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REVIEW

Farm digital tools: A systematic review of investments and environmental implications

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Abstract: Farm-level investment in digital tools is often viewed as a necessary part of the agroecological transition. However, its actual relevance remains unclear due to currently ambiguous definitions of farm investments in general and equipment investments in particular. We conducted a systematic review of the farm investment literature to characterize the different categories of digital tools investments seen and to determine how often the environment is considered in this field of research. A total of 131 articles met our eligibility criteria and were subject to further analysis. First, we found that research on farm investments has looked at general farm investments, investments in combined factors of production, and investments in specific factors of production. Second, we discovered that there are four main investment categories for farm equipment (including digital tools). Third, we noted that few studies have addressed the environmental implications of investing in digital tools. Our findings emphasize that, to facilitate the agroecological transition, it will be important to promote broader strategies that encourage farmers to invest in digital tools.

Keywords: farm investment, typology, digital tool investment, environment

1 Introduction

Agricultural systems are rapidly changing as they seek to feed the growing global population, a challenge that demands greater economic efficiency, environmental sustainability, and production levels. A key factor facilitating these transformations is farm-level investment in digital tools (DTs) [1–3]. For farms to remain economically viable and competitive, it is fast becoming necessary to employ DTs such as drones, sensors, software, and automated equipment [4]. This integration of DTs into agricultural systems represents a paradigm shift that is ushering in a new era of precision, productivity, and sustainability [5–8].

When investing in DTs, farmers are not simply adopting new technologies; they are fundamentally changing how they farm [9]. With DTs, farmers have access to real-time information, which allows them to enhance productivity [10, 11], minimize environmental impacts [12–14], and mitigate risks, thereby promoting the long-term viability of their operations [9, 15]. However, there is an absence of research examining how investments in DTs concretely affect farm economic and environmental performance. The few studies published to date have shown that effects on performance depend on the type of DT analyzed, the context of DT usage, and the performance indicators chosen.

While farmers invest in DTs for a range of reasons, they all tend to share the strategic objective of renewing or growing their assets. Levi et al [16] explained that renewal-centered investment focuses on replacing depreciated equipment. In contrast, growth-centered investment takes one of three forms: 1) investments that enhance working conditions and boost labor productivity; 2) investments that increase capital to expand production capacity [16]; 3) investments that aim to promote agricultural sustainability by mitigating the negative environmental impacts of farming practices [17].

Furthermore, DT investments vary in the degree of financial commitment required. For instance, some DTs require a substantial initial investment and represent long-term assets; examples include connected devices such as tractors, sprayers, and milking robot [18]. Other

DTs have regular supplementary costs and necessitate low levels of capital in the form of current expenses (e.g., internet contracts, purchase of a personal computer or smartphone).

The transition toward digital farming has the potential to greatly transform agricultural systems. However, understanding the dynamics of this transition will require less ambiguous definitions of the term "investment". To date, the perspective has been one of accounting: all operations that ultimately result in depreciation are considered to be investments. Other investment types, such as those involving intangibles, tend to fall outside this definition [19], even if intangibles such as human capital are essential for effectively utilizing farm equipment, including DTs [20]. As a consequence, DT investments lack a clear definition. Indeed, some researchers state that such investments only encompass initial expenditures on equipment [21], while other researchers include related expenses, such as the human capital, the cost of accessories, and any training expenses (needed for equipment installation) [22].

Despite this absence of clarity, it seems evident that investments in DTs extend beyond the mere acquisition of materials and software, as noted above. Additionally, there are crucial points of intersection between the environmental impacts of DTs and the complex financial landscape occupied by farms. To promote more sustainable agricultural systems, we must better understand the variety of DT investments and their relative consequences for the environment.

Here, we characterized farm investments in DTs by systematically reviewing the literature in the field of agricultural economics. Our main objective was to clearly situate DT investments within the greater context of farm investments. We explored the extent to which DT acquisition is treated as an investment and the type of investment it represents. We were specifically interested in research that addressed the environmental implications of DT investments (e.g., DT adoption was considered within an environmental context or the study was interested in how DTs could improve input use efficiency or farm environmental sustainability). A better understanding of DT investments and their environmental impacts could help inform public policies, paving the way for the agroecological transition and enhancing farm economic competitiveness.

In this study, we conducted a systematic literature review to summarize and synthesize current knowledge regarding farm investments in general and farm equipment investments in particular. We paid notable attention to research on DT investments. Based on our results, we propose a classification system for farm investments and farm equipment investments. Our findings paint a comprehensive picture of how investments in DTs interconnect, influence agricultural practices, and affect the environment. We offer key insights and a forward-looking perspective on the shifting landscape of DT investments and their importance in the agroecological transition.

2 Methodology

Systematic reviews are recognized for their rigor and objectivity. Using a robust and structured framework, they allow for the aggregation and synthesis of current knowledge [23–26]. In this study, we utilized an approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol (www.prisma-statement.org) to examine the existing body of research on farm investments.

Our systematic review comprised several key steps. First, we needed to formulate a target query related to farm investments in DTs. We performed a preliminary bibliographical search but found few publications on DT investments. This gap in the literature may exist because DTs are largely addressed from a usage perspective rather than an investment perspective. We consequently broadened the scope of our search to consider research on farm investments in general, which are likely to encompass investments in farm equipment, including DTs.

We carried out a Boolean search for the following combination of keywords in the titles of articles published in English or French: agricultur* OR farm* AND investment*. This search was conducted across seven databases: Google Scholar, ScienceDirect, Cairn, Taylor & Francis, Wiley Online Library, BASE, and Sage Journals. It was run for the last time on February 28, 2023. We retrieved additional references by manually searching the literature cited in a relevant subset of articles. A detailed description of our review methodology is depicted below (Figure 1).

Our initial search yielded 2,534 documents, from which we eliminated certain document types, including comment papers, case studies, informational notes, brief reviews, mini reports, PowerPoint presentations, and articles in languages other than French or English. Next, we imported the remaining references into reference management software (Zotero) to eliminate any duplicates. We then manually screened the titles and abstracts of the remaining 407 articles.

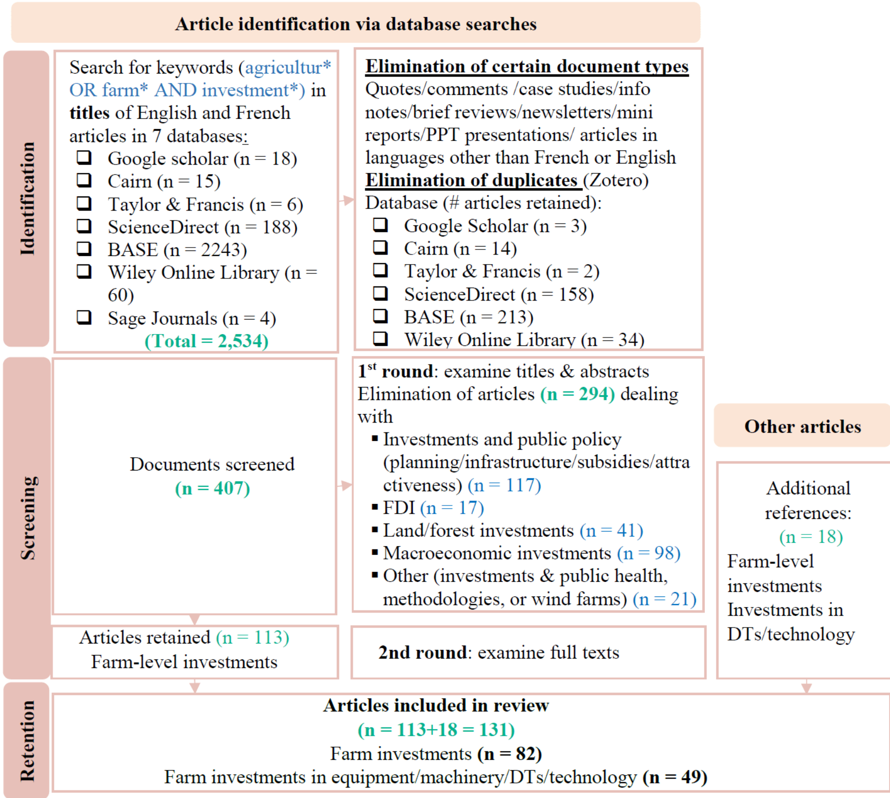

Figure 1 PRISMA-based methodology used in our systematic review

When it was unclear from the title and abstract whether an article was of relevance, we reviewed the full text.

We then assigned these 407 articles to one of the following categories based on their focal theme: (i) farm-level investments; (ii) investments and public policy (e.g., related to development, infrastructure, subsidies, and public aid/attractiveness); (iii) foreign direct investment (FDI); (iv) land and forestry investments; (v) macroeconomic investments; and (vi) other—the impacts of investments on public health; methodological research on investments; or investments in wind farms.

We excluded 294 articles that did not meet our eligibility criteria (i.e., focus, scale, and context). Our research objective was to examine farm-level investments. We therefore eliminated articles that had a macroeconomic perspective as well as articles that centered on investment sources (i.e., public, private, or foreign). We also eliminated articles examining the effects of intensive agricultural production on public health and those focused on wind farm investments.

We read the full texts of the 113 remaining articles and searched for additional references among their citations, which led to the identification of 18 additional articles of relevance. As a result, our review was based on a total of 131 articles focused on farm-level investments.

We then utilized an extraction technique to consolidate information on article author(s), year of publication, research context, research objectives, investment categories, investment details (e.g., scope, cost, components), and inclusion of environmental factors. We performed a descriptive analysis of this information using pivot tables.

3 Results

3.1 Trends in farm investment research in relation to time, country economic status, and production system

Based on the 131 articles used in the review, farm investment research has grown substantially since the 1960s in both low-to-middle-income countries and high-income countries (Figure 2). This finding indicates the topic has increased in academic interest and relevance over time, likely because of a burgeoning awareness of sustainable practices, environmental conservation efforts, and public policies promoting eco-friendly farm investments. These factors may then have prompted research into the economic implications of said investments [27, 28] and the role of related public policies [29–31].

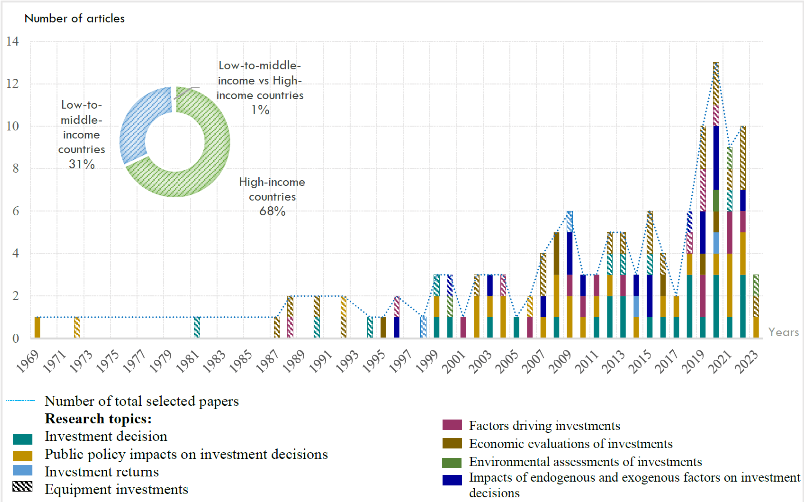

Figure 2 Appearance of farm investment research topics over time (n = 131 articles)

We found that farm investment research was sparse until the 1980s, which could be because few studies prior to this period were indexed in the online databases. However, we did observe a pronounced increase in publications starting in the 2000s. There were distinct peaks in 2019 (n = 10 articles), 2020 (n = 13 articles), and 2022 (n = 10 articles).

This rise in farm investment research can be explained by diverse factors, including shifts in agricultural conditions, market conditions (e.g., variation in input and product costs) [32, 33], and public policies (e.g., access to subsidies, public funding, credit) [34, 35], as well as the development of DTs [36, 37] and a growing awareness of environmental issues [38, 39].

We also noted that research is more focused on high-income countries than other countries (Figure 2; 68% of the articles). For example, 69 of the 131 articles described farm investments in European countries. This pattern in the literature likely results from the unique agricultural context in Europe [40, 41] and the considerable impacts of the Common Agricultural Policy (CAP) on farm investment decisions [40, 42, 43].

Poland in particular has experienced a surge in farm investment research, largely because of the country's unique political and agricultural conditions. Specifically, Poland experienced a significant demographic shift, marked by a decrease in rural populations. After becoming a member of the European Union, Poland implemented various measures to encourage and enhance farm investments. Consequently, a number of studies have examined how public sources of financial support and easier access to credit have affected farm investments [44–46].

Research in France and Italy has primarily focused on the investment behavior of farmers [47] and the factors influencing their investment decisions [48–50]. Compared to Europe, the United States has produced less research (n = 14 articles). The latter mainly occurred prior to the 2000s and focused on investments in specific equipment and technological devices, such as irrigation systems, tractors, milking robot, and various types of machinery [51–53].

Indeed, most of the articles from high-income countries addressed farm investments without specifying the production system in question. These studies primarily focused on decision-making during farm investments [54–56] and the impact of exogenous factors (e.g., public sources of financial support, access to credit, market conditions, off-farm income) on overall farm investment decisions [52, 57].

Our findings indicate that systems for breeding cattle, especially dairy cattle, and producing crops (e.g., cereals such as wheat and corn, as well as oilseeds such as sunflower and soybean) are the predominant production systems represented in farm investment research. This result is likely due to the greater financial requirements of these systems. Notably, to maintain economic and technical competitiveness, farmers must invest in capital assets such as buildings, livestock, materials, and DTs (e.g., automated milking systems, sensors, GPS-enabled devices) [58–60].

A lower percentage of the articles (32%) described research in low-to-middle-income countries. They examined farm investment decisions within specific production systems (e.g., rice, pineapple, cassava, tea, arboriculture, coffee, and coconut). In these studies, the aim was to explore farm investment dynamics under conditions of constrained resources, and the primary focus was placed on water and soil conservation practices and irrigation systems [29, 61–63].

Overall, researchers have broadly addressed the topic of farm investments, but their research objectives have greatly differed because of inherent disparities in public policies, production strategies, and context-specific economic dynamics. This diversity emphasizes that we must clarify the specific nature of farm investments to better characterize the scope of DT investments undertaken by farmers.

3.2 Different categories of farm investments

Based on our results, we propose that farm investments have been defined in diverse ways within the literature but can be classified into one of three broad categories: (i) general farm investments, (ii) investments in combined factors of production, and (iii) investments in individual factors of production (e.g., farm equipment, including DTs) (Table 1).

Table 1 Relative abundance of articles focused on each investment type

Investment category		% of articles	Examples
General farm investments		20.61% (n = 27 articles)	[16, 64–66]
Investments in combined factors of production (e.g., specific crops; new practices)		23.66% (n = 31 articles)	[27, 29, 39, 47, 62, 67–69]
Investments in individual factors of production	Factor of production	18.32% (n = 24 articles)	[20, 70–72]
	Equipment (e.g., DTs)	37.40% (n = 49 articles)	[21, 36, 37, 60, 73–75]
Total		100% (n = 131 articles)	

3.2.1 General farm investments

We found that researchers have often used a comprehensive approach when analyzing farm investments. They may adopt an accounting perspective that does not clearly identify the different components or factors of production associated with the investment. As a result, such work generates indicators and analyses based solely on financial definitions.

One of these key indicators is general farm investment, which refers to a farmer's allocation of financial resources toward various farm assets or activities [56, 65, 76]. Some researchers have focused on specific components of farm investment, namely capital investment, which is the allocation of financial resources toward factors of production [41, 77, 78] with a view to spurring improvements.

Researchers have also employed specific indicators, such as net investment, to quantify changes in capital stock, which can include long-term tangible assets (e.g., land, buildings, equipment), intangible assets (e.g., milk licenses, software), and financial assets (equity investments in other companies and non-commercial real estate). Certain researchers [35, 64, 79] have used net investments to explore farm investment dynamics. Another common metric is gross investment, which accounts for depreciation and thus provides a broader perspective on the investment landscape [80, 81]. The data needed to calculate net and gross investment are readily accessible, and these indicators are valuable tools for obtaining an overview of farm assets and, thus, farm investments.

However, many of the researchers who have examined farm investments in general have overlooked specific investments in farm equipment, including DTs. Their main research goal was to explore how general farm investments were affected by market variability [49], off-farm income [64], access to credit [82], and public policies [40]. Some researchers have delved into the relationship between agricultural investments and agricultural performance in the context of technological development [16]. However, they did not conduct a detailed examination of certain factors of production, such as farm equipment.

While this research approach has yielded information on different categories of capital, it does not clearly and consistently differentiate among investments in specific factors of production (e.g., land, equipment, livestock, services, knowledge) that are part of general farm investments. Indeed, in industrial firms, the main form of capital is equipment. Consequently, capital investment is primarily directed toward equipment, as it is the main factor driving production [83]. However, for farming operations, the situation is much more complex. The fixed capital on farms is equipment as well as land and livestock. Furthermore, capital investments extend beyond fixed capital to circulating, intangible, and human capital. As a result, it can be challenging to identify specific investments in different types of farm equipment.

3.2.2 Investments in combined factors of production

Some researchers have taken an integrated analytical approach to exploring farm-level investments and have examined different combinations of factors of production [72]. These combinations have included factors tied to fixed capital, such as land and buildings [84] as well as equipment and livestock [85, 86]. However, these factors may also be tied to circulating, intangible, or human capital (e.g., rental fees for specific machinery services [43], training and knowledge [87], input supply costs [34]. Each farm has specific input requirements, which are influenced by crop type, geographical location, and agricultural practices; these requirements can lead to variability in factor combinations. In crop production, the most common combination of factors includes land, equipment, machinery, buildings, and inputs [33, 47]. In arboriculture, the cost of plantations is added to this group [88–90]; in animal production systems, the cost of acquiring animals is included [58, 67, 91].

Other research has looked at long-term investments in combinations of factors aimed at promoting agroecological approaches, such as organic farming, water and soil conservation, and climate-smart agriculture. These approaches seek to limit environmental impacts, enhance climate resilience, and increase sustainability by gradually expanding a farm's suite of eco-friendly factors of production, such as those that boost soil quality, water management efficiency, and biodiversity. Additionally, these factors collectively help increase agricultural productivity over time. This overall tactic fits with fundamental investment principles: resources are strategically allocated to generate long-term benefits. As demonstrated by Kleemann et al. [69] as well as by Musshoff & Hirschauer [87], farmers invest in organic production systems for non-monetary reasons. Obtaining organic certification involves a range of investments: the costs associated with making technical changes, acquiring the necessary equipment, and providing the requisite training to ensure compliance with organic farming standards. Such investments involve not only financial expenditures, but also the development of human capital (e.g., the knowledge and expertise needed for organic farming).

Hoogeveen & Oostendorp and Musafili et al. [32, 62] examined the financial implications of investments in water and soil conservation. Their assessment encompassed input-related costs, such as soil amendments and erosion control measures, as well as expenses associated with land management [28, 92]. Depending on the conservation approach, such assessments might also need to consider additional time and labor costs, which highlights the diverse investments associated with sustainable land use practices [68].

Horrillo et al. [27] explored agroecological investments in biosecurity practices, namely those aimed at safeguarding livestock health and preventing disease outbreaks. Their evaluation accounted for the various costs engendered by the biosecurity measures, including non- financial expenses that help ensure the long-term protection of animal capital, an essential asset for sustainable production.

Adimassu, Amadu et al. and, Place et al. [29, 93, 94] studied climate-smart agricultural practices, which constitute an agroecological investment for adapting to and mitigating the effects of climate change. This type of investment involves a range of expenses, including those related to climate-resilient crop varieties, weather monitoring systems, and innovative soil management techniques. Included in their assessment was the additional labor and expertise needed for the successful implementation of these practices.

Work exploring this category of investment has primarily focused on the exploitation of new production systems and combinations of factors of production at an operational level. Thus, while the factors of production were well defined within their respective combinations, few details were available regarding the investment in each factor or regarding factor type, number, and nature; this information was not necessarily relevant to the researchers' primary objectives. We were therefore unable to distinguish investments in equipment from investments in other factors of production.

3.2.3 Investments in individual factors of production

Approximately 50% of the 131 articles focused on investments in specific factors of production. For example, farmer investment in land has been a focal study subject [95, 96] because agricultural land is a long-term asset that can generate a steady level of income, which distinguishes it from shorter-term assets.

The purchase of pathogen-resistant seeds or organic inputs is generally considered to be an investment [39, 70] because these supplies can enhance crop yields while contributing to economic viability and environmental sustainability over the long term. Their use creates more resilient agricultural conditions and promotes consistent production across seasons.

Certain researchers have viewed improvements to human capital as farm investments [20] because enhancing workers' skills can optimize resource utilization and improve operational efficiency. In general, such investments promote productivity, foster innovation, and ensure farm sustainability.

As would be expected given technological advances in farm equipment and the rise of precision agriculture, a fair amount of research (n = 49 articles) has focused on investments in equipment [38,42,97,98]. Interest in this topic has been fueled by the diversity of equipment and production systems, which each have distinct characteristics and applications, whether or not DTs are involved. However, this area of study is complex to navigate because it is challenging to define and explore investments associated with farm equipment in general and DTs in particular. For many other factors of production, it is easy to assess investment returns via production levels or operational efficiency. Furthermore, such investments frequently involve a one-time purchase or relatively simple cost-benefit calculations. Such is not the case for investments in farm equipment, which are continuously involved in shifting interactions. For example, farm equipment must be regularly maintained and updated to ensure its effectiveness, and workers must be trained in its proper usage [21, 99].

Overall, in work on farm investments, researchers have employed a variety of complementary approaches that consider different scales: some have used a general approach, some have used a combined approach, and others have used an individual approach. While their findings have provided valuable insights, it is important to note that farm equipment must be treated as a distinct factor of production when assessing investment consequences. Adopting this perspective will make it possible to examine all relevant factors, their scope of impact, and their interactions with other factors of production.

3.3 Farm equipment investments

3.3.1 Investment trends over time

We extracted data from the 49 articles focused on farm equipment investments. We found that investments in equipment have greatly shifted over time, moving away from traditional farming equipment, such as tractors and machinery, and heading toward DTs, such as automated and robotic systems (Figure 3).

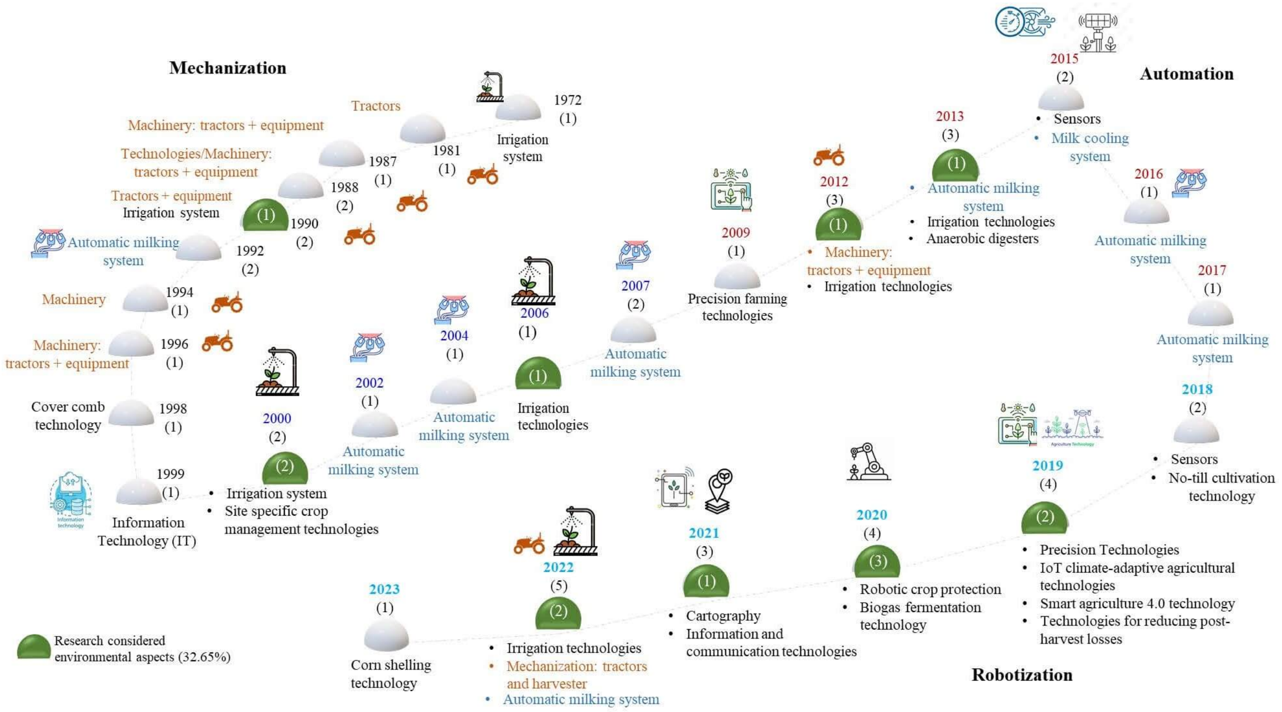

Figure 3 Changes in farm equipment investments over time (n = 49 articles)

From the 1970s to the 2000s, investments were primarily directed toward machinery (e.g., tractors and their accessories) [53, 54, 100–102]. During this era of mechanization, which arose on the heels of the Green Revolution, significant technological advances were made, and the introduction of new technologies played a crucial role in enhancing agricultural productivity [103, 104].

Next, investments shifted as agricultural practices were automated: farmers increasingly purchased higher-tech irrigation systems [33, 52, 55] and milkers [60, 99, 105].

As robotics became more sophisticated and various agricultural DTs were developed, farmers again changed their investment patterns. More recently, they have begun to purchase advanced DTs to improve farm performance and competitiveness. These DTs include precision agriculture devices [73], the Internet of Things (IoT) [106], automated systems [107], Industry 4.0 technologies [42], information and communication technologies (ICTs) [108], and robotic milking systems [46, 109].

In tandem, research on agricultural investments has begun to address the environmental effects of these technological advances, a trend that can be explained by a simultaneous shift in agricultural objectives: from pure financial gain to greater environmental stewardship. Thus, at this stage, it has become crucial for researchers to consider how investments in DTs can improve the sustainability of agricultural systems.

We observed that only 32.56% of the 49 articles on equipment investments concomitantly addressed the latter's environmental context (Figure 3).

Prior to 2012, research in this domain centered on the development of more efficient irrigation systems, given that the prevailing political objective was to preserve natural resources. This work was primarily conducted in the western United States, where state governments promoted water conservation by encouraging farmers to adopt more efficient irrigation technologies [52, 55].

Since 2019, several studies have highlighted how investments in DTs can improve farm agroecological performance and adaptation to climate change. Research of this type is especially relevant because public policies are increasingly informed by environmental considerations and are more frequently advancing DT-based solutions.

3.3.2 Different categories of farm equipment investments

Most of the research on equipment investments has focused on the cost of acquiring equipment, with certain studies also considering additional associated expenses. Such has been the case because investment breadth differs. Based on the results of our review, we propose that there are four categories of farm equipment investments (Figure 4).

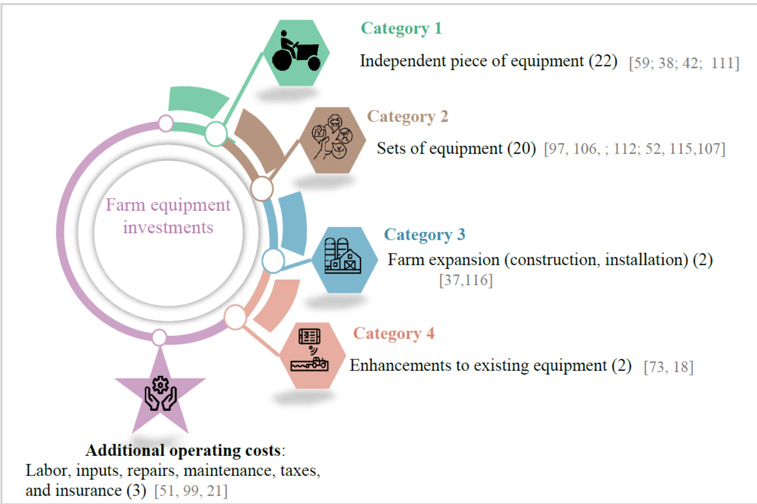

Figure 4 Main categories of farm equipment investments

The first category comprises the simplest investments: a single type of equipment that operates independently and that does not require any additional investment or accessories. Examples include sprayers, automated corn shelling machines, Industry 4.0 technologies, information and communication technologies, and no-till cultivation technologies. These DTs function as independent pieces of equipment. Thus, their investment cost is equivalent to their purchase cost and can be evaluated using accounting classification criteria if amortization occurs [98, 108, 110, 111].

The second category comprises investments in set combinations of equipment, including for example irrigation systems (e.g., pumps, wells, pipes, sensors) [97, 106, 112]; dairy milking and management systems [109,113,114], and piglet production technology [75]. These combinations may also be a mixture of mechanical and digital equipment (e.g., software and/or accessories). Examples include robotic systems for organic crop protection, which require the acquisition of drones and adapted software [107], or the use of information technologies in dairy cattle farming, for which computers and specific software are required [115]. In this category, DTs do not function independently—they are pieces of equipment within a system composed of tangible components (materials and robotic devices) and intangible components (sensors and software). The investment cost is the sum of the purchase or leasing costs and other essential expenses, such as software subscriptions and operational services. In contrast to the more traditional investment approach illustrated in the first category, second-category investments may not be subject to amortization. Instead, they are associated with services and software expenses.

The third category comprises investments made with the objective of expansion, such as when farmers invest in specialized types of facilities, which require specific types of farm equipment. One example is a pig farm's incorporation of biogas fermentation technology, which requires the presence of specific infrastructure for collecting and storing the biogas generated during organic fermentation [37]. Similarly, for robotic milking systems to function effectively, farmers need various types of buildings and other infrastructure—milking facilities, a resting area, a feeding zone, and a control or supervision room, as well as electrical and computer networks [116]. Thus, these investments are the sum of the costs for acquiring the farm equipment as well as the costs of setting up and constructing the facilities.

Finally, the fourth category comprises investments for enhancing existing farm equipment, when farmers acquire accessories or additional equipment to boost tool performance or to explore newer technologies. Examples include investments in precision agriculture, such as in nutrient reduction technologies [73] and investments in sensors on dairy farms [117]. Farmers make these investments because they have a longer-term vision for their agricultural practices. It is worth noting that, in such situations, there may be a phenomenon of path dependence [118] because an initial investment in certain DTs can significantly constrain the trajectory of future farming practices. Farmers potentially become locked into inflexible techno-economic paths and are limited in their capacity to adapt to environmental, economic, and institutional changes.

In addition, some researchers have also defined investments to include other expenses, such as the labor costs associated with operating the machinery [99], as well as the money spent on inputs (e.g., fuel and lubricants; [21]), repairs and maintenance, taxes, and insurance [119].

Investments in DTs also fall into these four categories. In some cases, DTs essentially function as independent pieces of equipment whose investment can be amortized using conventional accounting standards. In other cases, DTs enhance existing equipment, improving performance or allowing farmers to explore newer technologies. Finally, DTs may belong to a complex system composed of tangible and intangible assets and, potentially, human capital.

We can arrive at a better understanding of farm equipment investments and their relationship with shifts in the agricultural sector by exploring the nature of different investment strategies and their interactions with ecosystems. This work requires examining the environmental implications of equipment investments.

3.3.3 Environmental implications of farm equipment investments

Over time, shifts in farm equipment investments have occurred in tandem with increasing societal concern for the environment (Figure 3). Consequently, in more recent research, there has been a growing acknowledgment that farm equipment investments will have environmental impacts, given the economic complexities of the investment landscape. This change in research focus reflects an increasing awareness of the interconnectedness among agricultural systems, the economy, and the environment. Farmers make equipment investment decisions based on more than just profitability and productivity. They are also influenced by how their investment choices can affect the quality of ecosystems, air, water, and soil; the state of biodiversity; and the ability to adapt to climate change.

In some articles, researchers briefly mentioned the importance of environmental impacts when acknowledging conservation concerns or natural resource scarcity in the focal study system [120, 121] (Table 2).

To understand the environmental implications of these investments at different levels, certain

Table 2 Focus of articles addressing the environmental implications of DT investments

No. of articles	Environmental implications	References
3	Contextual: conservation and improved use of natural resources, sales of eco-friendly products	[107, 120, 121]
9	DT investments enhance resource use efficiency and improve environmental conditions, providing a means of mitigating climate change	[30, 36–38, 46, 52, 55, 97, 106]
2	Environmental concerns influence investment decisions regarding farm equipment	[73, 119]
Subtotal = 14 of 49 articles		

researchers have taken a more holistic approach, emphasizing the bidirectional relationship between DTs and the environment. They have evaluated the environmental impacts of DTs through the lens of optimizing resource utilization, and they have analyzed environmental incentives that promote DT investments.

Most of this research has found that DT investments have environmental benefits, which generally arise from optimized input utilization. DTs contribute to the preservation and efficient use of natural resources [52] and can help farmers adapt to climate change [36]. For example, legume farms in Singapore that employ DTs have significantly greater rates of resource use efficiency and, therefore, better environmental performance than do legume farms that employ traditional practices [106]. Similarly, farms that utilize site-specific crop management technologies can more rapidly respond to nitrogen contamination in surface waters and groundwater, resulting in pronounced environmental benefits [97].

Additionally, environmental concerns, especially about soil quality and on-farm conditions, are driving DT investments. For farmers, equipment investment decisions are tempered by individual convictions and especially the degree of environmental awareness [73]. Therefore, investments in DTs on farms are affected by public policies that promote resource conservation, as well as by the supply and demand dynamics of agricultural production. This situation illustrates the concept of induced innovation as described by Hayami and Ruttan [122]: social, economic, and regulatory frameworks that support environmental objectives can stimulate DT investments.

4 Discussion and conclusion

In this systematic review, we examined the various types of farm investments with a specific interest in exploring investments in equipment. We found that farm equipment has a high degree of functional complexity. While factors of production can have independent roles within agricultural production, farm equipment is generally interactive in nature. As a result, equipment effectiveness must be ensured via customization to fit current farm practices, regular updates, proper maintenance, continuous training, and appropriate adjustments.

Indeed, DTs often interact with each other (e.g., automated machinery interacting with sensors, data collection devices, management software) and with physical infrastructure (e.g., greenhouses, processing equipment). By systematically integrating DTs into their operations, farmers can fully harness the potential of digital technologies.

Our work emphasizes the limitations of traditional accounting methods, which primarily focus on the depreciation of tangible assets. These methods thus fail to capture the complexity of DT investments. First, investments in fixed capital, such as the buildings in which DTs are installed [37], are often excluded from balance sheets. Instead, they are categorized as investments in building and construction operations, which does not reflect the fact that DTs are an integral part of agricultural infrastructure. Second, a large portion of the expenses associated with DTs involve investments in circulating capital, such as the purchase of accessories or spare parts. Traditional accounting methods tend to overlook these additional costs, which are essential for maintaining and optimizing DT functionality [117].

Furthermore, investments in intangible capital, such as software and online service subscriptions, are crucial to the effectiveness and profitability of DTs [107]. They are essential if farmers wish to fully exploit the capabilities of DTs and ensure the latter's seamless integration into agricultural operations. Additionally, traditional accounting methods often underestimate investments in human capital. DTs cannot be used effectively without certain requisite skills and knowledge [20]; regular training, skill updating, and continuous technical support are necessary to optimally utilize digital technologies.

Going forward, researchers must recognize DTs as factors of production that are in continuous interaction with other forms of equipment, making them essential in the optimization of agricultural processes. From a functional perspective, their utility extends beyond simply providing information or acting as an independent piece of equipment. Instead, they are crucial elements in the technological ecosystem responsible for the efficiency, sustainability, and profitability of agricultural operations.

At present, most researchers in the field are defining DTs based on their functionality and apparent benefits. However, DTs are not just technologies that can reduce input costs and optimize field management via detailed spatial information [11, 123–125], nor are they simply devices for collecting and analyzing data [126]. They must also be understood as tools of greater breadth and complexity, considering their range of requirements for optimal functioning. In other words, DTs should be seen as complex systems composed of different types of capital. They are more than their physical manifestation—their effective and reliable usage requires certain accessories, the infrastructure into which they are installed, software, support services, and training programs.

In this investment perspective, DTs are viewed as interconnected rather than independent elements. When DTs are treated as goods or production services, it becomes possible to more accurately evaluate their impacts on farms and the broader digital ecosystem. To improve understanding of the interactive role played by DTs within farms, it is crucial to acknowledge that DTs are essential components of integrated systems. Thanks to this approach, DT effectiveness and profitability can be analyzed in detail, and it will become more straightforward to identify potential synergies with other agricultural technologies and practices. Moreover, farmers can increase their strategic use of DTs, leading to more sustainable, efficient, and adaptive agricultural practices.

Thus, the development of DTs is inherently connected to the agroecological transition, a relationship that could have significant implications for environmental sustainability [127–129]. The research we reviewed demonstrates that evaluations of DT investment decisions are increasingly accounting for the tools' environmental impacts. More specifically, DTs are seen as having the potential to promote conservation [30, 46] and help farmers adapt to climate change [36].

Indeed, recent research has demonstrated that DTs provide opportunities to enhance the efficiency of agricultural resource use [106], especially via optimized crop irrigation [52] and optimized crop fertilization and management [130]. For instance, digital monitoring systems enable farmers to closely monitor crop conditions, thereby minimizing water and input waste. Similarly, advanced weather forecasting models can help predict extreme weather events, giving farmers time to implement preventive measures [131]. Furthermore, DTs can facilitate the transition to more sustainable agricultural practices by facilitating the implementation of precision agriculture and agroecological practices. These approaches encourage targeted input usage, limiting environmental harm while improving agricultural productivity.

However, to date, research examining these impacts has not dealt with DTs as complex and interactive forms of equipment. Notably, it is important to recognize that DTs do not automatically yield environmental benefits; the result largely depends on tool type, implementation, and supplementary needs. For example, a DT could be environmentally friendly during stand-alone usage but become energetically costly as a consequence of required software and data processing services. Similarly, excessive reliance on technology can lead to greater resource use and higher energy consumption, potentially negating any anticipated environmental benefits. This situation can result in a rebound effect (e.g., Jevons paradox [132]).

Investments in agricultural DTs can have implications far beyond farm-scale economics and environmental impacts. Indeed, public policies are promoting a broader strategic vision of agricultural development [133] and digitalization [134].

In this vein, public policies must be re-evaluated if they are to better foster the adoption of agricultural practices that simultaneously espouse digital technologies and ecological sustainability. Notably, they must encourage a more comprehensive approach that treats DTs as integral components of a full-fledged agricultural system. It must become more broadly understood that DTs interact with many other components of agricultural operations, such as farm infrastructure and farming practices. Furthermore, public policies need to account for the diverse expenses (e.g., on software, support services, training, and accessories) that are necessary to ensure optimal DT usage. Finally, public policies should facilitate coordination among the various stakeholders involved in the development, implementation, and use of agricultural DTs. This work will involve building partnerships among government agencies, research institutions, the private sector, and farmers themselves, with a view to creating conditions conducive to innovation and the adoption of new technologies.

At this stage, it is crucial to analyze various means for promoting investments in DTs, especially with regards to potential public funding to ease the financial burden on farmers. For example, it would be worth considering whether to prioritize support for expensive DTs, which can be amortized over the long term, or whether to favor more affordable DTs. However, farmers may be less likely to adopt the latter, given that they cannot be amortized.

It is also important to consider the "economy of sustainability" that can arise from the widespread adoption of low-cost DTs. As more and more farmers commit to their use, resource use efficiency will grow at the landscape level. Regionally, the ecological footprint of agriculture could shrink as water consumption drops, inputs are applied more strategically, and crop management becomes more precise.

In this context, public policies should consider utilizing a balanced approach that accounts for both the economic and environmental implications of farm investments in DTs. Farmers should be encouraged to adopt low-cost DTs that furnish environmental benefits while also limiting environmental harm. This objective could be achieved through targeted subsidies, fiscal incentives, or informational programs aimed at promoting sustainable agricultural practices.

Conflicts of interest

The authors declare that they have no conflict of interest.

References

[1] Barrett H, Rose DC. Perceptions of the Fourth Agricultural Revolution: What's In, What's Out, and What Consequences are Anticipated? Sociologia Ruralis. 2020, 62(2): 162-189. https://doi.org/10.1111/soru.12324

[2] Kamilaris A, Kartakoullis A, Prenafeta-Boldú FX. A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture. 2017, 143: 23-37. https://doi.org/10.1016/j.compag.2017.09.037

[3] Miranda J, Ponce P, Molina A, et al. Sensing, smart and sustainable technologies for Agri-Food 4.0. Computers in Industry. 2019, 108: 21-36. https://doi.org/10.1016/j.compind.2019.02.002

[4] Digital Technology and Agriculture: Foresight for Rural Enterprises and Rural Lives in New Zealand. Journal of Agriculture and Environmental Sciences. 2017, 6(2). https://doi.org/10.15640/jaes.v6n2a7

[5] Arfa NB, Ghali M. Chapitre 6. Le numérique dans la chaine de valeur agroalimentaire : enjeux et opportunités. Références. Published online May 20, 2019: 159-191. https://doi.org/10.3917/edagri.danie.2019.01.0159

[6] Gutiérrez PA, López-Granados F, Peña-Barragán JM, et al. Logistic regression product-unit neural networks for mapping Ridolfia segetum infestations in sunflower crop using multitemporal remote sensed data. Computers and Electronics in Agriculture. 2008, 64(2): 293-306. https://doi.org/10.1016/j.compag.2008.06.001

[7] Langlais A. The new Common Agricultural Policy: reflecting an agro-ecological transition. The legal perspective. Review of Agricultural, Food and Environmental Studies. 2023, 104(1): 51-66. https://doi.org/10.1007/s41130-022-00183-1

[8] Salimi M, Pourdarbani R, Nouri BA. Factors Affecting the Adoption of Agricultural Automation Using Davis's Acceptance Model (Case Study: Ardabil). Acta Technologica Agriculturae. 2020, 23(1): 30-39. https://doi.org/10.2478/ata-2020-0006

[9] Balafoutis AT, Evert FKV, Fountas S. Smart Farming Technology Trends: Economic and Environmental Effects, Labor Impact, and Adoption Readiness. Agronomy. 2020, 10(5): 743. https://doi.org/10.3390/agronomy10050743

[10] Barnes AP, Soto I, Eory V, et al. Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. Land Use Policy. 2019, 80: 163-174. https://doi.org/10.1016/j.landusepol.2018.10.004

[11] Meyer-Aurich A, Gandorfer M, Heißenhuber A. Chapter 4: Economic Analysis Of Precision Farming Technologies At The Farm Level: Two German Case Studies. Agricultural Systems: Economics, Technology And Diversity. Nova Science Publishers, Hauppage. 2008, 67-76.

[12] Finger R. Digital innovations for sustainable and resilient agricultural systems. European Review of Agricultural Economics. 2023, 50(4): 1277-1309. https://doi.org/10.1093/erae/jbad021

[13] Balafoutis A, Beck B, Fountas S, et al. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. Sustainability. 2017, 9(8): 1339. https://doi.org/10.3390/su9081339

[14] Sarkar PJ, Chanagala S. A Survey on IOT based Digital Agriculture Monitoring System and Their impact on optimal utilization of Resources. Journal of Electronics and Communication Engineering (IOSR-JECE). 2016, 11(1): 1-4.

[15] Adenuga AH, Jack C, Olagunju KO, et al. Economic Viability of Adoption of Automated Oestrus Detection Technologies on Dairy Farms: A Review. Animals. 2020, 10(7): 1241. https://doi.org/10.3390/ani10071241

[16] Levi L, Latruffe L, Ridier A. Farm investment and performance in the French (Brittany) dairy sector. Journées de recherches en sciences sociales (JRSS). 2016: 26.

[17] Blasch J, van der Kroon B, van Beukering P, et al. Farmer preferences for adopting precision farming technologies: a case study from Italy. European Review of Agricultural Economics. 2020, 49(1): 33-81. https://doi.org/10.1093/erae/jbaa031

[18] Steeneveld W, Tauer LW, Hogeveen H, et al. Comparing technical efficiency of farms with an automatic milking system and a conventional milking system. Journal of Dairy Science. 2012, 95(12): 7391-7398. https://doi.org/10.3168/jds.2012-5482

[19] Gaillard Y, Thuillier G. Qu'est-ce qu'un investissement? Revue économique. 1968, 19(4): 607-637. https://doi.org/10.3406/reco.1968.407827

[20] Kuvaeva YV, Reshetnikova TV, Boronenkova NL. Knowledge economy changes in the perception of investment nature in agriculture. IOP Conference Series: Earth and Environmental Science. 2019, 341(1): 012220. https://doi.org/10.1088/1755-1315/341/1/012220

[21] Ji Y, Yu X, Zhong F. Machinery investment decision and off-farm employment in rural China. China Economic Review. 2012, 23(1): 71-80. https://doi.org/10.1016/j.chieco.2011.08.001

[22] Wang S, Tian Y, Liu X, et al. How Farmers Make Investment Decisions: Evidence from a Farmer Survey in China. Sustainability. 2019, 12(1): 247. https://doi.org/10.3390/su12010247

[23] Booth A, Sutton A, Clowes M, et al. Systematic Approaches to a Successful Literature Review. SAGE, 2021.

[24] Nambiema A, Fouquet J, Guilloteau J, et al. La revue systématique et autres types de revue de la littérature : qu'est-ce que c'est, quand, comment, pourquoi ? Archives des Maladies Professionnelles et de l'Environnement. 2021, 82(5): 539-552. https://doi.org/10.1016/j.admp.2021.03.004

[25] Rethlefsen ML, Kirtley S, Waffenschmidt S, et al. PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. Systematic Reviews. 2021, 10(1). https://doi.org/10.1186/s13643-020-01542-z

[26] Vindrola-Padros C, Brage E, Johnson GA. Rapid, Responsive, and Relevant?: A Systematic Review of Rapid Evaluations in Health Care. American Journal of Evaluation. 2021, 42(1): 13-27. https://doi.org/10.1177/1098214019886914

[27] Horrillo A, Obregón P, Escribano M, et al. A biosecurity survey on Iberian pig farms in Spain: Farmers' attitudes towards the implementation of measures and investment. Research in Veterinary Science. 2022, 145: 82-90. https://doi.org/10.1016/j.rvsc.2022.02.017

[28] Issanchou A, Daniel K, Dupraz P, et al. Soil resource and the profitability and sustainability of farms: A soil quality investment model. Agrocampus Ouest, 2018.

[29] Adimassu Z. Constraining the constraints: factors affecting farmers' investment in climate-smart land management. 2019.

[30] Anderson RC, Weersink A. A Real Options Approach for the Investment Decisions of a Farm-Based Anaerobic Digester. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie. 2013, 62(1): 69-87. https://doi.org/10.1111/cjag.12019

[31] Vondolia GK, Eggert H, Stage J. The Effect of Fertilizer Subsidies on Investment in Soil and Water Conservation and Productivity among Ghanaian Farmers Using Mechanized Irrigation. Sustainability. 2021, 13(15): 8242. https://doi.org/10.3390/su13158242

[32] Hoogeveen H, Oostendorp R. On the use of cost-benefit analysis for the evaluation of farm household investments in natural resource conservation. Environment and Development Economics. 2003, 8(2): 331-349. https://doi.org/10.1017/s1355770x0300172

[33] Ihli HJ, Maart-Noelck SC, Musshoff O. Does timing matter? A real options experiment to farmers' investment and disinvestment behaviours. Australian Journal of Agricultural and Resource Economics. 2013, 58(3): 430-452. https://doi.org/10.1111/1467-8489.12028

[34] Abokyi E. The impact of agricultural marketing program on farm investment: Evidence from Ghana. Cogent Economics & Finance. 2022, 10(1). https://doi.org/10.1080/23322039.2022.2111781

[35] Kusz D, Zajac S, Gedek S, et al. Endogenous determinants of investments in farms of selected countries of Central and Eastern Europe. 2014.

[36] Jeločnik M, Subić J, Zdravković A. Economic effects of investment in irrigation systems implementation at the small family farms. Ekonomika poljoprivrede. 2022, 69(3): 793-817. https://doi.org/10.5937/ekopolj2203793j

[37] Yao W. Biogas Investment Intention of Large-Scale Pig Farmers Under the EmissionTrading System. Nature Environment and Pollution Technology. 2020, 19(3): 1113-1117. https://doi.org/10.46488/nept.2020.v19i03.022

[38] Bennett JMcL, Roberton SD, Ghahramani A, et al. Operationalising soil security by making soil data useful: Digital soil mapping, assessment and return-on-investment. Soil Security. 2021, 4: 100010. https://doi.org/10.1016/j.soisec.2021.100010

[39] Weng F, Liu X, Huo X. Impact of Internet Use on Farmers' Organic Fertilizer Investment: A New Perspective of Access to Credit. Agriculture. 2023, 13(1): 219. https://doi.org/10.3390/agriculture13010219

[40] Sckokai P, Moro D. Modelling the impact of the CAP Single Farm Payment on farm investment and output. European Review of Agricultural Economics. 2009, 36(3): 395-423. https://doi.org/10.1093/erae/jbp026

[41] Vercammen J. Farm bankruptcy risk as a link between direct payments and agricultural investment. European Review of Agricultural Economics. 2007, 34(4): 479-500. https://doi.org/10.1093/erae/jbm040

[42] Annosi MC, Brunetta F, Monti A, et al. Is the trend your friend? An analysis of technology 4.0 investment decisions in agricultural SMEs. Computers in Industry. 2019, 109: 59-71. https://doi.org/10.1016/j.compind.2019.04.003

[43] Viaggi D, Raggi M, Gomez y Paloma S. An integer programming dynamic farm-household model to evaluate the impact of agricultural policy reforms on farm investment behaviour. European Journal of Operational Research. 2010, 207(2): 1130-1139. https://doi.org/10.1016/j.ejor.2010.05.012

[44] KUSZ D. The importance of local institutions in the support of investment activity of farms (the case of Poland). Scientific Papers Series Management, Economic Engineering in Agriculture & Rural Development. 2014, 14(4).

[45] Latruffe L. Farm credit and investment in Poland: a case study. 2004.

[46] Zalewski K, Bórawski P, Żuchowski I, et al. The Efficiency of Public Financial Support Investments into Dairy Farms in Poland by the European Union. Agriculture. 2022, 12(2): 186. https://doi.org/10.3390/agriculture12020186

[47] Femenia F, Latruffe L, Chavas JP. Responsiveness of farm investment to price changes: evidence from the French crop sector. Applied Economics. 2021, 53(34): 3972-3983. https://doi.org/10.1080/00036846.2021.1890686

[48] Benjamin C, Phimister E. Does loan type affect investment? A comparison using French and British farm level panel data. HAL, 1999.

[49] Benjamin C, Phimister E. Imperfection du marché du capital et investissement des exploitations agricoles. L'Actualité économique. 2009, 77(3): 357-383. https://doi.org/10.7202/602356ar

[50] Benjamin C, Phimister E. Does Capital Market Structure Affect Farm Investment? A Comparison using French and British Farm-Level Panel Data. American Journal of Agricultural Economics. 2002, 84(4): 1115-1129. https://doi.org/10.1111/1467-8276.00372

[51] Armstrong DV, Daugherty LS, Galton DM, et al. Analysis of capital investment in robotic milking systems for US dairy farms. Publication-european association for animal production. 1992, 65: 432.

[52] Huffaker R, Whittlesey N. The allocative efficiency and conservation potential of water laws encouraging investments in on-farm irrigation technology. Agricultural Economics. 2000, 24(1): 47-60. https://doi.org/10.1111/j.1574-0862.2000.tb00092.x

[53] Penson JB, Romain RFJ, Hughes DW. Net Investment in Farm Tractors: An Econometric Analysis. American Journal of Agricultural Economics. 1981, 63(4): 629-635. https://doi.org/10.2307/1241205

[54] Jannot Ph, Cairol D. Linear Programming as an Aid to Decision-making for Investments in Farm Equipment for Arable Farms. Journal of Agricultural Engineering Research. 1994, 59(3): 173-179. https://doi.org/10.1006/jaer.1994.1074

[55] Scheierling SM, Young RA, Cardon GE. Public subsidies for water-conserving irrigation investments: Hydrologic, agronomic, and economic assessment. Water Resources Research. 2006, 42(3). https://doi.org/10.1029/2004wr003809

[56] Tămăşilă M, Miclea Ş, Vartolomei M, et al. Cash Flow and Investment Decision: An Application on the Romanian Agriculture Sector. Procedia - Social and Behavioral Sciences. 2018, 238: 704-713. https://doi.org/10.1016/j.sbspro.2018.04.053

[57] Czubak W, Pawłowski KP, Sadowski A. Outcomes of farm investment in Central and Eastern Europe: The role of financial public support and investment scale. Land Use Policy. 2021, 108: 105655. https://doi.org/10.1016/j.landusepol.2021.105655

[58] Bradfield T, Butler R, Dillon EJ, et al. The impact of long-term land leases on farm investment: Evidence from the Irish dairy sector. Land Use Policy. 2023, 126: 106553. https://doi.org/10.1016/j.landusepol.2023.106553

[59] Rutten CJ, Steeneveld W, Oude Lansink AGJM, et al. Delaying investments in sensor technology: The rationality of dairy farmers' investment decisions illustrated within the framework of real options theory. Journal of Dairy Science. 2018, 101(8): 7650-7660.
https://doi.org/10.3168/jds.2017-13358

[60] Upton J, Murphy M, De Boer IJM, et al. Investment appraisal of technology innovations on dairy farm electricity consumption. Journal of Dairy Science. 2015, 98(2): 898-909.
https://doi.org/10.3168/jds.2014-8383

[61] Ghalawat S, Loura M, Malik JS, et al. Investment and Resource Use Pattern followed by Dairy Farmers in Haryana. Indian Journal of Extension Education. 2022, 58(1): 68-71.
https://doi.org/10.48165/ijee.2022.58115

[62] Musafili I, Ayuya OI, Birachi EA. Dynamics of gender preferences for farm investment strategies in Rwanda: A best-worst scaling experiment[. British Journal of Environmental Studies. 2021, 1(1): 32-43.

[63] Yigezu YA, Mugera A, El-Shater T, et al. Enhancing adoption of agricultural technologies requiring high initial investment among smallholders. Technological Forecasting and Social Change. 2018, 134: 199-206.
https://doi.org/10.1016/j.techfore.2018.06.006

[64] Bakucs LZ, Bojnec S, Ferto I, et al. The impact of non-farm income on the investment in agriculture: evidence from Hungary and Slovenia. EAAE Seminar: Rural Development: Governance, Policy Design and Delivery. 2010.

[65] Kolapo A, Ogunleye AS, Kehinde AD, et al. Effect of microcredit on investment decision of smallholder farmers in Osun State. Agriculturae Conspectus Scientificus. 2022, 87(1): 69-75.

[66] Letcher RA. A Method for Assessing the Importance of Farm Level Capital Investment Decisions in the Analysis of Water Reforms. Economics and Environment Network (EEN) NatiThe Australian National University, Canberra, Australia; 2003.

[67] Hertz T. The effect of nonfarm income on investment in Bulgarian family farming. Agricultural Economics. 2009, 40(2): 161-176.
https://doi.org/10.1111/j.1574-0862.2009.00367.x

[68] Kessler CA. Decisive key-factors influencing farm households' soil and water conservation investments. Applied Geography. 2006, 26(1): 40-60.
https://doi.org/10.1016/j.apgeog.2005.07.005

[69] Kleemann L, Abdulai A, Buss M. Is organic farming worth its investment? The adoption and impact of certified pineapple farming in Ghana. Kiel Institute for the World Economy (IfW), Kiel. 2014.

[70] Balietti A, Chesney M, Vargas C. Long-Term Investment Choices for Quinoa Farmers in Puno, Peru: A Real Options Case Study. SSRN Electronic Journal. Published online 2018.
https://doi.org/10.2139/ssrn.3175262

[71] Key N. Off-farm Income, Credit Constraints, and Farm Investment. Journal of Agricultural and Applied Economics. 2020, 52(4): 642-663.
https://doi.org/10.1017/aae.2020.25

[72] Radeva T. Investment activity of bulgarian farms under the conditions of cap 2014-2020, 2020.

[73] Konrad MT, Nielsen HØ, Pedersen AB, et al. Drivers of Farmers' Investments in Nutrient Abatement Technologies in Five Baltic Sea Countries. Ecological Economics. 2019, 159: 91-100.
https://doi.org/10.1016/j.ecolecon.2018.12.022

[74] Labajova K, Höhler J, Lagerkvist CJ, et al. Illusion of control in farmers' investment and financing decisions. Agricultural Finance Review. 2021, 82(4): 675-689.
https://doi.org/10.1108/afr-09-2020-0140

[75] Szűcs I, Szántó L, Szőllősi L. Investment analysis of a piglet producer farm – a Hungarian case study. Applied Studies in Agribusiness and Commerce. 2020, 14(3-4): 141-152.
https://doi.org/10.19041/apstract/2020/2-3/15

[76] Medeiros HR, Guimarães VP, Júnior EVH. Utilización de la programación linear para evaluar el impacto del crédito para inversión en pequeñas fincas de cabras. 2009.

[77] Alburquerque S. A polyperiodproduction-investmemntodel of growthof large-size livestockfarms in southwesvtirginia. 1969.

[78] Qian X. Production planning and equity investment decisions in agriculture with closed membership cooperatives. European Journal of Operational Research. 2021, 294(2): 684-699.
https://doi.org/10.1016/j.ejor.2021.02.007

[79] Olsen JV, Henningsen A. Investment Utilisation, Adjustment Costs, and Technical Efficiency in Danish Pig Farms. 2011.

[80] Curtiss J, Latruffe L, Medonos T, et al. Investment activity and ownership structure of Czech corporate farms. 2007.

[81] Ivanović S, Nastić L, Jeločnik M. Investment activity of Serbian farms comparing to neighboring countries: Application of FADN indicators. Ekonomika. 2020, 66(4): 73-84.
https://doi.org/10.5937/ekonomika2004074i

[82] Petrick M. Farm investment, credit rationing, and governmentally promoted credit access in Poland: a cross-sectional analysis. Food Policy. 2004, 29(3): 275-294.
https://doi.org/10.1016/j.foodpol.2004.05.002

[83] Creamer DB, Dobrovolsky SB, Borenstein I. Capital in Manufacturing and Mining: Its Formation and Financing. Princeton University Press, 2015.

[84] Feinerman E, Peerlings J. Uncertain Land Availability and Investment Decisions: The Case of Dutch Dairy Farms. Journal of Agricultural Economics. 2005, 56(1): 59-80.
https://doi.org/10.1111/j.1477-9552.2005.tb00122.x

[85] St-Pierre NR, Shoemaker D, Jones LR. The Next $120,000: A Case Study to Illustrate Analysis of Alternative Farm Investments in Fixed Assets. Journal of Dairy Science. 2000, 83(5): 1159-1169.
https://doi.org/10.3168/jds.s0022-0302(00)74982-4

[86] Szymańska EJ, Dziwulski M, Kruszyński M. Determinants of Fixed Asset Investment in the Polish Farms. Sustainability. 2021, 13(24): 13741.
https://doi.org/10.3390/su132413741

[87] Musshoff O, Hirschauer N. Adoption of organic farming in Germany and Austria: an integrative dynamic investment perspective. Agricultural Economics. 2008, 39(1): 135-145.
https://doi.org/10.1111/j.1574-0862.2008.00321.x

[88] Arango-Aramburo S, Acevedo Y, Sonnemans J. The Influence of the Strength of Financial Institutions and the Investment-Production Delay on Commodity Price Cycles: A Framed Field Experiment with Coffee Farmers in Colombia. De Economist. 2019, 167(4): 347-358.
https://doi.org/10.1007/s10645-019-09343-z

[89] Lambarraa F, Stefanou SE, Gil JM. The impact of dynamic technical inefficiency on investment decision of Spanish olive farms. 2009.

[90] Spiegel A, Severini S, Britz W, et al. Step-by-step development of a model simulating returns on farm from investments: the example of hazelnut plantation in Italy[J]. Bio-based and Applied Economics. 2020, 9(1): 53-83.

[91] Ivanovic S. Economic efficiency of investments in cattle production at family farms. Journal of Agricultural Sciences, Belgrade. 2008, 53(3): 223-234.
https://doi.org/10.2298/jas0803223i

[92] Kousar R, Abdulai A. Off-farm work, land tenancy contracts and investment in soil conservation measures in rural Pakistan. Australian Journal of Agricultural and Resource Economics. 2015, 60(2): 307-325.
https://doi.org/10.1111/1467-8489.12125

[93] Amadu FO, Miller DC, McNamara PE. Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. Ecological Economics. 2020, 167: 106443.
https://doi.org/10.1016/j.ecolecon.2019.106443

[94] Place F, Adato M, Hebinck P. Understanding Rural Poverty and Investment in Agriculture: An Assessment of Integrated Quantitative and Qualitative Research in Western Kenya. World Development. 2007, 35(2): 312-325.
https://doi.org/10.1016/j.worlddev.2006.10.005

[95] Maart-Noelck SC, Musshoff O. Investing Today or Tomorrow? An Experimental Approach to Farmers' Decision Behaviour. Journal of Agricultural Economics. 2012, 64(2): 295-318.
https://doi.org/10.1111/j.1477-9552.2012.00371.x

[96] Tubetov D, Maart SC, Musshoff O. Comparison of the Investment Behavior of German and Kazakhstani Farmers: an Experimental Approach. GlobalFood Discussion Papers, 2012.

[97] Khanna M. Investment in site-specific crop management under uncertainty: implications for nitrogen pollution control and environmental policy. Agricultural Economics. 2000, 24(1): 9-21.
https://doi.org/10.1016/s0169-5150(00)00111-0

[98] Kotu BH, Manda J, Mutungi C, et al. Farmers' willingness to invest in mechanized maize shelling and potential financial benefits: Evidence from Tanzania. Agribusiness. 2023, 39(3): 854-874.
https://doi.org/10.1002/agr.21801

[99] Shortall J, Shalloo L, Foley C, et al. Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system. Journal of Dairy Science. 2016, 99(9): 7700-7713.
https://doi.org/10.3168/jds.2016-11256

[100] Conway RK, Hrubovcak J, LeBlanc M. A forecast evaluation of capital investment in agriculture. International Journal of Forecasting. 1990, 6(4): 509-519.
https://doi.org/10.1016/0169-2070(90)90029-b

[101] LeBlanc M, Hrubovcak J, Durst R, et al. Farm machinery investment and the Tax Reform Act of 1986. Journal of Agricultural and Resource Economics. 1992: 66-79.

[102] Reid DW, Bradford GL. A Farm Firm Model of Machinery Investment Decisions. American Journal of Agricultural Economics. 1987, 69(1): 64-77.
https://doi.org/10.2307/1241307

[103] Hamdan MF, Mohd Noor SN, Abd-Aziz N, et al. Green Revolution to Gene Revolution: Technological Advances in Agriculture to Feed the World. Plants. 2022, 11(10): 1297.
https://doi.org/10.3390/plants11101297

[104] van Zanden JL. The First Green Revolution: The Growth of Production and Productivity in European Agriculture, 1870-1914. The Economic History Review. 1991, 44(2): 215.
https://doi.org/10.2307/2598294

[105] Hogeveen H, Heemskerk K, Mathijs E. Motivations of Dutch farmers to invest in an automatic milking system or a conventional milking parlour. Automatic milking, a better understanding. Published online October 10, 2004: 56-61.
https://doi.org/10.3920/9789086865253_005

[106] Montesclaros JML, Babu SC, Teng PS. IoT-enabled farms and climate-adaptive agriculture technologies: Investment lessons from Singapore. Intl Food Policy Res Inst, 2019.
[107] Kudryavtseva T, Skhvediani A. Effectiveness Assessment of Investments in Robotic Biological Plant Protection. International Journal of Technology. 2020, 11(8): 1589.
https://doi.org/10.14716/ijtech.v11i8.4528
[108] Jablanovic V. Investment in Information and Communication Technology in Agriculture and Soybean Production Stability: The Case of China. The 13th EFITA International Conference. Published online December 13, 2021.
https://doi.org/10.3390/engproc2021009034
[109] Baudracco J, Lazzarini B, Rossler N, et al. Strategies to double milk production per farm in Argentina: Investment, economics and risk analysis. Agricultural Systems. 2022, 197: 103366.
https://doi.org/10.1016/j.agsy.2022.103366
[110] Dooley AE, Parker WJ, Rauniyar GP, et al. Returns to investment in on-farm research: A case study of cover comb technology. New Zealand Journal of Agricultural Research. 1998, 41(3): 405-414.
https://doi.org/10.1080/00288233.1998.9513325
[111] Mujuka E, Mburu J, Ogutu A, et al. Returns to investment in postharvest loss reduction technologies among mango farmers in Embu County, Kenya. Food and Energy Security. 2019, 9(1).
https://doi.org/10.1002/fes3.195
[112] Lockwood B. Patterns of investment in farm machinery and equipment. Economic and Political Weekly. 1972: A113-A124.
[113] Schulte HD, Musshoff O, Meuwissen MPM. Considering milk price volatility for investment decisions on the farm level after European milk quota abolition. Journal of Dairy Science. 2018, 101(8): 7531-7539.
https://doi.org/10.3168/jds.2017-14305
[114] Tubetov D. Investment behavior in agriculture – an analysis of the explanatory potential of the real options approach [Internet]. Georg-August-University Göttingen. 2013.
https://ediss.uni-goettingen.de
[115] van Asseldonk MAPM, Huirne RBM, Dijkhuizen AA, et al. Dynamic programming to determine optimum investments in information technology on dairy farms. Agricultural Systems. 1999, 62(1): 17-28.
https://doi.org/10.1016/s0308-521x(99)00051-7
[116] Hyde J, Engel P. Investing in a Robotic Milking System: A Monte Carlo Simulation Analysis. Journal of Dairy Science. 2002, 85(9): 2207-2214.
https://doi.org/10.3168/jds.s0022-0302(02)74300-2
[117] Steeneveld W, Hogeveen H, Oude Lansink AGJM. Economic consequences of investing in sensor systems on dairy farms. Computers and Electronics in Agriculture. 2015, 119: 33-39.
https://doi.org/10.1016/j.compag.2015.10.006
[118] Kay A. Path dependency and the CAP. Journal of European Public Policy. 2003, 10(3): 405-420.
https://doi.org/10.1080/1350176032000085379
[119] Dowle K, Armstrong AC. A model for investment appraisal of grassland drainage schemes on farms in the U.K. Agricultural Water Management. 1990, 18(2): 101-120.
https://doi.org/10.1016/0378-3774(90)90024-s
[120] Chindarkar N, Chen YJ, Sathe S. Link between farm electricity supply management, farm investments, and farm incomes - Evidence from India. Energy Policy. 2020, 141: 111407.
https://doi.org/10.1016/j.enpol.2020.111407
[121] Varghese SK, Buysse J, Frija A, et al. Are Investments in Groundwater Irrigation Profitable? A Case of Rice Farms from South India1. JAWRA Journal of the American Water Resources Association. 2012, 49(1): 52-66.
https://doi.org/10.1111/j.1752-1688.2012.00690.x
[122] Hayami Y, Ruttan V. Agriculture et développement, une approche internationale. Inra-Quae, 1985.
[123] Griffin TW, Shockley JM, Mark TB. Economics of Precision Farming. ASA, CSSA, and SSSA Books. Published online June 8, 2018: 221-230.
https://doi.org/10.2134/precisionagbasics.2016.0098
[124] Schimmelpfennig D. Editor. Farm Profits and Adoption of Precision Agriculture. 2016.
[125] Wolfert S, Ge L, Verdouw C, et al. Big Data in Smart Farming – A review. Agricultural Systems. 2017, 153: 69-80.
https://doi.org/10.1016/j.agsy.2017.01.023
[126] Pham X, Stack M. How data analytics is transforming agriculture. Business Horizons. 2018, 61(1): 125-133.
https://doi.org/10.1016/j.bushor.2017.09.011
[127] Bellon Maurel V, Huyghe C. Putting agricultural equipment and digital technologies at the cutting edge of agroecology. OCL. 2017, 24(3): D307.
https://doi.org/10.1051/ocl/2017028
[128] Brown RM, Dillon CR, Schieffer J, et al. The carbon footprint and economic impact of precision agriculture technology on a corn and soybean farm. Journal of Environmental Economics and Policy. 2015, 5(3): 335-348.
https://doi.org/10.1080/21606544.2015.1090932
[129] Okayasu T, Nugroho AP, Arita D, et al. Sensing and Visualization in Agriculture with Affordable Smart Devices. Smart Sensors at the IoT Frontier. Published online 2017: 299-325.
https://doi.org/10.1007/978-3-319-55345-0_12

[130] Zheng S, Wang Z, Wachenheim CJ. Technology adoption among farmers in Jilin Province, China. China Agricultural Economic Review. 2018, 11(1): 206-216.
https://doi.org/10.1108/caer-11-2017-0216

[131] Kharin VV, Zwiers FW, Zhang X, et al. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change. 2013, 119(2): 345-357.
https://doi.org/10.1007/s10584-013-0705-8

[132] Jevons WS. The Coal Question: An Enquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines. Macmillan, 1866.

[133] Latruffe L, Desjeux Y. Common Agricultural Policy support, technical efficiency and productivity change in French agriculture. Review of Agricultural, Food and Environmental Studies. 2016, 97(1): 15-28.
https://doi.org/10.1007/s41130-016-0007-4

[134] Lajoie-O'Malley A, Bronson K, van der Burg S, et al. The future(s) of digital agriculture and sustainable food systems: An analysis of high-level policy documents. Ecosystem Services. 2020, 45: 101183.
https://doi.org/10.1016/j.ecoser.2020.101183