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PRECISION AND DIGITAL TECHNOLOGIES IN CLIMATE ACTION: ADOPTION PATHWAYS AND PRACTICES IN BULGARIA

Yifeng Qin[1], Rositsa Beluhova-Uzunova[2]*, Svetla Yancheva[2], Shengquan Che[1], Boryana Ivanova[2], Dobri Dunchev[2]

[1] Shanghai Jiao Tong University, School of Design, China
[2] Agricultural University - Plovdiv, Bulgaria
***E-mail: rbeluhovauzunova@gmail.com**

Abstract

The growing integration of precision and digital technologies is becoming an essential element in tackling the challenges related to climate change. This study outlines the adoption pathways, practices, and broader context of precision agriculture in Bulgaria, a country with agricultural potential but also considerable exposure to climate-related risks. The analysis focuses on how farmers and agribusinesses are beginning to use digital tools to raise productivity, more efficient use of inputs, and reduce environmental pressures. Particular attention is given to the way digitalization can improve resource efficiency and strengthen the resilience of farming systems. The results show that precision farming adoption is steadily increasing, especially among larger farms that have the financial resources and technical expertise to invest in such solutions. At the same time, significant obstacles remain: restricted access to capital, weak digital infrastructure, limited technical knowledge, and fragmented advisory support. The observed limitations have slowed the digital farming development and hinder the opportunities for the realization of the sector full potential. Based on the results it can be concluded that more targeted policy, investment and access to finance is key for the digital transformation in Bulgarian agriculture. In addition, the coordination and cooperation between shareholders is important for wider benefits not only for farmers but also for the contribution to the targets and goals related to the European Green Deal.

Keywords: climate action, digitalization, innovations, sustainability

INTRODUCTION

Precision technologies are reshaping agriculture and making it more productive, efficient, sustainable and climate-resilient. The precision agriculture is developing and evolving and the new digital solutions help address key issues such as climate change, resource scarcity, and food security (Sarfraz et.al, 2023, Ibukun et.al, 2024).

The expansion of technologies that developed the concept of Agriculture 4.0 represent a new phase in the digital transformation of farming. Precision agriculture and digitalization give opportunities for sustainable food systems and environmentally responsible production (Arvanitis and Symeonaki, 2020, Javaid et.al. 2022).

Climate change is challenges that influence the agricultural systems at global level, with more frequent extreme weather events and rising temperatures that decrease crop yields and impact resource stability (Petrovic, B., & Csambalik, 2025). The environmental issues are forcing farmers to find innovative strategies that enhance resilience and optimize input application. Precision agriculture technologies offer adaptive solutions that help farmers monitor moisture, crop health, and weather conditions in real time (Wolfert et al., 2017). On the other hand, McFadden et al. (2023) pointed out that while automation and sensors have gained traction, adoption remains uneven and data gaps persist in how broadly these tools are used to buffer climate impacts.

Precision agriculture technologies offer an adaptive strategy: the ability to apply inputs more precisely, monitor microclimate and soil in real time, and respond to weather anomalies helps build resilience related to climate stress. However, the successful implementation and diffusion of precision technologies, especially in the context of climate change face multiple barriers. Socio-economic, institutional, technological, and behavioural factors must all be addressed (Petrovic & Csambalik, 2025).

This study outlines the adoption pathways, practices, and broader context of precision agriculture in Bulgaria, a country with agricultural potential but also considerable exposure to climate-related risks. The analysis focuses on how farmers and agribusinesses are beginning to use digital tools to raise productivity, more efficient use of inputs, and reduce environmental pressures.

MATERIALS AND METHODS

Based on the literature review, a survey related to precision technologies adoption and implementation is conducted. The methodological framework use similar approach as Kernecker et al., 2020.

The study is based on an online survey conducted from May to August 2025. A total number of sixty questionnaires were validated. The study is focused on three main directions: (1) sociodemographic characteristics of the respondents; (2) the level of adoption of precision agriculture (3) drivers and barriers for implementation.

The data was collected through an online survey and respondents provided their consent in accordance with the General Data Protection Regulation of the European Union.

RESULTS AND DISCUSSION

Theoretical background

The implementation of precision technologies has emerged as a concept related to the transition toward more efficient, sustainable, and climate-resilient agricultural systems. Precision agriculture includes a wide range of digital tools such as global positioning systems (GPS), remote sensing, variable-rate technologies, drones, and farm management software. These technologies help with optimizing input use and reducing environmental impacts (Gebbers & Adamchuk, 2010; Wolfert et al., 2017).

Different studies indicate that soil health could be improved by 20–30% based on targeted nutrient and input management. The precision technologies could help in challenges such as poor soil fertility and resource use inefficiency (Ahmand &Dar, 2020, Monteneiro et.al, 2022). Water conservation is another important benefit, as sensor-based irrigation reduce water usage by 30–50% while increasing yields by 10–20% (Adeyemi et.al. 2017, Zafar et. al, 2020)

Precision and digital tools linked to pest and disease management have resulted fall in crop losses by 15–25% and pest outbreaks by 20–40% (Roberts et.al, 2021, Panda 2020). Regarding climate change, the modelling and climate data help farmers adapt farming practices, increasing crop resilience by 20% and decreasing adaptation costs by 10% (Roy& George, 2020, Balafoutis et al., 2017). Precision farming also reduces land degradation by 20% and carbon emissions by 15–25%, which contributes to low-carbon agriculture [Ahmand &Dar, 2020, Saiz-Rubio & Rovira-Más, 2020).

Despite their potential, the rate of adoption among farmers remains uneven. One of the most influential frameworks for explaining technology diffusion in agriculture is *Diffusion of Innovations Theory.* According to Rogers (2003), five attributes of innovations influence adoption rates: relative advantage, compatibility, complexity, trialability, and observability. In agriculture, these elements are seen as relevant. For example, smallholder often perceive precision technologies as too complicated or financially risky, while early adopters are younger, more educated, with larger farms (Pierpaoli et al., 2013)

The *Technology Acceptance Model* proposed by Davis (1989), focuses on the psychological determinants of technology use. It includes two key elements: **perceived usefulness** and **perceived ease of use**. In agriculture, these beliefs reflect farmers' perceptions of whether precision tools will increase productivity, reduce costs, and improve decision-making, as well as how easy are to operate (Adrian et al., 2005).

Venkatesh et al. (2003) developed the *Unified Theory of Acceptance and Use of Technology*. The model is based on eight earlier theories and introduces four major aspects: **performance expectancy, effort expectancy, social influence,** and **facilitating conditions.** Some studies show that opportunities, such as training, advisory networks, and government measures and initiatives, are among the important drivers for precision technologies adoption (Kernecker et al., 2020). This is particularly relevant in Bulgaria, where administrative capacity are still developing and face number of challenges. While general adoption theories outlined the main features of adoption process, agriculture require additional considerations linked with risk and socio-technical characteristics. The *Adoption and Diffusion of Agricultural Innovations* model (Kutter et al., 2011) highlights the role of farm structure, risk, and communication networks. On the other hand, *Socio-Technical Systems* model emphasizes that adoption is not only an economic decision but also a process involving farmers, technology providers, and institutions (Eastwood et al., 2017).

Literature review of the empirical studies shows several common **drivers** and **barriers**. Drivers include farm size, income, education, training access, and policy, while barriers are related to high investment costs, technical knowledge, and uncertain return on investment (Barnes et al., 2019; Kernecker et al., 2020).

Based on the theoretical perspectives, the adoption of precision agriculture technologies among Bulgarian farmers can be conceptualized as a multi-level process. Socio-economic characteristics (age, education, farm size, access to funding) influence.

Table 1: Main driver and barrier for precision technology adoption

Drivers of Adoption	**Barriers to Adoption**
Farm size	High investment and maintenance costs
Advisory services and training	Low digital skills and technical support
Common agricultural policy support	Unclear cost/benefit ratio
E-learning and demonstration farms	Low compatibility with existing machinery
Environmental and economic benefits	Cyber security and data

Source: Own interpretation based on Barnes et al., 2019

These perceptions shape the **behavioral intention to adopt**, which leads to **actual adoption** and **environmental benefits** related to climate-smart agriculture.

Farmers Adoption of Precision technologies

The analysis of socio-demographic characteristics provides useful insights into the respondents' profiles and link with precision technologies adoption. Regarding the age, the majority of farmers (60.5%) are between18–30 age. The group 31–45 represents 26.3%, while 13.2% are between 45 and 60 years old. The survey highlight that the farm managers are younger and middle-aged, influencing the results through their higher familiarity with technology and digital tools (Pierpaoli et al., 2013). In terms of gender, 63.9% of participants of the survey are male, while the other 36.1% are female.

In regards to marital status, more than half of the farmers (51.4%) are single, while 20% are married. In addition, 28.6% stated living in a domestic partnership, which show a relatively diverse composition. The dominance of single respondents might correlate with the younger age profile of the survey.

Regarding family structure, 72.2% of respondents have no children, 8.3% have one child, another 11.1% have two, and 8.3% have three. This profile suggests that most participants are in earlier stages of their personal and professional lives, which could influence their attitudes, or views toward innovation and precision technologies adoption.

In regards to farming experience, the majority of respondents have up to three years of experience, representing the largest segment in the sample (Figure 1). This suggests that a significant proportion of the participants are relatively new to farming, possibly first-generation or recently established farmers. In addition, 30% of farmers are with 3–10 years of experience. The result indicates a group of moderately experienced managers who may be adaptive to new agricultural technologies and methods. On the other hand, 13% of farmers point out 10–20 years of experience, while only a few have been active for over 20 years. This overall distribution highlight a young and dynamic respondent's structure that may be more open to innovation and digitalization in agriculture.

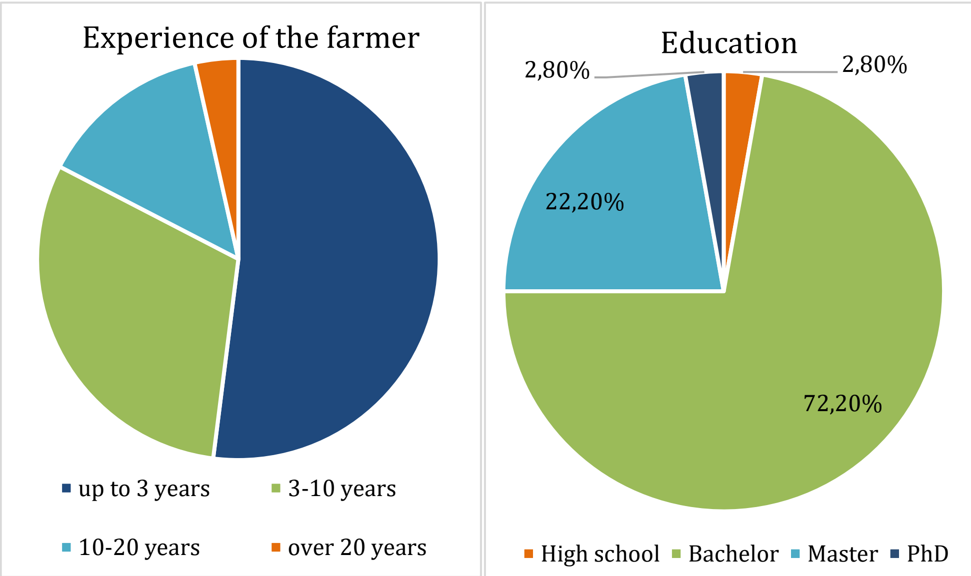

Figure 1: Experience and education level of the farmers
Source: Own survey

In terms of education, more than 72% have a Bachelor's degree and 22% Master degree, which shows high level of education. Smaller number report secondary education or PhD degree. The dominance of higher educational level indicates that most respondents could be open to modern technologies and sustainable practices. This educational profile supports the potential for successful adoption of precision agriculture and digital tools in farm management.

Regarding the farm specialization, the majority of the holding are crop producers (72%), while the livestock farms are 8% and 20% are represented by mixed farms.

In relation to the precision technologies adoption, 62% of the farmers implement precision technologies in their holding.

The data show that GPS technology is the most commonly applied, implemented by around 63% of the farmers (Figure 2). The result outlines that GPS remains the key tool of precision farming, helping accurate field mapping, navigation, and resource management.

Sensors and automated steering systems also are widely adopted by farmers, indicating greater interest in automation and real-time monitoring. These technologies improve profitability, reduce input costs, and stimulate accuracy in field operations.

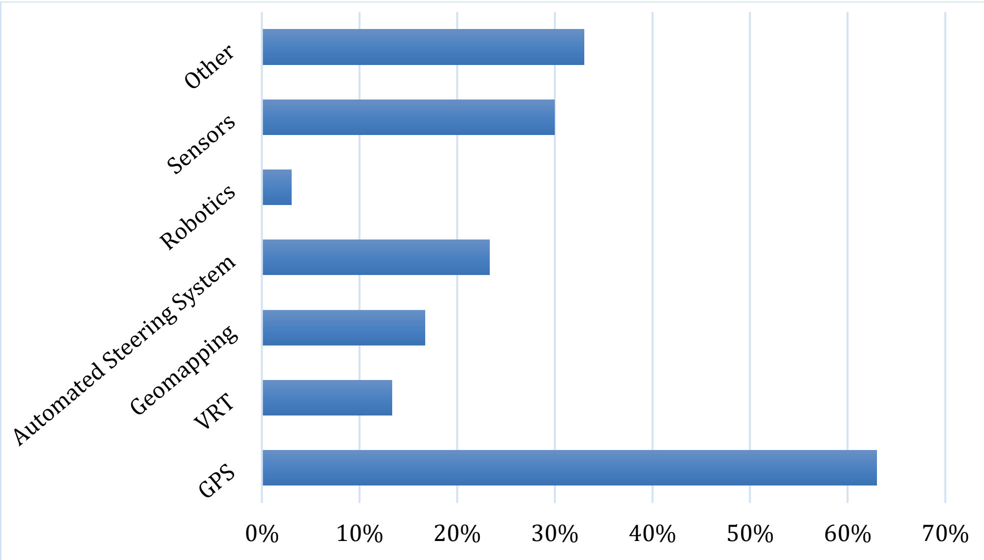

Figure 2: Types of implemented precision technologies
Source: Own survey

By contrast, geomapping and variable rate technology are less applied. This may be due to the higher costs and technical expertise needed for their implementation. Robotics shows the lowest adoption rate, which reflects the technology's limited accessibility and developing stage.

The results highlight that farmers are increasingly implementing GPS and sensors, while more advanced technologies like robotics and VRT are still not widely adopted, likely due to lower financial and technical capacity .

The results show that half of the respondents (50%) actively use these technologies, demonstrating a relatively high level of technological engagement and awareness of the benefits of precision agriculture (Figure 3).

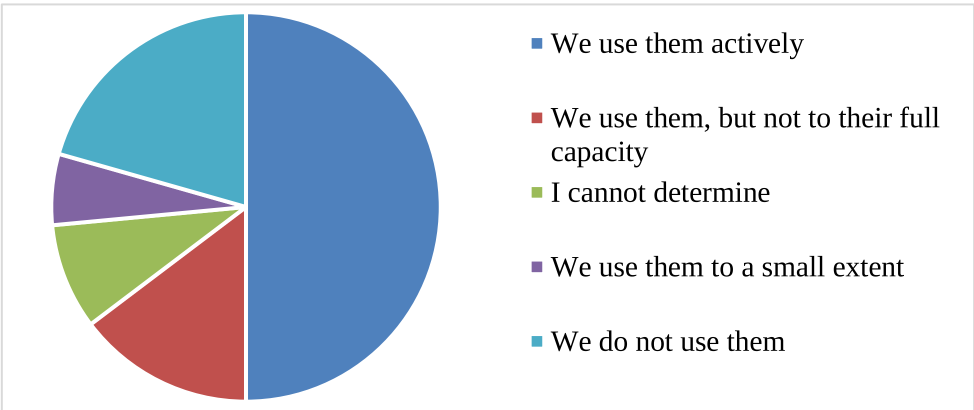

Figure 3: Level of Use of Precision Technologies among Farmers
Source: Own survey

However, 14.7% of farmers report using precision technologies but not to their full capacity, suggesting barriers such as insufficient technical knowledge, lack of training, or limited compatibility between equipment and software. In addition, 5.9% indicate that they use the technologies to a limited extent, outlining partial adoption. On the other hand, 20.6% of the farmers do not use precision technologies at all. The results reveal that despite the potential, a significant part of farmers remain disconnected from these innovations. Additionally, 8.8% were unsure about their application level, which may show limited awareness of what is defined as precision technology.

The results illustrate the main reasons why some farmers either do not use or only partially use precision agriculture technologies (Figure 4). The data shows that the two most common barriers are high costs (40%) and other unspecified factors (40%). The financial aspect clearly remains a significant obstacle, as the initial investment, maintenance, and operational expenses for precision technologies can be prohibitive, especially for small and medium-sized farms.

A lower share of farm managers, 10% reveal that they do not know the functions of the technologies well. The results indicate a lack of training or technical knowledge. In addition, more than 10% mentioned difficulties in maintenance services or purchasing consumables, which is associated with infrastructural and logistical challenges. There are in parallel findings from previous studies (Lowenberg-DeBoer & Erickson, 2019; Ehlers et al., 2021) indicating similar challenges.

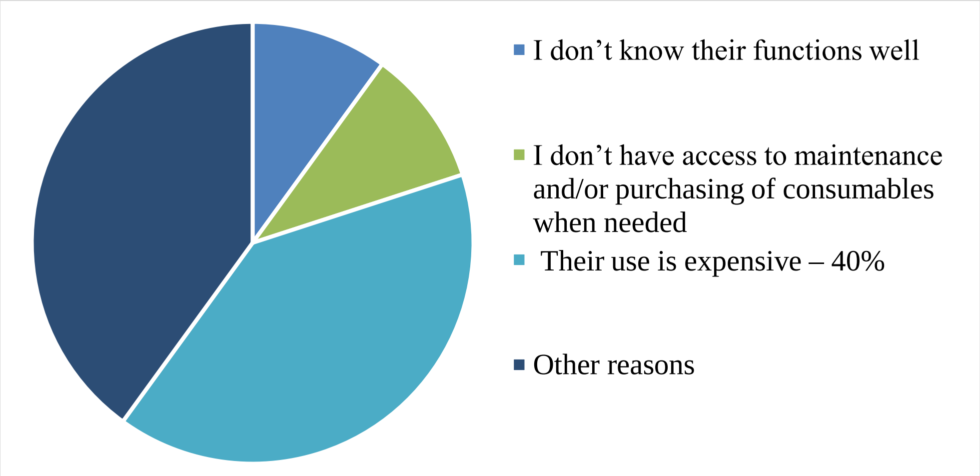

Figure 4: Barriers to the Adoption and Full Utilization of Precision Agriculture Technologies
Source: Own survey

The combination of higher costs, knowledge gaps and technical support continues to slow down the widespread adoption of precision technologies.

The data highlight the need for financial incentives, capacity building, and better support networks to help farmers fully integrate precision technologies into their operations.

The results reveal that the most frequently reported advantages include productivity growth (over 70%), labor cost reduction and improved management and monitoring (Figure 5). These findings suggest that farmers primarily associate digital tools with operational efficiency and improved decision-making. The results are similar to some surveys that emphasize profitability and optimize resource use as major benefits for farmers. (Barnes et al., 2019; Lowenberg-DeBoer & Erickson, 2019).

Additionally, input cost reduction and benefits for climate adaptation and resilience were also recognized as important. These responses reflect the growing awareness of the role of precision technologies in promoting climate-smart and sustainable agriculture.

The results highlight that farmers consider precision technologies as a path for increasing productivity and sustainability, cost reduction, and resilience to climate change issues. These results are similar to some researches showing that precision agriculture can improve economic performance and decrease environmental impact (Wolfert et al., 2017; Abiri et al., 2023).

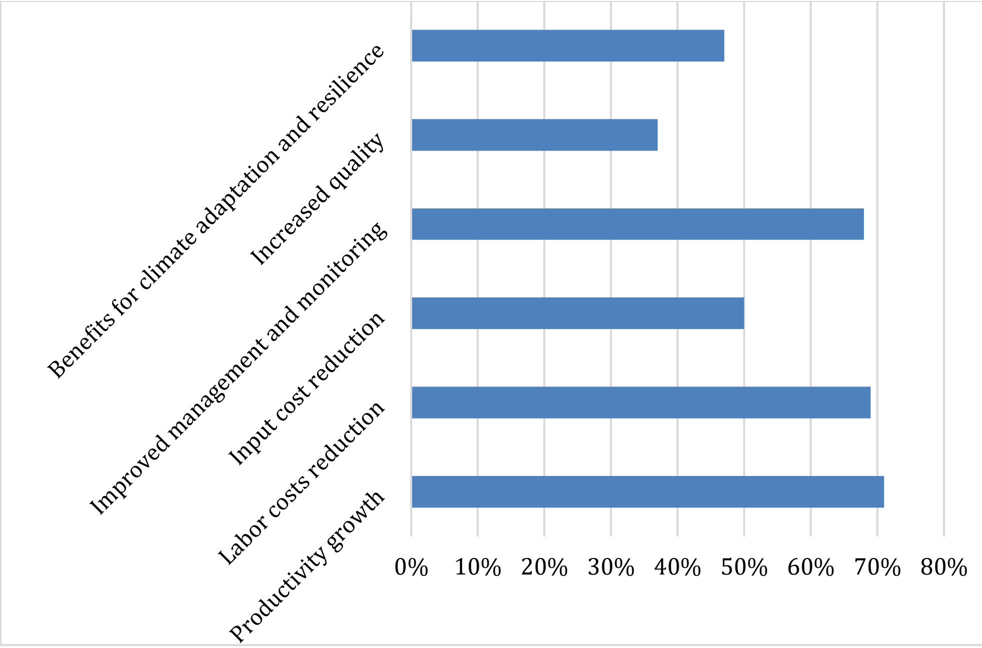

Figure 5: Benefits for precision technologies adoption
Source: Own survey

CONCLUSIONS

Based on the analysis some conclusion can be outlined:

1) Demographic structure of the survey indicates a strong potential for digital transformation in agriculture, as younger and more educated farmers tend to be more open to technological innovation;

2) In terms of farming experience, most participants reported up to 10 years in the sector, suggesting that the sample includes a generation of farmers more likely to experiment with new technologies and management practices. ;

3) The use of precision technologies varied, with GPS-based systems being the most widely adopted, followed by automated steering, sensors, and data-driven tools. However, robotics and geomapping were still less common.;

4) Despite growing awareness, the results also revealed significant barriers to adoption. High implementation costs and lack of technical familiarity were among the most frequently cited obstacle.

5) The perceived benefits of precision agriculture were, however, substantial. Farmers associated these technologies with higher productivity, reduced costs, and positive effects on climate adaptation and resilience.

The precision agriculture technologies and digital tools demonstrate economic and environmental benefits, but their full potential remains not boosted due to financial, technical, and infrastructural barriers. Based on the results it can be concluded that more targeted policy, investment and access to finance is key for the digital transformation in Bulgarian agriculture. In addition, the coordination and cooperation between shareholders is important for wider benefits not only for farmers but also for the contribution to the targets and goals related to the European Green Deal.

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