualizations of sustainability in the literature, albeit often implicit, they all reflect a hierarchical model of sustainability which prioritizes economic or environmental sustainability over social sustainability. The second argument is that there is a focus in the literature on economic sustainability above other dimensions. Across the multiple conceptualizations of sustainability, there is significant emphasis placed on increasing productivity or improving efficiency, aligning PA with the established productivist paradigms in modern agriculture rather than promoting genuine sustainability benefits. The result of the dominant discourse on sustainability is that it reinforces the prevailing paradigms in agriculture, overshadowing ecological and societal dimensions. Moreover, where there also exists a discrepancy between rhetoric and evidence regarding PA and sustainability questions arise about the integrity of the sustainability claims,

suggesting the presence of a potential element of “greenwashing,” or the deceptive promotion of a false sense of sustainability brought about by emerging agricultural technologies.

5.1 Constructing Sustainability

Sustainability is not a fixed or universally agreed-upon concept, not just within the literature on PA but across the literature on sustainability in general (see Ramsey, 2015; Rosen, 2018; Vos, 2007). In the literature on PA, various actors interpret sustainability differently and create distinct visions of the role of PA in promoting sustainability. Applying a constructivist lens to the analysis of sustainability literature reveals how both the concept of sustainability and the connection between PA and sustainability are actively shaped and co-constructed by proponents of PA. The existing models of sustainability in the literature represent the outcome of sets of values and principles that influence behaviours and decision-making related to sustainability, thus making sustainability a normative concept (Ramsey, 2015). Social constructivism helps us understand how these different actors construct and apply the concept of sustainability based on their values, beliefs, and social interactions.

As seen in the analysis of the literature (Chapter 4), there are several distinct models of sustainability present when it comes to PA, where the concept of sustainability encompasses multiple perspectives. Considering the literature presented, researchers have used the term sustainability in a variety of ways within the context of PA. For example, scholars often depict sustainability as intensification, where agricultural output increases without requiring additional land or additional agricultural inputs (see Balaine et al., 2020; Fabiani et al., 2020; Lindblom et al., 2017). Alternatively, it can be framed in terms of economic (see Bora et al., 2012; Kolady et al., 2021) or other ecological benefits (see Andretta et al., 2018; Claudia Lang et al., 2021; D’Antoni et al., 2012). This apparent diversity in discrete conceptualizations of sustainability

emerged from the analysis of academic literature and interview transcripts. Making sense of these findings further demonstrates that sustainability is not a monolithic concept but instead, it takes on different meanings with varying emphasis placed on the various dimensions of sustainability depending on who is defining or engaging with it.

But despite an apparent diversity in sustainability models, it is important to recognize that closer examination reveals a convergence towards a productivist framing of sustainability. And with that being said, it is important to note that this research did not seek to validate or invalidate how the literature defines sustainability or engage in debates about the semantics of sustainability. Instead, its focus was on recognizing the inherent complexity of the concept and how the academic literature portrays sustainability.

5.1.1 Influence of Industry

Today, the agricultural industry widely recognizes PA as the next revolution in agriculture with industry promising that applying PA technologies on farms will increase efficiency (Lowenberg-DeBoer, 2015; Robert, 1999). Indeed, industry and scholars describe PA as the fourth agricultural revolution, also considered agriculture 4.0, within which framing the narrative of economic sustainability takes on greater significance. Agriculture 4.0 represents a paradigm shift in which digital technologies, data analytics and automation are becoming increasingly integrated into farming practices (Benke & Tomkins, 2017; Rose & Chilvers, 2018). This change in the agricultural landscape amplifies the industry's commitment to economic sustainability as it envisions a future where data-driven decision-making, smart farming equipment, and PA techniques further enhance profitability and resource use efficiency.

The agriculture industry reflects society's contemporary industrial values which prioritize enhancing productivity and improving resource use efficiency (Clapp, 2020, p. 30). Throughout

the 19th century, the development of ploughs, irrigation systems, crop rotation, and the adoption of new crop varieties (Clapp, 2020, pp. 38–40) propelled productivity enhancements and extended the output potential of agricultural operations (Evenson & Gollin, 2003; F. M. L. Thompson, 1968). This trend has continued into the 20th century, driven by advancements in technology, including the Green Revolution of the mid-20th century, which introduced high-yielding crop varieties and synthetic fertilizers (Clapp, 2020, pp. 38–40). Rooted in "scientific" farming methods developed in laboratories, the industrial agricultural model involves heavy capital inputs, new hybrid seeds, chemical fertilizers, pesticides, monocropping, irrigation infrastructure, and mechanization for planting and harvesting (Clapp, 2020, p. 30). The dominant value being promoted both in the 20th and 21st centuries to farmers under this industrial model is that they ought to produce more with fewer inputs or achieve "intensification". These principles align with the concept of productivism. Although productivism extends beyond the realm of agriculture, scholars have defined agricultural productivism as "a commitment to an intensive, industrially based and expansionist agriculture with state support based primarily on output and increased productivity" (Lowe et al.1993, p. 221)

When considering economic sustainability in the context of PA and the actors involved, it is equally important to discuss the industry's interest in technology adoption and data collection, which extends beyond merely supporting farmers in their bid toward efficiency and intensification of land. To do so, the industry seeks to profit by selling equipment and, in this new era of digital technologies, by collecting data which itself becomes an asset (Bronson, 2019b). Through third-party data-sharing agreements, agricultural companies can monetize farm data, tapping into a new revenue stream (Bronson, 2019). This profit potential adds a further layer of explanation to why the agriculture industry actively promotes the adoption of these

technologies, emphasising their potential to boost farmers' profits and boost environmental gain – adoption allows companies to capitalize on emerging data markets created by increasing digitization occurring on farms (Miles, 2019).

From a constructivist perspective, when examining the relationship between PA, economic sustainability, and the agricultural industry, it becomes evident that the industry's influence on the conceptualization of sustainability is a result of the interplay between industry-driven objectives and broader societal values. As mentioned, the profit-driven agriculture industry places a high value on generating profits, not only for farmers but for corporations as well, directing significant attention towards economic-centric sustainability. In the context of PA, economic sustainability refers to the long-term viability of a farm (Spicka et al., 2019). It encompasses strategies that allow farmers and agricultural corporations to generate profits while minimizing negative impacts on the environment and society, to remain viable until passed on to a successor (Spicka et al., 2019). The assumption that increased profits, productivity and economic growth automatically lead to sustainable agricultural practices has become a prevailing perspective within the agricultural community and policy circles (Allen et al., 1991). Grounded in the belief that a financially prosperous agricultural sector can support ecological and social well-being; proponents equate economic benefits to sustainability. However, as I will discuss further, this perspective oversimplifies the complex interplay between economic, environmental, and social dimensions of sustainability within the realm of PA. And in this context, it is crucial to acknowledge that the emphasis on economic gains as sustainability reflects a normative perspective deeply rooted in contemporary societal values and economic paradigms. This pursuit of economic sustainability through PA aligns with the prevailing economic paradigms of the 21st century, prioritizing growth, and progress. Economic growth is a fundamental, albeit debated,

marker of success (Costanza et al., 2009), fuelled by the belief that expanding markets, increasing productivity, and continuous innovation are essential for economic prosperity (Grossman & Helpman, 1993; Maradana et al., 2017). PA aligns with these perspectives by offering novel solutions to well-established farming challenges, thereby contributing to the industry's 'productivist' approach. Together, dominant economic paradigms and values around growth and progress held by agricultural industry members have shaped the conceptualizations of sustainability in a way that promotes economic wellbeing as paramount, highlighting the industry's commitment to growing in an economically “sustainable” manner.

5.2 Is it Really About Sustainability?

In the subsequent sections, I will discuss the limitations in the current models or constructs of sustainability in the literature on PA. Notably, how the literature conceptualizes sustainability in terms of efficiency gains, productivity optimization, and responsible resource use, with a prominent absence of the social dimension, as I will elaborate on below. This alignment prompts questions about the authenticity of sustainability claims made in the academic discourse on PA. In presenting sustainability in this way, the literature reflects a convergence on productivist values which when coupled with the lack of empirical evidence to support the claimed environmental benefits raises concerns about potential greenwashing within the literature on PA.

5.2.1 Unrealized Three-dimension Model Present in the Academic Literature

In the findings section, I examined the diverse conceptualizations of sustainability found in the literature and perceived by academics, highlighting the actors shaping these discussions. As explained, various actors in the field, including industry and government, have undeniably

shaped the relationship between PA and sustainability, embedding their values into the conceptualization of sustainability in relation to PA. One group of actors of particular interest in my research is academics, as they have played a critical role in defining and redefining the connection between PA and sustainability, particularly under a three-dimensional model (see Chapter 4 Findings). Their intellectual contributions, research, and thought leadership have added depth and complexity to the discourse. However, their involvement has not only enriched the discourse but also inadvertently contributed to a tangled web of interpretations regarding the concept of sustainability.

Highlighting the interview findings, the interdisciplinary nature of the field of PA has resulted in diverse interpretations and varying degrees of emphasis on different aspects of sustainability, further complicating the understanding of sustainability within this context. As previously mentioned, academics in the fields of science, technology, engineering, and math tend to focus on the technical aspects of PA, researching efficacy and focusing on the active development and testing of novel PA solutions (Chen et al., 2020; Dammer & Wartenberg, 2007; Fabbri et al., 2020; Shadrin et al., 2019; Shen et al., 2017; Srivastava et al., 2019; Wu et al., 2020; Yue et al., 2012). On the other hand, social science academics tend to explore the societal implications of PA, delving into questions of ethics, farmer livelihoods, and the wider socio-economic impact of adopting these technologies (Bronson, 2019b, 2020; Bronson & Knezevic, 2016; Carolan, 2015, 2018; Duncan et al., 2021; A. Fraser, 2019; Gardezi et al., 2022; Gardezi & Bronson, 2020; Hackfort, 2021; Rotz, Duncan, et al., 2019). In this body of literature, often characterized by a more critical stance, some academics question the legitimacy of PA in contributing to sustainability (see Bronson, 2020; Carolan, 2020c; Duncan et al., 2022; Miles, 2019 as examples). This highlights the diversity among academics, coming from different

disciplinary backgrounds, in terms of how they define and emphasize sustainability within their research. Where scholars do not consider the semantics of such framings of sustainability, normative productivist views can become legitimized and cemented. This occurs when the predominant focus on technical efficiency and increased production becomes the unquestioned standard by which the literature measures and judges PA and sustainability, as seen in my analysis.

Referring to the section above, the three-dimensional conceptualization of sustainability provides a valuable model for framing the goals of PA and offers a clear and comprehensive representation of the interdependencies among environmental, economic, and social aspects. But, although a dominant framing of sustainability in the literature, it becomes evident that this three-dimensional model of sustainability, may not be truly realized under PA. Under a 3-dimension model, there is an understanding that there is an interconnected nature of the environment, the economy and society (Rosen, 2018; Todorov & Marinova, 2009). The multiple dimensions, also demonstrate the multidisciplinary nature of sustainability, and its link to diverse fields such as science, engineering, environmental science, ecology, economics, business, and sociology (Rosen, 2018; Todorov & Marinova, 2009). Fostering sustainability requires consideration of elements around resource use, economic development, rural development, environmental stewardship, and technology development (Rosen, 2018). And it requires cooperation and understanding of how different disciplines imagine and address these various factors (Rosen, 2018), which as per my analysis is not necessarily the case across the literature on PA.

Additionally, the three dimensions – economic, environmental, and social – frequently find themselves in conflict, as exemplified by the situation where social sustainability may come at the expense of economic and environmental sustainability. In my analysis, I observed that

many academics, both in the literature and in interviews, conceptualize sustainability through the three-dimensional model. While the three-dimensional model suggests an equitable balance among these dimensions, the actual emphasis leans towards prioritizing efficiency and productivity in both economic and environmental contexts (Purvis et al., 2019). This trend has also been identified in the wider sustainability literature where scholars have identified a hierarchical tendency within this model that often prioritizes economic considerations over environmental and social ones (Rosen, 2018; Struik & Kuyper, 2017; Todorov & Marinova, 2009). When considering sustainability in the agricultural context this observation holds true, as within this context, sustainability privileges either the environmental dimension or the economic dimension, often neglecting the social dimension (Struik & Kuyper, 2017). Examining this tendency in conjunction with the dominance of economic-centric sustainability, it becomes clear that the inherent shortfall of this model, as commonly presented in academic literature, raises questions about the true nature of sustainability within PA; It is evident that economic considerations take precedence, potentially at the expense of broader ecological and societal concerns.

5.2.2 Absence of Consideration for Social Sustainability

Building on the conversation about environmentally and economically centred sustainability models (or quasi-intensification), what remains intriguing is the consistent omission of the social dimension in sustainability discussions. While much emphasis has been placed on the ecological and economic aspects of sustainability within the context of PA the social dimension, which involves the well-being of communities, the equity of access to resources, and the impact on farmers and rural livelihoods (Janker & Mann, 2020), has often been overshadowed or relegated to the periphery. Both interviews and the analysis of the

literature reveal a pronounced emphasis on economic and environmental sustainability, to some degree, often at the expense of adequate consideration of social factors. And although social sustainability is present in the holistic models, it receives truly little attention in practice. This finding underscores the influence of social constructivism in shaping the connection between PA and sustainability, wherein societal values and priorities play a significant role in determining what aspects of sustainability receive attention.

Social sustainability ought to be an integral component of the overall sustainability paradigm, and its absence in the literature and minds of key academics is not an oversight but a reflection of the needs and values of shaping the discussion on PA. That is to say, how sustainability is constructed in relation to PA is done so predominantly by actors who prioritize economic and environmental aspects, reflecting the prevailing values and priorities of two dominant food system actors: agribusinesses and policy institutions. As previously demonstrated, those who have a dominant voice in the promotion of PA are large multinational agricultural corporations who prioritize productivist values or environmental protection over say rural livelihood (Clapp, 2021). The dominance of the productivist perspective influences the construction of sustainability in this context. And, although the ability of PA to contribute to increasing food security is present (Philips, 2014) and is often considered to be a form of social sustainability (Berry et al., 2015; Lang & Barling, 2012), it is important to consider other societal implications of PA. Beyond food security, this dimension of sustainability encompasses the well-being and equity of the people involved in the agricultural sector, including farmers, labourers, and rural communities (Janker & Mann, 2020). The limited emphasis on social sustainability is intriguing as it underscores the prevailing priorities of the actors involved in defining the relationship between PA and sustainability.

Problems Arising from Social Dimension Neglect. Although explainable via a social constructivist framework, the absence of social considerations is troubling. Critics have identified the potential for PA to exacerbate social inequalities within the food system and create new sociological challenges associated with data governance and machinery rights (Bronson & Knezevic, 2016; Carolan, 2018; Rotz, Duncan, et al., 2019). One central challenge lies in the potential for agricultural technology companies to exploit farmers through their data – a concerning trend in which corporations collect, share, and use the information generated by farmers without adequate transparency or reciprocity (Carolan, 2018). This data exploitation not only infringes upon farmers' privacy rights but also raises questions about who benefits most from these technological advancements. Furthermore, as PA equipment becomes increasingly sophisticated, farmers find themselves with limited rights to modify or repair their machinery (Bronson, 2018, 2022; Carolan, 2020a). Given these technologies contain embedded software and proprietary digital components, farmers find themselves digitally locked out of their equipment and must rely on authorized service providers to maintain their equipment (Carolan, 2018; Solon, 2017). This digital lockout exacerbates issues of control and agency (Carolan, 2018). These concerns highlight that social sustainability is not attainable if farmers are continually subjected to data exploitation, unequal power dynamics between farmers and input suppliers who now collect the farm data, and a loss of autonomy over their farming practices.

In addition to the risks of overlooking social sustainability within PA, it is essential to explore how the very nature of PA can undermine the potential for these technologies to promote social sustainability, exemplified by the concept of the digital divide. As PA relies on advanced technologies and data for farming practices, a significant disparity can emerge between those who have access to these resources and those who do not (Bronson, 2019; 2022). Farmers who

lack the capital, live in remote rural communities or are unable to adopt PA due to unsuitable field conditions (i.e., incompatible crops, too small of a field to require large machinery or significant variation in soil conditions) may find themselves on the wrong side of this divide, lacking the necessary infrastructure, devices, internet connectivity, and knowledge to be able to capitalize off the potential benefits of PA (Rotz, Gravely, et al., 2019). In this context, the digital divide underscores a socio-economic and technological gap that can hinder access to the opportunities and advantages presented by PA, creating disparities among farmers. The implications of the digital divide also extend beyond mere access to technology. It can reinforce existing inequalities, with farmers who are unable to access digital tools facing barriers to staying competitive, optimizing their practices, and adapting to changing agricultural landscapes (Jakku et al., 2019; Rotz, Gravely, et al., 2019). Thus, if the literature continues to define sustainability without consideration for the social dimension and instead of focusing narrowly on economics and environmental stewardship, it may inadvertently undermine the potential of PA to contribute to sustainability by not addressing the social challenges posed by emerging agricultural technologies.

Navigating the complexities associated with the social dimension of sustainability, such as the challenges of data exploitation, machinery rights, and the digital divide (Anidu & Dara, 2021; Rotz, Duncan, et al., 2019), appear to have made it difficult to clearly define and incorporate social sustainability within the PA paradigm. And, the dominance of economic and environmental considerations, coupled with the intricate sociological challenges presented by PA, poses significant hurdles to establishing a comprehensive model of social sustainability within the field.

5.2.3 Dominance of the Productivist Paradigm

The emphasis on economic values within PA discussed in detail in Chapter 4, reflects a concept known as productivism, wherein agricultural systems prioritize intensive, industrially driven and expansionist production based primarily on output and increased productivity (Lowe et al., 1993). This perspective challenges the holistic concept of sustainability promoted by the three-dimension models, put forth by the academic literature, highlighting the need for a critical examination of the sustainability discourse within the context of PA. Despite the common assumption that PA inherently embodies sustainability, my analysis of academic literature and interview transcripts with key informants from academia consistently reveals a tendency to equate economic benefits with sustainability, an idea constructed by the dominant actors involved in the promotion of PA – notably, industry. This economic perspective, rooted in the productivist paradigm of agriculture, is evident in the agriculture industry's emphasis on innovation and progression, where technology is primarily seen as a means to enhance output (Clapp, 2021, p. 30). This productivist lens significantly shapes the conceptualization of sustainability in PA, often emphasising increased productivity and output as primary indicators of success (Lowe et al., 1993), overshadowing broader ecological and social considerations. Despite appearing to be discrete models of sustainability, the primary conceptualizations identified through the analysis, all share a common emphasis on increasing production while reducing inputs.

The Problem with Productivism. As sustainability becomes intertwined with a productivist agenda, distinguishing between genuine environmental benefits from these emergent technologies versus productivity-driven practices promoted under the guise of sustainability can become challenging. The dominance of economic sustainability thus casts a shadow over the

equally crucial ecological and societal dimensions of sustainability within the context of PA. This overshadowing results in a narrowing of the sustainability models, side-lining key components necessary for creating a truly sustainable agriculture system (Bishop, 1993; Giddings et al., 2002). Specific instances exist where these critical ecological and societal aspects have been subordinated, perpetuating a fragmented vision of sustainability that does not align with what is presented in the literature. For instance, as seen in my analysis, in the context of literature on PA, a distinct alignment with the productivist lens emerges, as sustainability is often operationalized through measures of increased efficiency and optimization, primarily emphasizing the management of inputs. This approach seeks to maximize resources by minimizing waste and environmental impact, echoing the productivist paradigm's core tenets (Lowe et al., 1993). In essence, sustainability is operationalized by striving to do more with less, where a reduction in input use equates primarily to cost savings and is extrapolated to be reflective of reduced pollution for example. As highlighted through interviews and the literature review, much of the academic discourse on PA and sustainability centres on the input side (see Bora et al., 2012). While there is a notable focus on enhancing efficiency through minimizing inputs, such as fertilizers, water, and energy, this approach does not necessarily equate with a comprehensive understanding of sustainability. This emphasis on input reduction, while valuable for economic and environmental reasons, may not fully capture the complex interplay of ecological, economic, and societal factors necessary for a holistic and genuinely sustainable agricultural system (Bishop, 1993).

This inclination to associate sustainability with input reduction is indicative of a broader pattern within the literature on PA, where academics often equate minimizing inputs, such as fertilizers, water, and energy, with achieving sustainability goals, primarily those of

environmental stewardship. As illustrated in the analysis, even when the framing of sustainability emphasizes environmental-centric sustainability, there is a simplification of environmental sustainability gains to a reduction in inputs (Carballido et al., 2013; Kayad et al., 2021). While reducing inputs can be a positive step towards environmental sustainability, it is essential to recognize that this reduction alone does not guarantee overall environmental improvement (Pretty, 2008). The relationship between inputs and environmental outcomes is more nuanced and complex than a simple cause-and-effect relationship (Morelli, 2011; Pretty, 2008; Spangenberg, 2011). For example, if considering reducing inputs or increasing input use efficiency it is crucial to acknowledge that Jevon's Paradox might come into play. Jevon's Paradox suggests that improvements in efficiency and resource use may paradoxically lead to an overall increase in resource consumption (Jevons, 1866; Sears et al., 2018). In the context of PA, the emphasis on reducing inputs may inadvertently spur intensified agricultural practices, potentially counteracting the initial goals of sustainability of say reducing the amount of fertilizer applied to a field to reduce runoff. Adding to this idea, merely reducing inputs without a thorough understanding of the broader ecological context can lead to unintended consequences. In the context of PA, consider the technology of precision irrigation, which involves the use of drip irrigation instead of sprinkler irrigation. While precision irrigation offers more precise water application (Guiso et al., 2015), it's important to note that the environmental impact of precision irrigation may be higher than less sophisticated irrigation methods due to the production, installation, and disposal of plastic pipes associated with this technology (Bacenetti et al., 2020). And linking these ideas back to the primary productivist argument, relying on PA reinforces the dominant industrial modern agriculture system as these technologies have been developed to work within the modern agriculture system on large farms where there is a lack of variation and

topography within fields, and there is significant capital available for investments (Bronson, 2020). Favouring operation within a system dominated by commodity crops, grown on large plots of land continues to encourage the planting of monocultures of canola, soy, and corn in favour of more biodiverse polycultures, aligning closely with the conventional methods employed within established industrial agricultural systems (Clapp, 2020; Hendrickson, 2015). Reliance on this productivist system not only reinforces these monoculture modes of production and the subsequent intense use of agrochemicals which in the long term reduce insect biodiversity on and around farms (Grant, 2007), but also oversimplifies environmental sustainability, often disregarding the intricate interconnectedness of ecological systems (Lawrence et al., 2004). The productivist mode of agriculture tends to prioritize output and resource reduction as the primary metrics of success, which can lead to unintended consequences in the pursuit of sustainability.

And finally, the lack of consideration for social sustainability within the literature surrounding PA not only exemplifies productivism but is a subsequent outcome of the framing of sustainability in alignment with productivist paradigms; a framing that inadvertently reinforces the status quo of the existing industrial agriculture system. The focus on economic growth and profit often overshadows the importance of social well-being, equitable access to resources, and fair labour practices. This neglect of the social dimension can perpetuate inequalities within the agricultural sector and fail to address the needs and rights of farmworkers, rural communities, and other stakeholders. As previously discussed, various actors have reinforced the intersection between sustainability and productivism, perpetuating what has become a myopic perspective on sustainability. Müller (2023) shares this sentiment as they discuss how emerging agri-tech through its perceived ability to enhance efficiency, food security, health of livestock and crops

and sustainability ends up reinforcing the productivist paradigm (Müller, 2023). In the context of PA, tends to be reduced to a measure of productivity (Müller, 2023). Indeed, scholars have raised this critique against PA, suggesting that it reinforces productivist practices and a heavy reliance on intensification (Bronson, 2019; Cook et al., 2015; Godfray, 2015; Mahon et al., 2017). And, if these technologies fall short of delivering on their promises of environmental sustainability, their continued adoption could result in further adverse consequences. A large portion of literature more critical of PA predicts that emerging agricultural technologies will reinforce intensive, industrial modes of production and farm consolidation, eroding farmer autonomy (Bronson, 2018; Bronson & Knezevic, 2016; Carolan, 2018, 2020b; Wolf & Buttel, 1996; Wolfert et al., 2017). As mentioned above, pA technologies have been developed to work within a productivist strategy, to maximize the output of commodity crops, typically grown on large plots of land for international export (Bronson, 2020). Expensive equipment and the data used in the production of the digital maps needed for variable rate application are only suitable for large industrial farms with suitable fields and substantial capital available for investment compared to smaller farms (Bronson, 2020). The exorbitant costs associated with PA equipment and data-intensive processes create substantial barriers that only these larger farms with substantial capital can overcome. Therefore, adopting these technologies becomes disproportionately advantageous for large-scale industrial operations, consolidating their influence and competitive advantage over smaller farms (Bronson, 2019b; Rotz, Gravely, et al., 2019). By excluding smaller farmers, who often prioritize values such as local resilience, biodiversity, and regenerative or agroecological farming practices, PA reinforces a model of agriculture that prioritizes large-scale industrial operations, hindering the broader development of sustainable and resilient farming systems (Bronson, 2018). Consequently, investment into emerging agricultural technologies is as

Bronson states, “currently making little attempt to overcome” these productivist strategies, which in turn further entrenches dominant food regimes and prevents alternatives from flourishing (Bronson, 2020, p. 342).

5.2.4 Potential for Greenwashing

While this research highlights a notable emphasis on promoting various forms of sustainability within the context of PA, as discussed earlier, the empirical evidence supporting these claims, especially those regarding environmental sustainability, is limited. The absence of concrete evidence, when considered alongside the insights gathered from discussions with academics who supported this finding, as well as what they said about the role of industry in shaping notions of sustainability, suggests the potential for greenwashing within discussions of PA in the academic literature.

Greenwashing refers to the deceptive practices of promoting a false impression of the sustainability of a product or service (Yang et al., 2020). This deception frequently takes the form of creating a misleading impression of environmental sustainability. It becomes apparent when advocates employ vague terminology like "eco-friendly" (or sustainable), present irrelevant information to divert attention from actual environmental performance, use green jargon, and omit evidence to substantiate their sustainability claims (Parguel et al., 2015). Or, in the case of PA, label technology as “sustainable” while prioritizing increased productivity and profitability at the expense of broader ecological and social considerations. Such practices might not genuinely align with comprehensive sustainability principles and may, instead, prioritize short-term economic or production gains. The suggestion that greenwashing may be taking place within the literature on PA prompts reflection on the intentions and consequences of emphasising

various sustainability benefits, such as input savings and reductions in GHG emissions of PA technologies.

Previous research (Bronson et al., forthcoming) as well as discussions with the interviewed key informants from academia, highlights the absence of substantial empirical evidence supporting the assertion of environmental sustainability benefits associated with PA. Many of these scholars openly acknowledge the lack of substantial evidence available that supports the notion that PA contributes to sustainability. This observation points to a potential greenwashing concern: the promotion of PA as sustainable without substantial supporting data. It also raises the question of whether the environmental angle presented in technology discussions is a form of greenwashing, where productivist values are masked under sustainability claims. Although not a conclusive link, by looking at the literature on adoption we can see that farmers often decide to adopt these technologies on the basis that they have environmental benefits (Batte & Arnholt, 2003; Lee et al., 2021; Ofori & El-Gayar, 2021). By adopting PA, farmers perceive an opportunity to align their agricultural practices with sustainable environmental goals (Batte & Arnholt, 2003; Lee et al., 2021; Ofori & El-Gayar, 2021). The prospect of optimizing resource use, minimizing the ecological footprint of their farming activities, and contributing to broader efforts to combat climate change and environmental degradation entices farmers to adopt these technologies (Batte & Arnholt, 2003; Lee et al., 2021; Ofori & El-Gayar, 2021). This alignment between PA and environmental sustainability is evident in the increasing number of farmers who are integrating these technologies into their agricultural operations with the expectation of simultaneously achieving both economic and environmental gains, yet there is limited evidence to confirm these technologies can achieve these environmental gains specifically. It is this

discrepancy between the perceived environmental benefits and the actual evidence that may be seen as a form of greenwashing.

Implications of Greenwashing: Considering the potential for greenwashing in PA, it is important to recognize the implications this has for the future of agriculture's contribution to environmental harm or mitigation. When various interpretations of sustainability are used to mask a productivist agenda in agriculture, the expectation of progress toward a sustainable agricultural system through technological innovation may be hindered (Wilson & Burton, 2015). By promoting these technologies under the guise of sustainability, proponents might be inadvertently steering the narrative and the real practice towards a more neutral view of technologies which may or may not hold any potential for real environmental change. Many proponents of PA consider these emerging agricultural technologies to be an effective solution to mitigate environmental, economic and food security challenges faced within food production (Powell, 2017; Ryder, 2014; Sonka & Cheng, 2015). Although some of the literature presents a critical view on the use of precision technologies in agriculture (Bronson, 2018; Bronson & Knezevic, 2016; Carolan, 2018, 2020b; Wolf & Buttel, 1996; Wolfert et al., 2017), the dominant view of PA technologies is optimistic and full of promise. This optimistic view aligns with the historical and standard narrative regarding the of involvement technology in mitigating climate change and minimizing environmental degradation (Arvesen, Bright, & Hertwich, 2011).

Our contemporary society is innovation-centric and productivity-oriented, often celebrating technological advancements deemed beneficial to society (Godin, 2016; Hallonsten, 2023). Technology is often thought to have a vital role in achieving growth beyond the Earth's capacity and we often believe we may be able to innovate our way out of catastrophe (Goklany

& Trewavas, 2003). Humans have come to imagine science and technology are viable ways to solve complicated problems, often pushing beyond what was thought to be possible and seeking control of what should be considered uncontrollable (Allenby & Sarewitz, 2011). This connection between technology and its perceived ability to deliver on sustainability is prominent within the PA literature and is so significant that it is often described as a "paradigm shift" away from production-oriented agricultural objectives, moving toward the establishment of a sustainable agricultural system (Bronson, 2020).

The promotion of PA under the guise of sustainability, while fosters innovation and technology adoption, may inadvertently cultivate unchecked technological optimism, and reinforce the existing productivist paradigm present in modern agriculture. Emerging agricultural technologies are believed to play a pivotal role in the pursuit of pushing beyond current limits, with the envisioned potential to increase yields without exacerbating harm to the planet and humanity (E. D. G. Fraser, 2020; Gebbers & Adamchuk, 2010; Sonka & Cheng, 2015). These beliefs can lead to an overreliance on technical solutions for issues that are fundamentally social and political in nature and may inadvertently introduce additional complexities (Sarewitz, 2004). When we attempt to apply science and technology to complex issues that are not merely technical, challenges of values, uncertainty and polarization are introduced, further obscuring already complex problems, leading away from addressing many of the root causes of environmental issues (Sarewitz, 2004). And an increasing reliance on technology to address one societal problem may lead to the emergence of unintended consequences and additional or novel problems (Basiago, 1994). The eagerness to embrace the promises of increased productivity, efficiency gains, and sustainability benefits, often associated with productivist thinking, can overshadow the need for a thorough analysis of the long-term effects on ecosystems,

employment dynamics, and societal structures (Basiago, 1994). This phenomenon not only jeopardizes the ability to address pressing environmental and social challenges but also risks perpetuating an unsustainable agricultural paradigm that prioritizes productivity over comprehensive ecological and societal well-being.

This enthusiasm around PA has inadvertently led to a situation where the critical assessment of technology's impacts is often not at the forefront. In an era where the pace of technological change outpaces our ability to comprehensively understand its consequences, critics seem to be very rare (Hallonsten, 2023). In the context of agriculture and food scholarship Carolan (2015) remarks, "This relative silence among critical agro-food scholars is made even more pronounced when one considers how much research colleagues in the information and crop sciences do on the subject, who all evaluate practices through a distinctly productivist lens" (p.4). This scarcity of critical viewpoints, those that question, probe, and evaluate the potential drawbacks and unforeseen ramifications of technology, creates a void in the discourse surrounding its implementation. The consequence of this void is the potential oversight of ethical, social, and environmental concerns that may only manifest over time (Basiago, 1994). Such oversight is particularly significant in the academic realm, where scholars play a crucial role in shaping the perspectives around technological advancements. Academics provide information that informs decisions, policies, and practices, and providing seemingly misleading information can inadvertently provide decision-makers with ammunition to implement policies that may not be based in substantial evidence.

While I cannot, based on my findings alone, outright claim that academic greenwashing is happening as my research does not prove intent to mislead, it is essential to acknowledge that there may be unintentional bias in these discussions – one that warrants further scrutiny. It is

imperative to strike a balance between promoting benefits from technologies and ensuring comprehensive evaluation of the technology's actual environmental and social impacts, allowing for informed and transparent decision-making within the agricultural community. This finding does not mean we should not remain optimistic about the integration of technology within agriculture. The technologies which make up PA are full of promise and should not be discredited but rather we should remain cautiously optimistic when imagining their role in creating a sustainable agriculture system. In this pursuit, it is important to acknowledge that while PA holds potential, its alignment with productivist strategies may inadvertently re-enforce the status quo of the current industrial agricultural system and overshadow the valuable contributions of more diverse and sustainable modes of production. Integrating precision technologies with proven sustainable or alternative agricultural practices can address challenges related to environmental degradation and food security. For example, the sustainable agriculture practice of intercropping – growing two or more crops in proximity – requires less land and has exhibited reductions in agrochemical requirements, GHG emissions, and soil erosion and improved yields, improving the outlook for future agriculture (Fung et al., 2019; Martin-Guay et al., 2018). Such an approach not only leverages the benefits of technology but also acknowledges the value of diverse and sustainable agricultural systems. The future of PA is not yet solidified into a concrete socio-technical system as Bronson (2020) states, there is time to carefully shape digital innovations and their infrastructures for a diversity of food system actors.

5.3 Summary: The Dominant Framing

The literature on PA presents a complex landscape regarding sustainability, with various perspectives on how PA can enhance agriculture's well-being, whether in economic, environmental, or social terms. While the literature often explicitly conceptualizes sustainability

in terms of a three-dimensional model, the literature often implicitly links economic and environmental gains with the broader concept of sustainability. The emphasis on economic and environmental sustainability seen throughout the literature raises questions about whether PA can truly promote sustainability as conventionally understood. In this context, the prevailing three-pillar model of sustainability, which encompasses economic, environmental, and social dimensions, faces limitations when applied to PA.

The 3-dimensional model highlights the interconnected nature of these dimensions and the multidisciplinary nature of sustainability. However, in the literature on PA, there is a lack of consensus and varied emphasis on different aspects of sustainability, depending on the academic discipline or actors involved. This perceived diversity of interpretations and emphasis appears to lead to productivist views dominating the discourse, where technical efficiency and increased production take precedence. When acknowledging environmental sustainability, academics often oversimplify it by predominantly emphasizing the reduction of inputs and resource use, equating these benefits to sustainability. Additionally, they often consider this dimension as a secondary benefit when improving an economic parameter, while the social dimension of sustainability overall, conspicuously receives significantly less attention. The prevailing approach seems to prioritize economic aspects and considers environmental aspects as secondary while side-lining social considerations, prompting questions about the comprehensiveness of the sustainability framework in the literature on PA.

While it is important to acknowledge that various conceptualizations of sustainability exist, there appears to be a convergence towards a framing of productivity as sustainability as seen across the literature. I am not arguing this is the only way to model sustainability in the context of PA; however, my analysis indicates a prevailing vision of sustainability that prioritizes

productivity with some, albeit not comprehensive, consideration for the environment and society. Considering the current discourse on PA and sustainability, we must recognize the necessity of taking a more comprehensive and balanced approach. While the economic and environmental aspects of sustainability undoubtedly hold significance, we must not overlook the social dimension. PA has the potential to transform the agricultural landscape, but measuring its success should not solely focus on increases in efficiency or reduced resource consumption. The social dimension, encompassing the well-being of farmers, rural communities, and equitable access to resources, is equally vital. Neglecting this dimension risks perpetuating disparities within the agricultural sector and failing to achieve true sustainability. Once again, this is not to say that optimism about the promise of PA is unwarranted; indeed, it holds great potential. However, we must first clarify its vision before continuing to perpetuate sustainability claims. To make meaningful progress, we must embrace a holistic view of sustainability in PA, one that acknowledges the interconnected nature of economic, environmental, and social aspects, and ensures that no single dimension takes precedence over the others.

Chapter 6 Conclusion

6.1 Contributions

This research had two main objectives: first, it sought to establish a thorough comprehension of the sustainability models or conceptualizations within the academic discourse on PA and second, it aimed to identify the contextual factors linking PA and sustainability and investigate their influence on shaping the inherent connection between these two concepts. Together, through a systematic literature review and interviews with key informants, in conjunction with previous research conducted alongside Dr. Bronson, this research explored how the academic discourse on PA conceptualizes sustainability. From my analysis, the literature reveals a common use of the three-dimensional model of sustainability and other agricultural models like sustainable intensification. Additionally, the literature most often frames sustainability in terms of economic or environmental benefits, leading to the emergence of models of sustainability which are representative of some form of intensification. However, through a critical analysis of how the academic literature perceives and conceptualizes sustainability, this research contributes to a further understanding of how the current presentation of sustainability in the academic literature on PA inadvertently reinforces existing productivism paradigms in agriculture, focusing on productivity enhancement, cost reduction, and economic gains.

Considering these main findings, this research provides further investigation into the connection between PA and sustainability. Ultimately my research uncovered that sustainability in the context of PA can serve as a cloak for concealing underlying productivist values held by various proponents, thus further contributing to the existing literature which questions the

revolutionary potential of PA. This finding further enriches the ongoing discourse within the academic community that questions the transformative potential of PA (see Bronson, 2020; Chapman et al., 2022; A. Fraser, 2020; Miles, 2019; Rose et al., 2020), inviting a re-evaluation of its sustainability claims and their alignment with broader sustainability goals.

Moreover, as this research identified the dominance of productivist paradigms, coupled with the absence of empirical evidence supporting the claim that PA has sustainability benefits (as indicated by the previous research, Bronson et al. forthcoming), it provides valuable insights into the potential occurrence of greenwashing within the context of PA. This finding extends the understanding of the complexities surrounding the portrayal of sustainability in PA and contributes to the discourse on potential misalignments between stated sustainability goals and the actual benefits, particularly environmental sustainability benefits, of PA practices. By shedding light on the possibility of greenwashing, the research adds a critical dimension to the evaluation of PA's environmental claims, urging a closer examination of its true sustainability implications.

6.2 Study Limitations

6.2.1 Key Informant Engagement

While my research offered valuable insights into the interplay between PA and sustainability, it is essential to acknowledge the limitations and constraints of this research. The main limitation of this research was the limited number of key informants engaged with. Identifying academics who had made valuable contributions to the body of literature was straightforward but soliciting their participation during the summer months proved to be a challenge. As I needed to continue to make progress on my research, I began contacting my key informants in May to give scheduling flexibility through June, July, and August. Additionally,

the choice to solicit participation via email may have limited the number of participants engaged with, as academics often receive a high volume of emails, and it is possible that my invitations were inadvertently overlooked amidst busy correspondence. This seasonal constraint coupled with the choice of email correspondence resulted in a smaller pool of academic informants, potentially limiting the range of perspectives and insights included in this study.

Furthermore, despite attempting to capture academics who publish on PA and have written about its connection to sustainability, some academics who agreed to participate could only speak partially to this issue. This is not an issue on the side of the academics, but rather a challenge that resulted from the nature of the academic landscape. It became evident that the multidisciplinary nature of PA, spanning fields from agronomy to various engineering disciplines, can lead to variations in the depth of knowledge regarding sustainability. As a result, while some academics possessed comprehensive insights into the sustainability aspects of PA, others were naturally less equipped to provide extensive commentary on this element of my research.

Remaining on the topic of key informants and considering how this research evolved, only considering academics limits the perspectives and insights that my research could have investigated. While academics undoubtedly bring valuable expertise on the academic, industry and government perspectives, they represent just one proponent who shapes the narrative on PA and sustainability. The absence of interviews with industry experts, government officials, and farmers within the PA ecosystem is a notable limitation. Incorporating more diverse perspectives could have enriched this research by providing a more holistic understanding of how PA and sustainability intersect in practice, beyond that offered by the academic perspective. This

limitation opens the possibility of future research to investigate the sustainability narrative further by engaging directly with industry, government, and farmers.

6.2.2 *Temporal Limitations*

Given the evolving nature of the field of PA, my research only captures a snapshot in time of the literature reviewed in this research. The literature collected for this literature review dates to July 2020 when it was initially collected, leading to the omission of articles published in the last 3 years. As a proactive measure, I considered revisiting the data collection process to include articles published in 2021, 2022, and 2023. However, it became evident that this would have resulted in an extensive collection of articles, far exceeding the practical limits of this research endeavour. This is not a significant limitation because given the deeply rooted connection between sustainability and PA, the core principles and approaches in the field remain relatively stable over a short span of a few years. The foundational concepts that underscore the sustainability narrative within PA are unlikely to undergo significant transformations in such a brief period. Consequently, while this research may not encompass the very latest developments, it still provides a robust and relevant understanding of the ongoing discourse surrounding PA and its sustainability implications.

6.3 Potential Future Research

This investigation builds upon previous research by providing an understanding of various conceptualizations of sustainability and the values that underpin them, adding to the collection of research investigating the connection between PA and sustainability. However, additional research is necessary to further the understanding of the dynamics between sustainability, productivism and intensification in relation to PA. This research is essential to

gain a more comprehensive picture of how emerging agricultural technologies can potentially contribute to sustainability within the agriculture sector and to obtain deeper insight into the seemingly inherent link between PA and sustainability.

Given this research exclusively focuses on academic literature and academic key informants, it becomes imperative to acknowledge the need for further in-depth, interdisciplinary studies to explore how different proponents of PA, beyond academics, perceive and prioritize sustainability within PA. Such interdisciplinary research should encompass an assessment of promotional materials created by the agricultural industry responsible for marketing these technologies and government agencies actively promoting initiatives aimed at subsidizing research and development as well as the adoption of PA technologies. This holistic approach will enable a more inclusive and nuanced understanding of how sustainability is perceived, integrated, and promoted across various sectors and stakeholders involved in PA. Further investigation into the connection between PA and sustainability may also include longitudinal studies to improve our understanding of how this connection emerged over time, comparative analysis between stakeholders to better understand where differences lie in how stakeholders promote the sustainability aspect of PA, and network analysis to better pinpoint and track an origin(s) of these sustainability claims in the literature.

As a part of this additional research, there should be consideration for scale. To truly evaluate sustainability and the ability of PA to contribute to sustainability, this investigation should occur within defined boundaries as sustainability manifests differently at different scales – ranging from the field to the farm and on a global level. At the field level biodiversity, soil health, and resource use play significant roles in contributing to sustainability. Expanding this assessment to the farm level provides insights into the holistic sustainability of agricultural

operations, encompassing factors such as economic viability and rural community engagement. And at the global scale factors such as climate change, food security and international trade come into play, shaping the broader extent to which PA may facilitate sustainability. Further research should consider these different scales to better assess how we can measure sustainability and assess the effectiveness of PA in promoting sustainability.

Furthermore, an investigation into the potential phenomenon of greenwashing within the discourse on PA is warranted. While the academic literature frequently asserts that PA will play a pivotal role in promoting sustainability, my analysis reveals that the predominant representation of sustainability in this context often aligns itself with productivism values, prioritizing intensification over genuine sustainability benefits. Considering these observations, it becomes evident that additional research is essential to comprehensively investigate how PA is promoted and marketed, the specific sustainability claims made, and the extent to which these claims are supported by empirical evidence. Such an investigation should also direct inquiry towards understanding if the misleading claims made in the academic literature are intentional, to truly be able to label this phenomenon as “greenwashing”. Future research into the potential greenwashing occurring in the academic literature can aid in the development of strategies aimed at fostering transparency and accountability within academia to ensure promotion of credible claims made around sustainability in the context of PA.

6.4 Concluding Remarks

As climate change poses significant threats to global food security, the (Pörtner et al., 2022) adoption of precision technologies in agriculture is widely touted as a solution to mitigate environmental degradation, reduce resource consumption, and enhance productivity (E. D. G. Fraser, 2020; Lowenberg-DeBoer, 2015; Ryder, 2014; Sonka & Cheng, 2015). The optimistic

vision of PA suggests that it can contribute to a more sustainable food system, benefiting both the environment and society (Bewley, 2010; de Koning, 2010; Finco et al., 2023; Franco et al., 2017; E. D. G. Fraser, 2020; Gebbers & Adamchuk, 2010; Hatfield & Kitchen, 2013; Kiran Kumara et al., 2020; Math & Dharwadkar, 2020; McKinion et al., 2001; Mulla, 2013). However, as shown in previous research (Bronson et al., Forthcoming) ambiguity exists around the ability of PA to contribute to sustainability because limited empirical evidence exists to support these claims of increased sustainability. Through my research, I sought to further investigate this intrinsic link between PA and sustainability, seeking to understand the models of sustainability present in the academic literature and uncover the factors which have influenced the creation and continual promotion of this link. Analysing how sustainability is defined, operationalized, and has evolved in the academic literature and through discussions with scholars reveals that academics present a seemingly multifaceted view of sustainability, demonstrating differing visions of how it is conceptualized in relation to PA. Despite this multiplicity of conceptualizations, there is a prevailing focus on economic success with limited consideration for the environment and even less attention to the social dimension. This skewed approach raises questions about the completeness of the sustainability framework in PA literature.

As Allen et al. (1991) aptly acknowledges, there is often a feeling that we need to devote less time talking about the meaning of sustainable agriculture and more time to implementing it. Yet, if we want agriculture to pursue a path different from that of conventional agriculture, one that considers the environment and society on top of production, scholars need to explicitly state and gain some consensus on sustainability goals and agree upon a comprehensive definition of sustainability (Allen et al., 1991). Academics and stakeholders alike must embrace a balanced perspective to ensure PA is developed in a manner that genuinely fulfils its intended

sustainability goals. This entails recognizing and addressing the significance of all elements of sustainability and evaluating sustainability on its impact across all three dimensions. Attaining a balanced and comprehensive definition necessitates collaboration among researchers, policymakers, and stakeholders, fostering the development of strategies that ensure a sustainable future for agriculture, benefiting all. Moreover, if holistic sustainability does not align with the vision of PA, there is a need for a collective reframing of how sustainability is presented to avoid ambiguity and the risk of greenwashing. As we strive for a future where agriculture plays a central role in environmental stewardship, food security, increased farm viability and rural well-being, we must continue to scrutinize and refine the vision of sustainability facilitated by PA.

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Appendix A: Interview Guide

Introduction/Preamble

Thank you for agreeing to participate in this interview. I am a graduate student from the University of Ottawa, and I am researching the link between precision agriculture and sustainability. The purpose of this interview is to discuss your understanding of precision agriculture and its relation to sustainability.

Throughout this interview, I will ask you a series of questions; I am looking to gain your perspective on sustainability and precision agriculture. Feel free to ask for clarification or take time to think about your answers. We can always return to questions if you would like to add more information or for clarification. Please understand there are no wrong answers to any question and if you choose not to answer a question that is okay as well.

I have received your consent form through email, and I would like to confirm that by participating today you still agree with the terms outlined in that form OR I did not receive your consent form through email, I have sent it again before this interview. If you could please take 5 minutes to review that form and if you agree we can proceed with the interview. I would also like to ask if it is okay if I record this conversation; you can keep your camera off/turn your camera off if you wish. This interview is going to take about 80 minutes. This is the first interview I am conducting.

Do you have any questions before we begin?

Body of Interview

Chapter 7 Introduction

Question 1: Can you tell me what you do for a living?

Probes:

- What was your path to your current position? How did you get into this field of work?
- Can you describe your research interests and how they are related to precision agriculture?
- Can you describe how your position or work relates to precision agriculture?

Question 2: Do you think there may be sustainability implications from using precision agriculture? And if so, what might they be?

Transition: I am getting the sense you feel sustainability is an important element of precision agriculture...

Question 2: If you had to define sustainability, how would you describe or define it?

Probes:

- a) Are there any specific environmental, social, or economic elements that you believe are critical to defining sustainability? (Examples: Reduction in harmful chemicals, reduced labour load for farmers, increased productivity, and profitability)
- b) Do you consider sustainability to be an important element of precision agriculture? Why or why not?
- c) Are there any specific environmental, social, or economic aspects of sustainability that you believe are most impacted, positively, or negatively, by precision agriculture practices? (Example: Some believe precision agriculture helps farmers reduce their input costs resulting in a more economically sustainable operation).

Question 3: *Within the context of precision agriculture, what do you think is the most important aspect of sustainability?*

- a) Can you identify any external factors (e.g., environmental concerns) which have contributed to the development of the connection between precision agriculture and sustainability?
- b) Do you believe that the integration of sustainability in precision agriculture is driven by the need to address environmental concerns, social or economic benefits, or a combination?
- c) In your opinion, what role has environmental concern played in the integration of sustainability in precision agriculture?
- d) Do you believe economic benefits have been a driving force behind the link between precision agriculture and sustainability? If so, can you explain how?

Transition: Now that we have established that you believe there may be a connection between precision agriculture and sustainability...

Question 4: Can you elaborate about when or how you first heard of or thought of the connection between precision agriculture and sustainability?

Probes:

- a) What papers or academic articles do you believe are important to this link?
- b) Are there any papers that provide evidence, in your opinion, which supports or refutes the claim that precision agriculture has sustainability benefits?
- c) Can you discuss any government initiatives or policies that may have sparked your interest in precision agriculture and its connection to sustainability?

Question 5: Why do you think sustainability has become an important selling point of precision agriculture?

Probes:

- b) In your opinion, where do you think this link comes from?
- c) In your opinion, has sustainability always been an element in the discourse on precision agriculture? Why or why not?

- d) Have you observed any changes in the way precision agriculture is discussed in academic literature, industry, or policy publications over time, in terms of its connection to sustainability? How has it changed?

Question 6: What actors have played a role in forming the link between precision agriculture and sustainability?

Probes:

- a) Do you think academia/industry/government has played a role in shaping the narrative around precision agriculture and sustainability? Why or why not?
- b) What actors, academia/industry/government has played the biggest role in shaping the narrative around precision agriculture and sustainability?
- c) Which industry stakeholders or policymakers do you believe have played a significant role in promoting the connection between precision agriculture and sustainability?
- d) Repeat from question 3: Can you discuss any government initiatives or policies that have influenced the discourse on precision agriculture and its connection to sustainability?
- e) What do you think are the underlying assumptions and values that have shaped the discourse around precision agriculture and sustainability?

Concluding remarks

That concludes our interview, are there any questions you would like to go back to any questions?

From the recording I took today, I will transcribe the interview and I will share a copy with you to review. You can expect this by email within the next 30 days once I have conducted all the interviews. You can contact me via email with any questions regarding this interview. Do you have any final questions?

Appendix B: Coding Schemas

Table 4 The final coding schema related to models of sustainability employed for the analysis of transcripts and articles.

Category	Code	Description
Sustainability defined?	Yes	The article provides a definition or context to the meaning of sustainability.
	No	The article does not provide a definition or any context to define sustainability.
How is sustainability defined?	3 pillars	Sustainability is defined using economic, environmental, AND social dimensions.
	Economic	Aspects of sustainability related to the economic viability of a system or practice. Looking for definitions on financial stability, profitability, cost-efficiency, and economic impacts
	Environmental	Focus on the impact of a practice on the natural environment. Look for info on environmental conservation, resource management, pollution control, and efforts to reduce GHGs.
	Social	Aspects of sustainability, such as equity, social justice, and community well-being. Look for discussions about inclusivity, social responsibility, social cohesion, and the effects of sustainable practices on society.
	Intensification	Intensification of agricultural or production practices in a sustainable manner. Seek information about strategies to increase productivity while minimizing negative environmental and social impacts.
	Other	Any other models of sustainability placed here to determine if new code could be created.
Measuring sustainability	Efficiency/Optimization	Efficiency measures how well resources are utilized to achieve a specific outcome, often in terms of cost, time, or energy. Look for examples of how efficiency metrics are used to assess sustainable practices, such as reduced energy consumption or minimized waste production. Look for studies that discuss how optimization models or techniques are applied to maximize sustainability outcomes, like balancing environmental impact with economic benefits
	Reduction in inputs	Reduction in inputs focuses on minimizing the use of resources, such as raw materials, water, or energy, to achieve sustainable objectives. Look for cases where innovative approaches or technologies have led to significant reductions in resource inputs while maintaining or improving overall performance.

Table 2 continued

Category	Code	Description
Measuring Sustainability	Other Benefit	Benefit measurement evaluates the positive impacts or advantages generated by sustainable practices, encompassing economic, social, and environmental benefits.
Type of Article	Adoption	Articles focusing on the adoption of sustainable practices, policies, or technologies. Look for Factors influencing adoption rates, barriers, and drivers of sustainability initiatives
	Critique	Articles that critically assess or analyse existing sustainability practices or policies. Discussion of strengths and weaknesses of current PA approaches, alternative recommendations, or areas for improvement.
	Economic Efficacy	Articles examining the economic aspects of sustainability, such as cost-benefit analyses or financial implications. Looking at articles that assess the economic outcomes of various PA technologies, impact on budgets and profits, and potential long term economic benefits
	Environmental Efficacy	Articles focusing on the environmental outcomes and impacts of PA technologies.
	Technology Efficacy	Articles that investigate the effectiveness of specific PA technologies based on a variety of indicators.
	Review	Literature reviews or meta-analyses summarizing existing research on PA.

Table 5 Final coding schema for analysing interview transcripts, focusing on the origins of sustainability claims.

Category	Code	Description
Re-enforcing values	Environmental Stewardship	This code relates to any discussion or mention of practices, attitudes, or actions that demonstrate a commitment to protecting or conserving the environment. Looking for statements or content that discuss efforts, strategies, or perspectives related to reducing environmental impact, conserving resources (e.g., water, soil), minimizing pollution, or promoting sustainability within precision agriculture practices.
	Economic viability	This code pertains to content within the interview transcripts that relates to the financial aspects and profitability of precision agriculture, including factors influencing economic success. Looking for Search for discussions or references to cost-effectiveness, return on investment, financial challenges, profitability, market dynamics, economic benefits, or any other financial considerations associated with precision agriculture practices.
Re-enforcing actors	Academics	Academics refer to researchers, scholars, and experts in the field of Precision Agriculture. Look for instances where academics are cited or mentioned as sources of information, studies, or expertise related to PA and sustainability. Note if interviewees discuss academic research findings or theories that support or shape their views on these topics.
	Industry	Industry actors encompass companies, organizations, and professionals directly involved in the agriculture and technology sectors. Look for references to industry players promoting or advocating for specific technologies, products, or practices within the realm of PA and sustainability. This may include mentions of businesses' interests, innovations, or market trends driving the narrative.
	Government	Government actors represent governmental bodies, agencies, and policymakers at various levels (local, regional, national) involved in agricultural and environmental regulations and initiatives. Look for instances where government policies, regulations, incentives, or funding programs related to PA and sustainability are discussed in the transcript. Also, note any interactions or collaborations between interviewees and government entities that influence the narrative.
Other Factors	Intrinsic Value	This code refers to instances where interviewees discuss Precision Agriculture and sustainability as being closely interconnected or dependent on each other. Look for statements or narratives in the transcripts where interviewees emphasize the inherent connection between PA and sustainability. This could include discussions on how PA practices inherently contribute to or are essential for sustainable agricultural practices.
	Historical Context	Look for any references to significant innovations, technological advancements, or changes in agricultural practices over time, which may have led to the emergence of PA and its relation to sustainability.