FARMER ADOPTION OF NITROGEN MODELING TOOLS: PERCEIVED BARRIERS AND IMPORTANT FACTORS

by

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ABSTRACT

Agricultural nitrogen runoff contributes around 45% of nitrogen entering the Chesapeake Bay, significantly affecting its water quality. Despite various efforts, the 2025 water quality goal for the Chesapeake Bay Watershed has not yet been achieved. In-season nitrogen modeling tools (NMTs) help farmers optimize nitrogen application, improve Nitrogen Use Efficiency, and reduce environmental nitrogen loss. However, the adoption of NMTs among U.S. farmers is low. While existing studies have explored factors influencing best management practices, nutrient management practices, and agricultural technology adoption, little is known about factors that influence farmers' adoption decisions specifically on the use of NMT. This study examines the role of perceived important factors (e.g., economics, time, and environment) and perceived barriers (e.g., resources and information) in current and future NMT adoption decisions. A mail survey was conducted among 204 grain farmers in the Mid-Atlantic region of the United States. To bring more clarification on quantitative results, a semi-structured interview was conducted among 20 farmers. Survey data were analyzed using exploratory factor analysis and ordered logistic regression models, and interview data were analyzed using thematic analysis. Survey results showed that the importance farmers placed on time investments was positively correlated with current adoption and the likelihood of future adoption. Additionally, the influence of environmental awareness and compliance importance, time investment importance, belief barriers, and equipment and technology barriers on farmer adoption decisions for NMT varied by farm size. Farmers with larger cropland area were more likely to adopt NMT both currently and in the future. Farmers' enrollment in the Conservation Reserve Program, Conservation Stewardship Program, and State Agriculture Cost-Share Program was found to influence their adoption decisions. Through qualitative analysis, we found that farmers considered NMT as a time and accuracy-efficient tool once they were initially set up, and they were willing to invest additional time if the tools proved profitable. These findings inform organizations such as the U.S. Department of Agriculture (USDA) and the Mid-Atlantic 4R Alliance, which promote nutrient management and NMT adoption, to emphasize the time-saving and cost-saving benefits of NMT and design programs that address adoption barriers based on farm size.

Chapter 1

INTRODUCTION

In 2023, approximately 247.6 million pounds of nitrogen entered the Chesapeake Bay (Chesapeake Bay Program 2024a). These excess nutrients contribute to the formation of harmful algae blooms, which block sunlight from reaching underwater vegetation and lead to the development of oxygen-depleted “dead zones” (Chesapeake Bay Program 2024b). This excessive nitrogen (N) loading is negatively impacting the Bay’s water quality (Chesapeake Progress 2023) and adversely affecting the health of its ecosystem (Chesapeake Bay Foundation 2022). Despite various efforts by the Environmental Protection Agency, the required nitrogen load reduction to meet the 2025 water quality goal for the Chesapeake Bay Watershed (CBW) (214.88 million pounds) has not yet been achieved (Boesch 2019; Ritter 2019). Leaching or run-off nitrogen from agricultural fields is one of the major sources of nitrogen loading in the Chesapeake Bay, contributing around 45% of the nitrogen delivered in the Bay (Chesapeake Progress 2023). Research has shown that excessive application of nitrogen fertilizers, above the required rate, leads to significant nutrient leaching (Goulding et al. 2000). Furthermore, the Nitrogen Use Efficiency (NUE) of crops, for example, global cereal production, is found to be quite low, around 33% (Raun and Johnson 1999). Thus, appropriate nutrient management–applying the Right Source of nutrients at the Right Rate, at the Right Time, and in the Right Place (known as the 4Rs[1])–is crucial to enhance nitrogen use by crops and reduce N loss to the environment (Johnston and Bruulsema 2014).

One 4R practice that can improve nitrogen efficiency is the use of in-season nitrogen modeling tools (NMTs). NMTs are cloud-based software that aggregate data on local weather, site location, and crop conditions to calculate the optimal nitrogen required for crops in real-time situations. These decision support tools aid farmers in applying nitrogen at the right rate, place, and time while increasing marginal return, improving NUE, and reducing environmental nitrogen loss (Wang et al. 2021; Cui et al. 2011; Sela et al. 2017).

Despite promotion as a 4R nutrient management practice (NMP), it is anecdotally known that there is low adoption of NMTs among U.S. farmers. This is not surprising given prior evidence that farmers' adoption of other nitrogen management practices is also low (DeLay et al. 2022). Even the farmers who are adopting other NMPs are not consistently using them across all of their farm fields (Ulrich-Schad et al. 2017). Given the demonstrated private and public benefits of NMTs, it is crucial to understand the adoption decisions of farmers for NMTs to support the mitigation of nitrogen leaching and improve the CBW water quality. This study addresses four key research questions to contribute to the NMT literature and inform policy: (1) How important do farmers consider various factors, such as economic implications, environmental concerns, and time use, in their adoption decision for NMTs? (2) How do the identified important factors influence the adoption of NMTs? (3) What barriers, such as resource barriers and information barriers, do

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[1] The 4R's of nutrient management practice are a suite of Best Management Practices (BMPs) that guide farmers to apply nutrients from the right source, at the right rate, right time, and right place.

farmers perceive that limit the adoption of NMTs? (4) How do the identified perceived barriers influence the adoption of NMTs?

Prior literature has shown factors such as environmental concerns, economic factors, management decisions, the threat of regulation, farm characteristics, and beliefs affect the adoption decisions of farmers for BMPs (Ulrich-Schad et al. 2017; Ghazalian, Larue and West 2009), NMPs (Osmond et al. 2015; Baumgart-Getz et al. 2012), as well as agricultural technologies (Lambert et al. 2015). Studies have highlighted economic factors such as yield improvement and cost reduction as important attributes in farmers' decisions to adopt precision agricultural technologies (Thompson et al. 2019) and agricultural Best Management Practices (BMPs) (Ulrich-Schad et al. 2017). Similarly, farmers who place importance on environmental concerns are found more likely to adopt NMPs such as the corn N rate calculator (Gao and Arbuckle 2022). Our study extends the literature by examining the importance of different factors, such as economic, environmental awareness and compliance, and time investment, in the adoption decision for NMTs.

Furthermore, existing literature has identified different factors as barriers to the adoption of NMT. The time demand of practices has been found as a barrier to the adoption of conservation practices such as cover crops (Reimer, Weinkauf and Prokopy 2012). Ulrich-Schad et al. (2017) illustrated that farmers are not likely to adopt the NMPs, such as conducting soil tests and nutrient management plans, when they consider the lack of access to the required equipment important in their adoption decision. Moreover, barriers (e.g., resource barriers or uncertainty) can vary across different nitrogen management practices (Rudnick et al. 2023). Our study extends literature on adoption barriers by exploring the extent of limitations that different perceived barriers, such as resource barriers or information barriers, have on the farmer's adoption decision for NMTs.

The theory of Planned Behavior, formulated by Ajzen (1991), has shown how the attitude toward the behavior, subjective norms, and perceived behavioral control determine human intention, which eventually drives their behavior. Furthermore, McCormack et al. (2022) suggested that psychological factors such as perceived usefulness and perceived ease of use have a positive influence on the farmer's attitude toward the future likelihood of adopting a nutrient management plan. Here, perceived usefulness reflects that a nutrient management plan is important to farming needs, increases production and profit, and is better than none, and perceived ease of use reflects that a nutrient management plan saves time and is easy to understand and use. Furthermore, behavioral factors such as self-efficacy and perceived capacity become barriers to the adoption of 4-R nutrient management practices when farmers do not have the belief in themselves that they can reduce nutrient loss (Upadhaya, Arbuckle and Schulte 2023). Ramsey et al. (2019) elucidated that farmers' perceptions of yield risk have negative impacts on the adoption of agricultural conservation practices, while perceptions of environmental benefits have a positive impact. Our study further explores how the farmer's attitude toward the importance of different factors and barriers influences the adoption decision regarding NMT.

To date, there are a few studies on the factors influencing the farmer adoption decision regarding NMPs, BMPs, and agricultural technologies. Specifically, these studies have addressed the impact of factors such as socioeconomics, beliefs, farm and operator characteristics, information access, farm resources, and the environment on the adoption of NMP, BMP, and agriculture technologies in general (Paudel et al.

2008; Lambert et al. 2015; Rudnick et al. 2023; Giampietri et al. 2020; Luther et al. 2020). However, to our knowledge, no studies to date have explored farmers' perception of the importance of different factors (e.g., economic, environmental, and time) or perceived barriers (e.g., resource barrier and information barrier) and their role in farmers' adoption decisions, precisely on the use of NMTs.

Previously, some studies have incorporated both the future likelihood of adoption and current adoption status as a categorical measure of adoption (Zhang et al. 2016) , whereas some have focused their study solely on either the current state of adoption (Luther et al. 2020) or future likelihood of adoption (McCormack et al. 2022). In this study, we have estimated separate models for the current adoption status and future likelihood of the adoption decision of farmers to better understand what drives the current adoption level of NMT and what might encourage further adoption in the future. Therefore, firstly, we explore the farmers' perception of the importance of different factors and their correlation with current and future adoption decisions for NMT, respectively. Secondly, we examine the extent of the limitation of different barriers to the use of NMT and their association with current and future adoption decisions for NMT, respectively.

We used data from a mail survey of 204 farmers in the Mid-Atlantic region of the United States (Delaware, Maryland, Pennsylvania, and Virginia) from December 2021 through January 2022. Data was first analyzed through factor analysis to obtain latent important factors and perceived barriers, respectively, which were then further analyzed using the ordered logistic regression models. Moreover, we incorporated the data from the semi-structured interview, which was conducted among 20 Delaware and Pennsylvania farmers from February 2025 through March 2025. Overall, this study aimed to provide insight into the farmers' perceptions of important factors and barriers and their role in their decision-making for the adoption of NMT.

The findings from this study may assist policymakers and stakeholders, such as the Mid-Atlantic 4R Alliance, the U.S. Department of Agriculture (USDA), etc., in designing programs to improve nutrient management. Additionally, the results may provide valuable insight for organizations, such as the Mid-Atlantic 4R Alliance, that promote the use of NMTs, on strategies to better communicate and inform farmer perspectives. Understanding the role of various factors in farmers' decisions to adopt NMTs could assist stakeholders and organizations in identifying and addressing key drivers and barriers to adoption. Ultimately, these insights could contribute to reducing agricultural nitrogen runoff by emphasizing promotions to help overcome those barriers that are highly limiting farmers from adopting these tools, as well as targeting promotion campaigns that focus on the most valuable factors in farmer adoption decisions.

The subsequent sections of this paper are organized in the following way. In Chapter 2, we present a review of the relevant literature related to our research question and hypothesis. In Chapter 3, we define our hypotheses and methodology, including data collection, econometric model, and statistical analysis. Chapter 4 presents the results that were obtained from statistical analysis laid out in the methods and hypotheses section. Chapter 5 summarizes and discusses the findings and concludes the thesis by highlighting key insights and their implications.

Chapter 2

BACKGROUND

2.1 Nitrogen Loading in the Chesapeake Bay and Agriculture Runoff

The Chesapeake Bay, the largest and historically most productive estuary in the United States, spans approximately 200 miles in length and up to 34 miles at its widest point (Cestti et al. 2003). The Bay's watershed covers parts of six states – Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia (Cestti et al. 2003). Nitrogen enters the Chesapeake Bay from various sources, such as wastewater, runoff, and air pollution, and fuels harmful algae blooms that prevent the sunlight from reaching underwater grasses. And, when algae bloom decompose, they create low-oxygen "dead zones", suffocating the marine life (Chesapeake Bay Program 2024b). The total nitrogen entering the Bay decreased from 297.8 million pounds in 2009 to 247.6 million pounds in 2023 (Chesapeake Bay Program 2024a). The states of Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and the District of Columbia have achieved 9%, 100%, 83%, 65%, 29%, 80%, and 100% of the 2009-2025 nitrogen reduction goal, respectively (Chesapeake Bay Program 2024a). However, the 2025 nitrogen load reduction target, i.e., 214.88 million pounds, has been yet to be achieved (Chesapeake Progress 2023).

Agriculture is a significant source of nitrogen pollution in CBW, contributing 111.29 million pounds, which is approximately 45% of the total nitrogen delivered to the Bay (Chesapeake Progress 2023). The applied Nitrogen is converted into nitrate, which is prone to leaching beyond the soil-plant system and into water bodies, exacerbating pollution concerns (Bijay-Singh and Craswell 2021). This issue becomes even more critical as the population is rising steadily, which is causing an increase in nutrient use in crop production to meet the rising food demand (Nesme, Metson and Bennett 2018).

2.2 In-season Nitrogen Modeling Tools

Nitrogen management in crop fields presents significant challenges, as the precise application of nitrogen in the field depends on various factors, including weather conditions, existing soil nitrogen levels, and crop growth conditions. Managing these factors manually is laborious, and some data are beyond the control of farmers. In-season N modeling tools, which are cloud-based software, can address these challenges by using soil characteristics, nutrient application, crop growth, and real-time site-specific weather conditions to determine the optimal nitrogen rate required for crops throughout the growing season (Twining and Agri-Service 2024). The use of model-based in-season economic optimal N rate (EONR) has shown the considerable potential to increase yield–based marginal returns to N application rate by \$120-183 per hectare compared to farmers' N rates, and by \$0 – 83 per hectare compared to regionally determined optimal N rates, while improving nitrogen use efficiency by 8-71% and 1-38%, respectively, without negatively impacting the crop yield (Wang et al. 2021). Thompson et al. (2015) found that employing active canopy sensing for in-season nitrogen management in corn led to higher nitrogen use efficiency while crop modeling (Maize-N) better-protected yield, suggesting that a combined approach may optimize nitrogen application decision. Similarly, a dynamic simulation-based N management tool, Adapt-N, has been observed to significantly reduce N application, produce higher or comparable yields, and reduce environmental

N losses relative to the Maximum Return to N approach (MRTN) approach, a static N management which estimates the most profitable N rate quantifying the relationship between N rate and yield (Sela et al. 2017). Cui et al. (2011) observed a 75.6% reduction in nitrogen loss in wheat production using an in-season nitrogen management strategy which involved the application of the optimal nitrogen fertilizer rate.

2.3 Adoption Status of NMP, BMP, and Agricultural Technologies in U.S.

The existing research shows relatively low levels of adoption of NMPs, BMPs, and precision agricultural technology in the US, even though levels vary depending on the specific practice or technology being studied and the study area.

In a 2005 survey of 1215 cotton farmers across 11 southern states of the U.S., only 9% (98 farmers) were using Remote Sensing for Variable-rate technology (VRT) application of inputs (Larson et al. 2008). Likewise, a lower adoption rate for cover crops was observed in a study conducted in two watershed regions of Indiana, U.S. (Reimer et al. 2012). Weber and McCann (2015) found that 7%, 11%, and 6% of corn producers in the United States in 2010 adopted variable-rate fertilizer, GPS soil maps, and remote sensing N management tools where remote sensing aids in in-season N application.

A survey in 2013, reflecting cotton producers in 13 southern states of the U.S, reported that precision technology such as yield monitors with GPS, grid soil sampling, zone soil sampling, aerial imagery, satellite imagery, soil survey maps, handheld GPS, COTMAN, electrical conductivity, and digital maps were used only on 22%, 22%, 12%, 13%, 7%, 12%, 8%, 3%, 6%, and 3% of cotton crop respectively (Lambert et al. 2015).

A 2014 survey of agricultural producers and landowners in Indiana found that 85% of farmers used regular soil tests, while only 65% used application timing, 56% used variable rate application technology, and 46% used NMPs (Ulrich-Schad et al. 2017). It is noteworthy that even among those who adopted these practices, not all farmers applied them uniformly across their entire farmland, and some reported not fully adhering to NMP guidelines.

A 2016 survey of corn farmers in New York, Pennsylvania, Michigan, and Ohio reported 17%, 7%, 1%, 18%, 9%, 10%, and 5% of adoption rates for yield mapping, soil mapping, remote sensing, guidance system, VRT seeding, VRT fertilizer, and VRT pesticides, respectively (Schimmelpfennig and Lowenberg-DeBoer 2020).

A survey of corn and soybean farmers in 2017 across the eastern Corn Belt states (Illinois, Indiana, Ohio, and Michigan) revealed that no more than 20% of farmers regularly use practices such as cover cropping, variable-rate nitrogen application (VR-Nitrogen), variable-rate seeding (VR-Seeding), the pre-side dress nitrate test (PSNT), and aerial scouting; however, more than 40% of farmers regularly used soil mapping, yield mapping, and variable-rate phosphorus and potassium application on their farms (Luther et al. 2020).

A farmer's survey conducted in 2017 in South Dakota showed a lower rate of adoption of information-intensive precision agricultural technologies (PATs) such as Aerial imagery (30.8%), crop tissue sampling (37.6%), grid soil sampling (44.2%), prescription field maps (50.5%), variable-rate system (50%), yield monitor (68.7%) than that of embodied-knowledge PATs such as automatic section control (55.1%), GPS guidance system (75.1%), and autosteer (73.7%). Here, embodied-knowledge

PATs are relatively simple and easy to operate, whereas information-sensitive technologies PATs generate large numbers of data and require specialized skills for interpretation and effective utilization (Kolady et al. 2021).

A survey of Florida farmers in 2018 reported a current adoption rate of 17.7% for tissue testing for nitrogen (N), phosphorous (P), and potassium (K), and 12.0% for soil moisture sensors as BMP, where the farmer reported economic factors – the economic cost of installation, finance, etc. – as a main barrier to the adoption (Yehouenou et al. 2020).

2.4 Factors Affecting the Adoption of NMP, BMP, and Agricultural Technologies

Economic considerations are one of the primary drivers in the adoption of agricultural technologies, NMPs, and BMPs. Thompson et al. (2019) conducted a choice experiment highlighting financial benefits, such as yield improvement and cost reduction, as the most important attributes for the adoption of precision farming technologies. Farmers perceived that variable rate fertilizer application is more likely to increase profit either through increased yield, reduced production costs, or both, compared to precision soil sampling, guidance and autosteer, and yield monitoring. Buckley, Howley and Jordan (2015) found a significant and positive association between the number of NMPs adopted by farmers and factors such as farm stewardship (good farm business management), and productivist (maximizing farm output). Similarly, Prokopy et al. (2019) reported a positive correlation between yield and the adoption of one or more soil or water conservation practices. However, input costs could act as a barrier to the adoption of some conservation practices, such as cover crops and grassed waterways (Reimer et al. 2012). A systematic review of all

U.S.-based qualitative studies on the adoption of conservation practices and programs highlighted that the cost of the practices and potential yield improvements were discussed almost equally as both a motivating factor and a barrier to adoption (Ranjan et al. 2019). Farmers primarily oriented toward optimizing income were found less likely to adopt soil mapping, while no significant relationship was obtained for other practices such as cover cropping, VR-Nitrogen, VR-phosphorus and VR-potassium, VR-Seeding, PSNT, aerial scouting, and yield mapping (Luther et al. 2020). Farmer perception regarding economic factors is found to influence their adoption decision; for instance, farmers to whom the evidence of economic benefit is important in making decisions about nutrient management are more likely to adopt application timing BMP (Ulrich-Schad et al. 2017). A similar result was observed regarding the adoption of PATs; farmers who perceive that using PATs will increase profitability are more likely to adopt them (Kolady et al. 2021). Furthermore, a study conducted in Vietnam reported awareness of the cost and benefit evaluation of agricultural technology adoption among farmers, prioritizing benefits over initial investment costs (Nguyen et al. 2024). However, Gao and Arbuckle (2022) suggested that perceived economic pressure has a varying impact on the adoption of different practices such as Growing Season N application, variable rate nitrogen application, corn N rate calculator, and N Stabilizer. Though some literature has shown an insignificant impact of economic factors, most of the literature has proven the significant influence of these factors on the farmer adoption decision, which is found to vary for different agricultural practices or technologies.

Environmental motivation also plays a significant role in farmers' decisions to adopt. Buckley et al. (2015) found that the number of nutrient management practices adopted by farmers was significantly and positively associated with ecocentric motivations (protecting the environment) and negatively associated with anthropocentric motivation (focused on farmers' needs). The stewardship motivation, which measures the importance farmers place on variables such as maintaining or enhancing productivity, maintaining or improving soil health, reducing the environmental impact, protecting the land, etc. in their decision-making to incorporate conservation practices, was observed to be positively correlated with the adoption of nitrogen rate based on corn N rate calculator (MRTN) and N stabilizer use (Gao and Arbuckle 2022). Similarly, Baumgart-Getz et al. (2012) reported the positive impact of environmental awareness on the adoption decision of BMP such as soil, water, nutrient, integrated pest, and landscape management practices. However, Ulrich-Schad et al. (2017) observed no significant importance of environmental benefits evidence on the farmers' decision-making to adopt nutrient best management practices such as conducting soil tests, VR application, and application timing. Therefore, most of the literature reported a significant influence of environmental concern factors, though some reported an insignificant impact.

Moreover, farm and farmer characteristics are another determinant for the adoption of agricultural technologies and practices. Farmers with large farms, higher education, and those involved in environmental organizations are more likely to adopt BMPs, such as herbicide control practices, crop rotation, and riparian buffer strips (Ghazalian et al. 2009). McCormack et al. (2022) found that farmers with large farms and full-time involvement in farming were more likely to adopt and use nutrient management plans. Likewise, a positive and significant association was obtained between cropland areas and the adoption of embodied-knowledge PATs as well as information-intensive PATs (Kolady et al. 2021). Similarly, Larson et al. (2008) and Baumgart-Getz et al. (2012) noted that younger cotton growers were more likely to use Remote Sensing for VRT decisions and BMP, respectively. The survey of southern states' cotton producers showed a negative association of producer age with the adoption of precision technologies such as yield monitors with GPS, grid soil sampling, zone soil sampling, aerial imagery, satellite imagery, soil survey maps, handheld GPS, COTMAN, electrical conductivity, and digital maps whereas farm size and farm income proportion had a positive relationship with the adoption (Lambert et al. 2015). Similar to this result, Paxton et al. (2011) reported an increase in the number of PATs (e.g., yield monitor with GPS, COTMAN plant mapping, etc.) adopted by cotton producers with an increase in the share of farm income in total household income. Additionally, land ownership dynamics play a role in adoption, as leased land has been identified as a barrier to the adoption of conservation practices. Some farmers reported that it is difficult to get support from landowners for implementing conservation practices, and some stated that they would prioritize conservation on owned lands and look for leased land if the contract is long-term (Kalcic et al. 2014). A similar result was observed by Reimer et al. (2012): land ownership restrictions were recorded as limitations to the adoption of BMPs - grassed waterways. Having training and technical skills in technology is also found to be positive and significantly associated with the adoption or willingness to adopt one or more soil and water conservation practices (Prokopy et al. 2019). However, some research has reported an insignificant effect of farm and farmer characteristics on the adoption of agricultural technologies. Daberkow and McBride (2003) reported age and education having insignificant effects on the adoption of at least one precision agricultural technology

(Daberkow and McBride 2003). Gross farm income and farmers' education level are also found to be non-influential factors in the adoption of PATs (Castle, Lubben and Luck 2016; Isgin et al. 2008). Moreover, the share of total operated acres rented is recorded as having an insignificant effect on the adoption of a number of precision farming tools (e.g., yield monitor with GPS, COTMAN plant mapping, etc.) by cotton farmers in the southern U.S. (Lambert et al. 2015).

The nuances of the agricultural practices, for instance, time requirement and compatibility of management practices, also influence the adoption decisions of farmers. Ranjan et al. (2019) observed that compatibility with farm management, farm management effort, and time requirements are often viewed as barriers to adopting conservation practices rather than motivations. Similarly, the complexity and time demand of practices like grassed waterways and cover crops have been reported as barriers to their adoption (Reimer et al. 2012). Some farmers were found considering the attractiveness and value of the practice as the motivation behind the adoption of grassed waterways, where they quoted that "*It adds value to a farm; a farm that has good established waterways is attractive to me"* and *"It gives you the appearance of a farm being well taken care of*" (Reimer et al. 2012).

Access to information and equipment also plays a crucial role in the decision-making process of the adoption of agricultural technologies and practices. Luther et al. (2020) suggested that farmers with access to a public source of information are more likely to adopt precision technologies such as VR-N, VR-Seeding, PSNT, aerial scouting, and yield mapping; however, they found no effect on the adoption of conservation practices. A similar result was observed by Toma et al. (2018); access to technological information also primarily influences individual behavior and intention to adopt crop technologies. Farmers who perceive "*not having access to the equipment*" as highly important in their nitrogen management adoption decision are less likely they are to use NMPs such as conducting soil tests; a similar result was obtained for the adoption of variable rate application, nutrient management plan, and application timing even though it is not significant (Ulrich-Schad et al. 2017).

Farmer belief is another important factor that influences the adoption decision of farmers. Farmers having positive attitudes toward the practices are more likely to adopt the practices; this result was observed in the case of the adoption of conservation practices (Prokopy et al. 2019). Farmers' degree of risk aversion, positively related to their subjective belief of expected crop losses due to adverse weather, was found to significantly impact their decision-making (Menapace et al. 2013). The prior experience of the practice was found to influence the farmers' adoption decision. Kalcic et al. (2014) cited a farmer's statement that reflects the positive impact of prior experience: "*Grassed waterways are real easy – yes, we do them, we'll keep doing them, even if we pay for them.*". Farmers who have previously engaged in a specific conservation practice or other similar conservation practice are more likely to adopt that conservation practice (Prokopy et al. 2019). A similar result was obtained by Barnes et al. (2019) in the context of PATs; farmer having other PATs on their farm are found to be more likely to adopt variable rate nitrogen technologies (VRNT) bundles. In addition, farmers who are less uncertain about the outcome of VRNTs are more likely to adopt them (Barnes et al. 2019).

2.5 Farmer Attitude

Understanding farmers' attitudes toward technologies regarding various factors, such as economic factors, environmental factors, farm characteristics, and characteristics of technology, is crucial for comprehending their adoption decision-making process. The widely used theoretical framework in farmer behavior research, the Theory of Planned Behavior/Reasoned Action Approach, asserts that behavior is driven by intentions (Ajzen 1991; Fishbein and Ajzen 2011). Ajzen (1991) formulated the Theory of Planned Behavior, which illustrates that the attitude toward the behavior, subjective norms (perception of the level of social pressure to practice), and perceived behavioral control (level of ease to conduct the behavior) predict the human intention to adopt a given behavior, which eventually influences the actual behavior. Daxini et al. (2018) modified this TPB approach by incorporating the concept of perceived resources, finding that attitudes (personal belief toward the positive outcome of applying fertilizer based on soil test results), subjective norms (farmer's perception of the level of social pressure to apply fertilizer) perceived behavioral control (ease farmers feel that they can conduct the behavior), and perceived resources (farmer's perception on having enough resources) all have a significant positive influence on farmer's intentions to apply fertilizer based on the soil test result. This suggests that psychological factors or farmer' attitudes toward agricultural technology play a crucial role in shaping their intention to adopt those technologies, a finding supported by other studies (Zeweld et al. 2017; Borges and Oude Lansink 2016; Lalani et al. 2016).

Additionally, the Technology Acceptance Model (TAM), first introduced by Davis (1989), proposes that acceptance of technology is determined by two key attitudinal components: perceived usefulness and perceived ease of use. Here, perceived usefulness means the degree to which a person believes that using a particular system would help them perform their job better, whereas perceived ease of use refers to the degree to which a person believes that using a particular system would be easy to operate. Research has shown that perceived usefulness (economic motivation) and perceived ease of use (ease of understanding and saving time) are stronger drivers of technology adoption among farmers (McCormack et al. 2022). Additionally, farmers' self-efficacy and collective efficacy – measuring their belief in individual ability to implement NMPs and the capacity of collective action effort in reducing nutrient loss through the Iowa Nutrient Reduction Strategy, respectively – were found to be positively associated with the adoption of practices like nitrogen rate based on the corn N rate calculator (MRTN), and response efficacy - reflecting their belief in specific management practice capacity – was found to be positively associated with the N stabilizer adoption (Gao and Arbuckle 2022). This indicates that farmers' confidence in their abilities and the efficacy of practice could significantly augment their adoption behavior.

Moreover, Reimer et al. (2012) found that farmers' perceived advantages and barriers varied not only between practices but also among different producers. The authors reported that many adopters of grassed waterways emphasized the economic and operational benefits, whereas others highlighted the environmental benefits as a key factor in their decision to adopt this practice. The study further demonstrated a correlation between favorable perceptions of practice and its adoption, suggesting that practices perceived more positively by farmers are more likely to be implemented.

Chapter 3

METHODS AND HYPOTHESES

3.1 Hypotheses

Table 1 presents the research questions, associated hypotheses, and proposed methods of analysis for this study. Research questions R_1 and R_3 were explored through descriptive statistics, which provide insights into which factors are considered most important by farmers while deciding whether to adopt NMTs and to what extent farmers perceive that barriers limit their adoption of NMTs. To answer research questions R_2 and R_4, this study has four main hypotheses (Table 1) regarding the farmers' perception of important factors and barriers and their association with the adoption of NMT (current and future likelihood), which are stated as alternative hypotheses.

Table 1: Research question, hypotheses, and methodology

S.N	Research Question	Main hypotheses to be tested	Methods
		Perceived Important factors	
A	**R1**: How important do farmers consider various factors such as economic implications, environmental concerns, and time use in the adoption decision for NMTs?		Descriptive statistics
	R2: How do the identified important factors influence the adoption of NMTs?	**H_a1**: Perceived important factors, such as economic, environmental, and time use, are significantly correlated with current adoption status of NMTs.	Factor analysis and ordered logistic regression
		H_a2: Perceived important factors, such as economic, environmental, and time use, are significantly correlated with farmers' future likelihood to adopt decision of NMTs.	Factor analysis and ordered logistic regression
		Perceived barriers	
B	**R3**: What barriers, such as resource barrier and information barrier, do farmers perceive that limit the adoption of NMTs?		Descriptive statistics

Table 1 continued

S.N	Research Question	Main hypotheses to be tested	Methods
	R4: How do the identified perceived barriers influence adoption of NMTs?	**H_a3**: Perceived barriers, such as resource barrier and information barrier, are significantly correlated with current adoption status of NMTs.	Factor analysis and ordered logistic regression
		H_a4: Perceived barriers, such as resource barrier and information barrier, are significantly correlated with farmers' future likelihood to adopt decision of NMTs.	Factor analysis and ordered logistic regression

Analysis of Hypothesis 1 and Hypothesis 2 explored how perceived important factors are correlated with current adoption and the likelihood of future adoption of NMTs, respectively. Analysis of Hypothesis 3 and Hypothesis 4 investigated the association of perceived barriers with their current adoption and the future likelihood of adoption of NMTs, respectively.

3.2 Survey

3.2.1 Data Collection

This study was approved by the University of Delaware Institutional Review Board (IRB), protocol number [1694064-1]. A quantitative survey was conducted in the Mid-Atlantic region of the United States from December 2021 through January 2022 (Davidson 2022). Eligible participants included corn, soybeans, or small grains growers who were primary decision-makers and were at least 18 years old. Partnering with the Nature Conservancy and the Mid-Atlantic 4R Alliance, we compiled a list of eligible farmers from Delaware (DE), Maryland (MD), Pennsylvania (PA), and Virginia (VA). Participant lists of Delaware and Maryland were provided by the state departments of agriculture, including all the farmers with registered nutrient management plans. The Delaware participant list excluded farms with zero acres of cropland to account for the large number of poultry growers in the state. The Virginia participants' list was provided by the Virginia Department of Agriculture and included farmers who were registered as certified private pesticide applicators. Penn State University Extension provided a list of Pennsylvania farmers, including those who were registered to receive information about agronomic crops, cover crops, pesticide education, fertilizers, and forages. For Pennsylvania and Virginia, the lists were further filtered to include only counties within the CBW. The final mailing list included 18,472 farmers, from which 2,700 farmers were randomly selected to receive the survey: 651 farmers in DE, and 683 farmers in each MD, VA, and PA state. The lower number of farmers selected in DE is because the selection of DE farmers was limited by the number of farmers on the nutrient management list.

The survey was mailed with a paper survey and cover letter, which included a web link and corresponding QR code for an online option via the Qualtrics platform. A consent form was included in the mailing. Participation was voluntary and was incentivized with a raffle drawing where participants who completed the survey were randomly selected to receive a Visa gift card: ten $250 cards, twenty $100 cards, and ninety-nine $50 cards. The raffle drawing and corresponding amounts were suggested by the partner organizations and university extension personnel. A total of 362 responses were received (13.4% response rate). However, several respondents were not eligible (e.g., no longer farming). Thus, the sample includes 204 usable responses, a response rate of 7.6% (84 from Delaware, 56 from Maryland, 40 from Pennsylvania, and 24 from Virginia). Johansson, Effland and Coble (2017) reported a decline in the response rate of the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) surveys from 80-85% in the early 1990s to around 60% in 2016.

3.2.2 Survey Overview

This study is part of a larger survey on 4R BMPs and thus includes questions beyond the use of NMTs. The survey data that we used for this study is from Davidson (2022). The full survey can be referenced in Appendix B. The survey started with an eligibility question asking if a respondent was a primary decision-maker on their farm and was extended with questions about current farming practices. The survey included questions about the current adoption and future likelihood of adopting the eight 4R nutrient management practices[2]: Written nutrient management plan, Grid soil sampling, Liquid manure injection, Injection of incorporation of commercial nitrogen fertilizer, Cover crop, Split nitrogen (N) application, Variable Rate application (VRT), and NMTs. The survey also included in-depth perception questions about three practices of interest: NMTs, split N application, and VRT. Respondents were asked to report their perceptions of changes in different factors after using the practices, which were reflected by eight statements, and were also asked to rate their importance in their decision-making (Table 2). To elicit perceived barriers, farmers were asked to rate the extent to which thirteen potential barriers limit the use of each practice (Table 2). The design of these statements was informed by focus group discussions and semi-structured interviews with farmers, as well as consultation with partners at the Mid-Atlantic 4R Alliance and The Nature Conservancy. At last, the survey included questions regarding their perception of nutrient management, preferred methods for receiving information, enrollment in environmental or cost-share programs, and sociodemographic details.

3.2.3 Key Survey Question

To understand the extent of importance that the given factors have in farmers' decisions to implement NMTs and their association with the adoption of these tools, we used farmers' responses to the 'perceived important factors' question in the survey

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[2] This study is part of a larger project investigating the adoption of a suite of 4R NMPs. The current study focuses on questions in the survey specific to NMT.

(Table 2). There were eight statements/variables measuring the importance of different factors in the farmer's decision to adopt NMTs, on a 3-point Likert scale with the following possible responses: not important (1), moderately important (2), and very important (3), as shown in Table 2. To understand barriers that are limiting farmers from adopting NMTs and their relationship with the adoption of NMTs, we analyzed farmers' responses to the survey question regarding perceived barriers (Table 2). Respondents were given 13 potential barriers and were asked to present the extent of a limit that farmers think potential barriers have on the use of these tools through a 5-point Likert scale question with possible responses ranging from 1 (Not at all) to 5 (very much). In addition, to clarify the result, we used the impact of NMTs' question to understand farmers' perception of the impact of using NMT on the various factors in which we asked farmers about their perception of the impact of NMTs (Table 2).

Table 2: Key survey question for analysis

Perceived Important Factors
How important each factor was in your decision to implement/not implement in-season nitrogen modeling tools? (Not important, Moderately important, Very important) 1. Crop yield 2. Input costs 3. Profitability 4. Time spent in the field 5. Time spent on farm management decisions 6. Soil health and productivity on my farm 7. Environmental quality in my community 8. My compliance with government regulations

Table 2 continued

Perceived Impact of NMTs	
Indicate if you think using in-season nitrogen modeling tools will cause an increase, no change or decrease in each of the following factors (Decrease, No change, or Increase): The impact of the practice on: 1. Crop yield 2. Input costs 3. Profitability 4. Time spent in the field 5. Time spent on farm management decisions 6. Soil health and productivity on my farm 7. Environmental quality in my community ***8.*** My compliance with government regulations	
Perceived Barriers	
How much do you think each of the following factors limit farmers' use of in season nitrogen modeling tools? [1(Not at all) – 5 (Very much)] 1. Finding information about the practice 2. Having enough time to learn about the practice 3. Getting a return on investment from the practice 4. Cost of the practice 5. Difficulty implementing the practice because of timing and weather 6. Having the right equipment to implement the practice 7. Having the right technology to implement the practice 8. Finding services related to the practice (e.g. crop advisor, custom applicator, soil testing) 9. Believing the practice is better suited for larger operations. 10. Difficulty implementing the practice on leased land. 11. Having a previous negative experience trying the practice. 12. Preferring to use practices they are more familiar with. 13. Believing that new technologies are too difficult to use.	
Adoption of NMTs	
What is your current experience with the practice?	• I currently use this practice on at least half of my acres. • I currently use this practice on less than half of my acres. • I have used this practice in the past but no longer use it. • I have never used this practice.

Table 2 continued

Adoption of NMTs	
How likely are you to start using or expand acreage of the practice in the next 3 years?	• Not likely • Somewhat likely • Very likely • N/A I already use this practice on at least half of my acres

3.3 Factor Analysis

We applied exploratory factor analysis (EFA) to the perceived important factors and perceived barriers statements in Table 2, respectively, to characterize the latent important factors and latent perceived barriers in NMT adoption. EFA simplifies complex data sets by regrouping variables into a limited set of clusters and identifying underlying factors that explain the observed correlation among variables (Yong and Pearce 2013; Comrey and Lee 2013; DeCoster 1998). According to the rule of thumb, the ratio of respondents to the number of items used for analysis should be at least 10:1 (Mooi, Sarstedt and Mooi-Reci 2018). This criterion is met by this data because the ratio is at least 45:2 (180:8, considering the smallest number of respondents among eight statements regarding importance) for important factors and at least 184:13 (considering the smallest number of respondents among 13 barrier statements) for barriers. Before conducting a factor analysis, we checked whether the given data is appropriate for conducting EFA or not by assessing multicollinearity, the identity matrix, and sampling adequacy (Watkins 2021). To evaluate the multicollinearity problem, we assessed the value of the determinant of the correlation matrix of the data; the determinant of the correlation matrix will equal one only when all correlations are equal to zero, otherwise, it will be less than 1 (Stata 2024b). The multicollinearity problem is likely not a concern if the determinant of the correlation matrix is greater than 0.00001 (Field et al. 2012). To determine if the correlation matrix is an identity matrix (where all the diagonal element are 1 and off-diagonal element are 0), Bartlett (1950) test of sphericity was used, which tests the null hypothesis that the correlation matrix is an identity matrix; if it is an identity matrix, the variables are not intercorrelated and thus not ideal for factor analysis. The Kaiser-Meyer-Olkin (KMO) statistic, a measure of sampling adequacy, indicates whether the variables share enough common variance to be considered suitable for factor analysis (Kaiser 1974; Mooi et al. 2018). Kaiser (1974) recommended that KMO values below 0.5 are unacceptable, and some literature recommends acceptable values greater than 0.6 (Tabachnick and Fidell 2013; Mvududu and Sink 2013). We run "*factortest*" in Stata, which gives the determinant of the correlation matrix, Bartlett sphericity tests, and Kaiser-Meyer-Olkin test (Watkins 2021).

The principal Factor (PF) extraction method was used in Stata to extract the factors from the given Likert scale statements instead of other extraction methods because the Principal Component Factor (PCF) focuses on reducing observed variables into linear components that maximize variance retention without distinguishing between common and unique variance, making the components not latent variables (Watkins 2021). Similarly, another method, the Maximum Likelihood (ML) method, assumes multivariate normal observations (Stata 2024a), which does not hold in our data. Moreover, Acock (2016) recommended to use PF instead of PCF if the goal is to identify distinct and interpretable two or more latent factors rather than maximizing the total variance explained by a single factor.

For determining the number of factors to retain, we used the scree plot and parallel analysis as recommended by Watkins (2021). The scree plot generates a graph of the eigenvalues from a covariance or correlation matrix to determine the number of factors by identifying an “elbow” in the plot where the eigenvalue significantly drops, and the number of factors before this drop is retained since they explain most of the variance in the dataset (Cattell 1966; Fabrigar et al. 1999; Mooi et al. 2018). Parallel Analysis (PA) is another method that compares the eigenvalues from the random data with those from the given data and suggests retaining the number of factors as long as the real eigenvalues are greater than the corresponding random eigenvalues (Watkins 2021).

This gave us complex factors that overlap with many variables, making them difficult to interpret. Therefore, we used factor rotation, which rotates the factor matrix into a form that is mathematically equivalent but represents more useful and interpretable factor constructs for scientific purposes than the unrotated factor constructs, without altering the underlying data structure (Comrey and Lee 2013; Tabachnick and Fidell 2013; Watkins 2021). We used oblique rotation over orthogonal rotation because, unlike orthogonal rotation, oblique rotation factors allow the factors to be correlated. In social science and psychology, factors are often correlated to some extent (Fabrigar et al. 1999; Watkins 2021; Schmitt and Sass 2011). Therefore, we used oblique rotation to obtain a more accurate and realistic representation of factor relationships. Promax and oblimin rotation methods are commonly used oblique rotation methods (Mooi et al. 2018), among which we chose the promax rotation method since different rotation methods within the orthogonal and oblique rotation categories are likely to produce similar results (Bandalos and Finney 2018; Watkins 2021). This factor rotation led to factors being in a more interpretable form.

A factor loading measures how much a variable contributes to a factor; high factor loadings indicate that the variable strongly defines the factor (Yong and Pearce 2013). We set the factor loading cut-off point at 0.32, as factor loadings above 0.32 are considered strong enough to be meaningful from both practical (10% variance) and statistical ($p < 0.05$) perspectives where statistical significance is calculated with the formula $\frac{3.92}{\sqrt{N-2}}$ for 5% level of significance and $\frac{5.152}{\sqrt{N-2}}$ for 1% level of significance (Watkins 2021; Norman and Streiner 2014). Further, a meta-analysis found 0.32 as the average factor loading across the factor analysis studies (Peterson 2000). Factor scores, the linear combination of the items, were then predicted and used for subsequent analysis (Mooi et al. 2018).

3.4 Econometric Model

The relationship between farmers' perceived important factors and barriers with the current and future likelihood of adoption of NMTs was elicited using the survey questions described above in Table 2 as the dependent variable. Farmers were asked to report their current experience with the NMTs. In addition, they were asked about their likelihood of starting using or expanding acreage for the NMTs in the next 3 years, except for those who are using these tools on at least half of their acres (Table 2).

To evaluate the association between perceived important factors and perceived barriers with the level of adoption of NMTs, we used ordered logistic regression analysis (Equations 1-3). This model is appropriate because our dependent variables – current adoption status and future likelihood of adopting NMTs – are ordinal and categorical, classified in terms of the level of adoption. The ordered logit model exploits the ordinal nature of the dependent variable (Greene 2008) and employs a proportional odds cumulative logit approach to analyze data (Gao and Arbuckle 2022). Both ordinal dependent variables had three different categories. The current adoption category of NMTs takes the value of 0 if the respondent has never used these tools; 1 if currently using on less than half of total acres; and 2 if currently using on at least half of total acres. Here, we drop the "used in the past but not now" response and assume the dependent variable is ordinal in terms of acreage expansion. Likewise, another dependent variable, the future likelihood of adopting NMTs, takes the value 0 if the respondent is not likely, 1 if somewhat likely, and 2 if very likely to adopt or expand the use of these tools in the next three years. Here, we drop the "already use NMTs on at least half of my acres" response. Since both continuous latent dependent variables (Y^*) could take three different values, they have two threshold points (k_1 and k_2), respectively, where,

$Y_i = 0$ if $Y^*_i \leq k_1$

$Y_i = 1$ if $k_1 \leq Y^*_i \leq k_2$

$Y_i = 2$ if $Y^*_i \geq k_2$ (1)

Equation 2 shows the probability of respondent i being in the three different categories ($Y_i = j$) classified in terms of either the current level of adoption status or future likelihood of adopting the tools, depending on the model.

$P_{i,j} = \Pr(Y_i = 0) = \frac{1}{1+ e^{-k_1+X_i\beta}}$

$P_{i,j} = \Pr(Y_i = 1) = \frac{1}{1+ e^{-k_2+X_i\beta}} - \frac{1}{1+ e^{-k_1+X_i\beta}}$

$$P_{i,j} = \Pr(Y_i = 2) = \frac{1}{1+ e^{-k_2+X_i\beta}}, \tag{2}$$

Where X_i is a vector of independent variables and β is the corresponding estimated parameter vector (coefficients). $P_{i,j}$ indicated the probability of a farmer i adopting a percentage of agricultural land within category j conditioned on the independent variables for each farmer. k_1 and k_2 are the threshold points in the unmeasured continuous latent variable that divide the three categories of the ordinal dependent variable. The ordered logit model is represented as:

$$Y^* = \beta_1 PerceivedImportantFactor + \beta_2 PerceivedBarrier + \propto X + \varepsilon \tag{3}$$

Here, *PerceivedImportantFactor* and *PerceivedBarrier* are vectors of continuous variables that are obtained through the exploratory factor analysis described in section 3.3. *X* represents the vector of other covariates, including other NMP, demographic variables (total cropland, age, education level), and farm characteristics (farm income, enrollment in environmental or cost-share programs, and location of farmland). The binary variable otherNMP is equal to 1 if the respondent is currently using at least one of other nutrient management practices (grid/zone sampling, liquid manure injection, commercial nitrogen fertilizer, cover crops, split nitrogen application, variable rate nitrogen application) and 0 otherwise, and was obtained by combining the responses, where "never used" and "used in the past but not now" were grouped into the category "currently not using" and the responses "used on less than half of acres" and "used on at least half of acres" were grouped into the category "currently using" (Table 6). TotalCropland and Age are the continuous variables that represent the total acres of cropland per 100 acres and the age of primary decision-makers, respectively (Table 6). The binary variable LandLease is equal to 1 if the respondent's more than half proportion of total cropland is leased and 0 otherwise (Table 6). The binary variable CollegeDegree is equal to 1 if the respondent has at least some college degree as the highest level of education and 0 otherwise (Table 6). FarmIncome is a binary variable that is equal to 1 if the respondents earn more than 50% of their household's gross income through farming, as described in Table 6. CRP, CREP, CSP, EQIP, and ACP are binary variables that are equal to 1 if an individual is enrolled in the Conservation Reserve Program, Conservation Reserve Enhancement Program, Conservation Stewardship Program, Environmental Quality Incentive Program, and State Agricultural Cost-Share Program, respectively (Table 6). State is a categorical dummy variable that represents the location of most of the cropland of a farmer – Delaware (DE), Maryland (MD), Pennsylvania (PA), and Virginia(VA) – where we consider "Delaware" as a reference category (Table 6).

To check the robustness of the model, we included interactions of total cropland size with perceived important factors and perceived barriers. These interaction variables evaluate whether the influence of perceived important factors and perceived barriers on adoption decisions varies with farm size. In this case, the ordered logit model is represented as:

$$Y^* = \beta_1 PerceivedImportantFactor + \beta_2 PerceivedBarrier + \beta_3 TotalCropland \times PerceivedImportantFactor + \beta_4 TotalCropland \times PerceivedBarrier + \propto X + \varepsilon \quad (4)$$

Here, *TotalCropland×PerceivedImportantfactor* and *TotalCropland×PerceivedBarrier* are the vectors of continuous variables that represent the interaction between the "*TotalCropland*" and "*PerceivedImportantFactor*" and "*PerceivedBarrier*" variables, respectively. Other covariates remain the same as in equation 3.

Equations 3 and 4 were analyzed using ordered logistic regression with the *"ologit"* command in statistical software Stata. Furthermore, we compared the two model specifications using the Likelihood ratio test and Akaike and Bayesian Information Criterion (AIC and BIC).

3.5 Sensitivity Analysis–Missing Data Imputation

There was a total of 5.23% missing data across the 15 variables (other NMPs, demographic, and farm characteristics) in the dataset, as shown in the table presenting the count of missing observations for each variable in Appendix A–Table A1. The result of the analysis could be biased if the missing data proportion is greater than 10% (Bennett 2001) and Schafer (1999) stated that a missing proportion of 5% or less is inconsequential. To check the robustness of the model and test sensitivity to missing values, we applied imputation to handle missing data and subsequently analyzed the dataset. There are three types of missing data based on the possible reason behind the missingness: missing completely at random (MCAR), missing at random (MAR), and missing not at random (MNAR). Data are said to be MCAR if missing data are independent of any observed or unobserved variables. MAR assumes that the missingness is related to the other observed variables in the dataset, but not to the specific variable that has missing data. MNAR assumes that missingness is related to the unobserved value of the missing variables themselves, which is very challenging to identify (Bennett 2001; Zhong, Hu and Penn 2018). There are several methods for dealing with the missing value. One of them is deletion, which excludes the observation with missing data, and it is found to be effective if the MCAR applies to missing data patterns (Zhong et al. 2018). Stata automatically operates this imputation technique in regression analysis. Another method is mean imputation, which replaces missing values with the observed mean, and it is reasonable to use if the MCAR applies (Zhong et al. 2018). We couldn't use this method in our analysis since we have categorical variables, which makes mean imputation not appropriate. Multiple Imputation (MI) is a widely used and reliable method for handling missing data. It imputes each missing value with *m* plausible values to create *m* complete datasets, which are analyzed separately, and the results are averaged and pooled to obtain a final estimate (Little and Rubin 1987). It is found to be an appropriate method for data MAR assumptions (Zhu 2014; Zhong et al. 2018). Even if the data satisfied MCAR assumptions, imputation based on the MAR assumption will not bias the analysis (Zhong et al. 2018). MI imputes categorical and continuous variables simultaneously and can operate imputation on the model like discrete, continuous, categorical, or mixed (Zhong et al. 2018). We employed the deletion method and multiple imputation method to assess the robustness of the results drawn from each approach.

3.6 Qualitative Methods: Semi-structured Interview

3.6.1 Qualitative Data Collection

To bring more clarification on farmers' perception of economic and time investment factors, we conducted supplementary qualitative analysis. We recruited farmers during the annual Delaware Agriculture Week event and Nitrogen Support Tool meeting in Pennsylvania from January 2025 through February 2025, through a pre-interview survey. During Delaware Agriculture Week, the survey was distributed to farmers attending the Grain Marketing Meeting. The survey included demographic questions, questions about nitrogen application decisions and NMTs, and questions about their preference to participate in follow-up interviews. Through a pre-interview survey, 20 interviewees, including both adopters and non-adopters of NMTs, were selected who were corn farmers and were from Delaware and Pennsylvania. We then conducted semi-structured interviews via phone calls as per the farmers' convenience from February 2025 through March 2025. Each interview lasted approximately 20 to 30 minutes and was conducted by at least two interviewers. Participation was voluntary, and farmer received a $50 Amazon or Walmart gift card as a token of appreciation for their time after completion of the interview. The interviews were part of a broader study focusing on understanding barriers to farmer adoption of NMTs. For the current analysis, we included the two key interview questions and follow-up questions related to economics and time investment (Table 3).

Table 3: Key interview questions

Interview Questions	
Economic importance factor	1. Is it most important for you to increase yield and profitability or to reduce/keep input costs low? **Follow-up question:** • NMTs increase input cost because of the per acre fee. What factors would make that cost increase worthwhile for you? **Prompt:** yield, profitability, soil health, productivity, reduced nitrogen cost
Time investment importance factor	1. We have a question about some of our previous research findings. Farmers say time is important, but also think NMTs would increase their time. Why do you think those farmers are saying they are more likely to adopt the tool? **Follow-up question:** • Do you think these tools are more time-effective compared to other nutrient management practices? • Do you think a practice is more valuable if it requires more time to implement? • Are you willing to invest more time to adopt new tools?

3.6.2 Qualitative Data Analysis

Each interview was audio recorded and later transcribed for analysis. The quantitative response (ranking and binary) and qualitative responses were analyzed using descriptive statistics and thematic analysis, respectively. Specifically, thematic analysis underscored significant statements focusing on repeated or common themes or quotes. We then generated a Word Cloud to show the most common themes.

Chapter 4

RESULTS

4.1 Descriptive Statistics

The following summary statistics highlight the respondents' current adoption status of NMTs, their future adoption intentions, their perception of the importance of various factors influencing adoption, and the perceived barriers limiting NMT adoption. The summary statistics of respondent socio-economic characteristics are also presented in this section. The sample size varies due to missing values in some questions.

Table 4 shows the farmers' current adoption status of NMTs. From survey respondents, 65.13% reported that they have never used these tools, 4.10% reported they have used them in the past but are not currently using them, 10.77% reported they are currently using these practices in less than half of their total acres whereas only 20% of farmers reported that they are currently using this practice on at least half of their total acres. A similar pattern of adoption status was observed in all four states – Delaware, Maryland, Pennsylvania, and Virginia.

Table 4: Summary statistics on the current adoption status of NMT

	N	At least half of the total acre	Never used	Less than half of total farm	Used in the past but not now
Delaware	78	26.92%	61.54%	7.69%	3.85%
Maryland	55	12.73%	74.55%	12.73%	0.00%
Pennsylvanian	39	12.82%	64.10%	15.38%	7.69%
Virginia	23	26.09%	56.52%	8.70%	8.70%
Total	195	20%	65.13%	10.77%	4.10%

Table 5 presents the farmer's likelihood to start using or expanding the NMTs in the next three years among those who were not currently using NMTs on at least half of their total farm acres. Overall, 58.50% of farmers indicated that they are not likely to use or expand the use of NMTs, while 28.57% reported being somewhat likely, and only 12.93% expressed a high likelihood of adopting NMT in the future. A similar response was observed in all four states, respectively. Among farmers who reported they have never used this tool, 65.55% stated they are not likely to adopt NMT, 26.89% are somewhat likely, and only 7.56% are very likely to use this tool in the next three years (Appendix A–Table A2).

Table 5: Summary statistics on the likelihood to start using or expanding the NMT

	N	Not likely	Somewhat likely	Very likely
Delaware	53	54.72%	35.85%	9.43%
Maryland	46	58.70%	30.43%	10.87%
Pennsylvanian	33	63.64%	18.18%	18.18%
Virginia	15	60.00%	20.00%	20.00%
Total	147	58.50%	28.57%	12.93%

Table 6 shows the summary statistics of farmer' socio-demographic characteristics and their perception of the importance of different factors and potential barriers. The respondent's average total cropland size was 642.21 acres, larger than the representative average total cropland size of four states, according to USDA (2017) (Table 7). On average, 39% of farmers had leased more than half of their total crop area. The respondent's average age was 60 years, which is closer to the average age of farmers in four regions, which means the sample is representative of farmers in four states based on age (USDA 2017) (Table 6). Considering farmers' highest level of education, 53% of farmers had at least a college degree as the highest level of education. Regarding the proportion of a household's gross income earned through farms, 58% of farmers earned more than 50% of their gross income through farming. 94% of farmers had adopted at least one other 4R NMP (grid/zone sampling, liquid manure injection, commercial nitrogen fertilizer, cover crops, split nitrogen application, variable rate nitrogen application).

Table 6: Summary and descriptive statistics of independent variables

Variable	Description	N	Mean	Std. Dev.	Min	Max
Farm Characteristics						
TotalCropland	Total cropland size in hundred acres	201	6.42	9.54	0.04	57.25
LandLease	=1 if Higher than 50% of total cropland	201	0.39	0.49	0	1
Farmer Characteristics						
Age	Age of primary decision maker in year	184	60.39	15.29	21	89
Education	**Highest level of education**					
CollegeDegree	= 1 if have at least college degree	193	0.53	0.50	0	1
Farm income	**Level of income earned through farming**					
FarmIncome	=1 if farm income more than 50%	192	0.58	0.50	0	1
Farmers' perception on the importance of variables in their decision to implement/not implement NMT						
Yield	Crop yields	182	2.45	0.71	1	3
Cost	Input costs	183	2.51	0.64	1	3
Profit	profitability	182	2.65	0.58	1	3
TimeInField	Time spent in the field	182	2.12	0.73	1	3
TimeInFarmManagement	Time spent on farm management decision	180	2.10	0.68	1	3
SoilHealthAndProductivity	Soil health and productivity on my farm	180	2.51	0.67	1	3
EnvironmentalQuality	Environmental quality in my community	181	2.33	0.72	1	3
ComplianceWithGovernment	My compliance with government regulations	181	2.19	0.75	1	3

Table 6 continued

Variable	Description	N	Mean	Std. Dev.	Min	Max
Farmers' perception on the barriers to the use of NMT						
Information	Finding information about the practice	189	3.28	1.13	1	5
EnoughTime	Having enough time to learn about practice	190	3.50	1.12	1	5
ReturnInvestment	Getting return on investment from practice	191	4.07	0.95	1	5
CostLimitation	Cost of the practice	190	4.28	0.93	1	5
TimeAndWeather	Difficult to implement due to time & weather	191	3.98	1.02	1	5
RightEquipment	Having right equipment to implement	191	4.33	0.95	1	5
RightTechnology	Having right technology to implement	190	4.25	0.99	1	5
Service	Finding services related to practice	190	3.62	1.15	1	5
LargeOperation	Believing practice is suited for large operation	191	3.67	1.31	1	5
DifficultLeased	Difficulty to implement on leased land	186	3.07	1.41	1	5
NegativeExperience	Having previous negative experience of using	184	2.59	1.29	1	5
PreferFamiliar	Preferring to use familiar practice	190	3.69	1.13	1	5
NewTechnology	Believing new technology is difficult to use	190	3.26	1.25	1	5
Adoption of other NMPs						
OtherNMP	= 1 if adopted at least one of similar NMP (grid/zone sampling, liquid manure injection, commercial nitrogen fertilizer, cover crops, split nitrogen application, variable rate nitrogen application)	198	0.94	0.24	0	1

Table 6 continued

Variable	Description	N	Mean	Std. Dev.	Min	Max
Enrollment in any environmental or cost-share programs						
CRP	=1 if enrolled in Conservation Reserve Program	183	0.21	0.41	0	1
CREP	=1 if enrolled in Conservation Reserve Enhancement Program	183	0.16	0.37	0	1
CSP	=1 if enrolled in Conservation Stewardship Program	183	0.15	0.36	0	1
EQIP	=1 if enrolled in Environmental Quality Incentives Program	183	0.32	0.47	0	1
ACP	=1 if enrolled in State Agricultural Cost-Share Program	183	0.39	0.49	0	1
Most of the croplands' location						
DE	= 1 if state is Delaware	204	0.41	0.49	0	1
MD	= 1 if state in Maryland	204	0.28	0.45	0	1
PA	= 1 if state is Pennsylvanian	204	0.20	0.40	0	1
VA	= 1 if state is Virginia	204	0.12	0.32	0	1

Table 7: Comparison between sample population and population statistics of the region for representativeness of data

	Respondent Average	**Population statistics according to USDA**			
		Delaware	**Maryland**	**Pennsylvania**	**Virginia**
Average cropland (acres)	642.21	279.83	154.52	104.67	96.10
Average age of primary producer (years)	60	59.70	59.50	57.10	60.70

(USDA 2017)

Figure 1 shows the farmers' perception of the importance of different factors in the decision to adopt NMT. The result suggests profitability was the most important factor in farmers' decisions to adopt NMT, as 70% of farmers reported it as very important, and 24% reported it as moderately important. Also, the majority of farmers revealed other factors, such as soil health and productivity, input cost, and crop yields, as very important factors in their decision to adopt NMT. On the other hand, around half the proportion of farmers reported time spent in the field and farm management decisions as moderately important, and a higher proportion of farmers (approximately 20%), compared to other factors, indicated time requirement as not important.

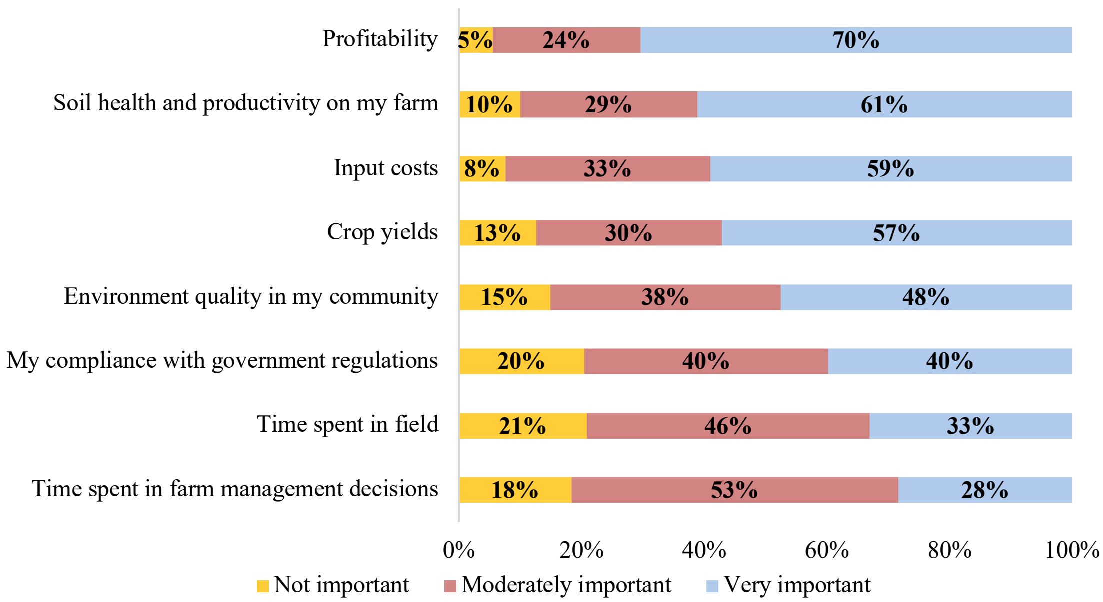

Figure 1: Level of importance of factors in the decision to adopt NMT

Figure 2 shows farmers' perceived barriers to the adoption of NMT. 84% of farmers believed that having the right equipment is a barrier that highly limits the adoption of NMT. Likewise, other perceived barriers that highly limit the adoption of NMT were the cost of the practice (82%), having the right technology (80%), return on investment (74%), and timing and weather constraints (70%). 62% of farmers believed that NMT is better suited for larger operations, so small farm size was a barrier, and 41% reported difficulty implementing NMT on leased land constraints limited the adoption of these tools. 60% of farmers believed that preference toward familiar technology could be a highly limiting barrier, however, only 44% of farmers perceived that new technologies are too difficult to implement. 54% of farmers perceived that time to learn the use of NMT limits the adoption of these tools. Likewise, 57% of farmers stated that finding services related to the practice (e.g., crop advisor or custom applicator), and 43% of farmers believed that finding information about NMT limits the use of NMT. Only 24% of farmers perceived negative past experience with the use of NMT as a highly limiting barrier to adoption, which could be because the majority of respondents had never used these tools and had no experience with these tools to think of this barrier as a highly limiting.

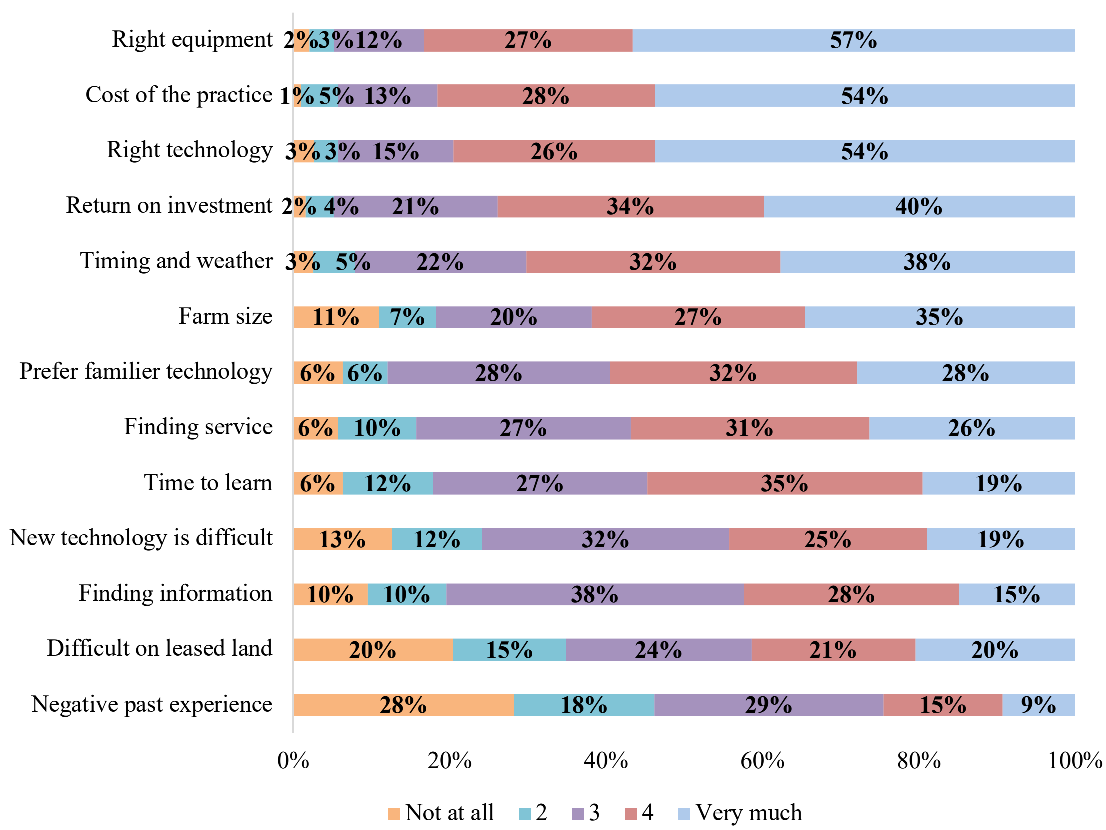

Figure 2: Level of limitation of potential barriers in the use of NMT

Figure 3 shows the belief of farmers (who have never used NMT) about the impact of NMT (decrease, no change, or increase on various factors). The majority of farmers believed the use of NMT increases crop yield, profitability, and soil health and productivity, whereas it reduces or has no change in input cost, which shows the farmers' belief in the economic benefit of NMT. However, the majority of farmers had a perception that the use of NMT increases time spent in the field and time spent on farm management decisions. Similarly, the majority of farmers believed that the use of NMT has no change in the environmental quality and compliance with government regulations.

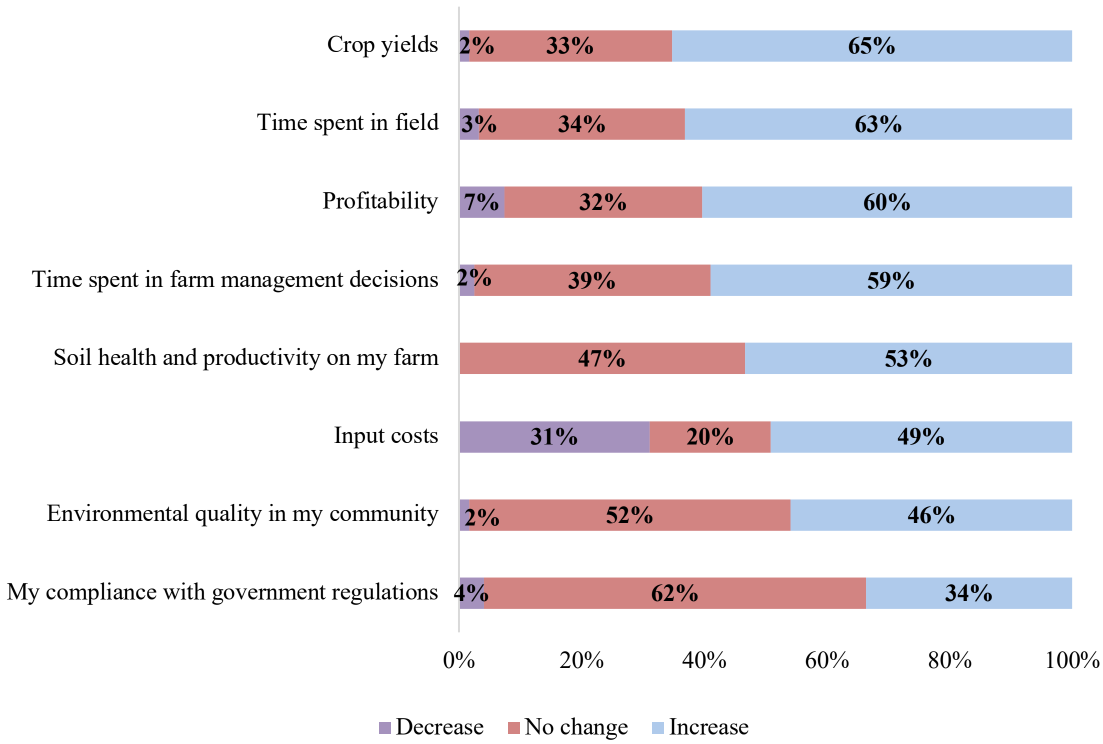

Figure 3: Farmer perception of the impact of NMT on different factors (never used categories)

Figure 4 shows the perception of farmers (who currently use NMT) about the impact of NMTs (decrease, no change, or increase on various factors). Here, respondents who reported currently use of this tool on "less than half of total acres" or "at least half of their acres" were considered as "currently using NMTs". A similar response as in the never-used category was observed regarding the economic benefit of the tool; the majority of farmers reported that they believe the use of NMT increases yield, profitability, and soil health and productivity, and reduces or has no change in input cost. However, the majority of farmers believed that the use of NMT increases time spent on farm management decisions, whereas it decreases or has no change in time spent in the field. Also, the majority of the farmer had a perception that the use of NMT increases environmental quality and their compliance with the government. The result illustrates that the perception of farmers who had never used NMT could be different than the perception of farmers who were currently using NMT.

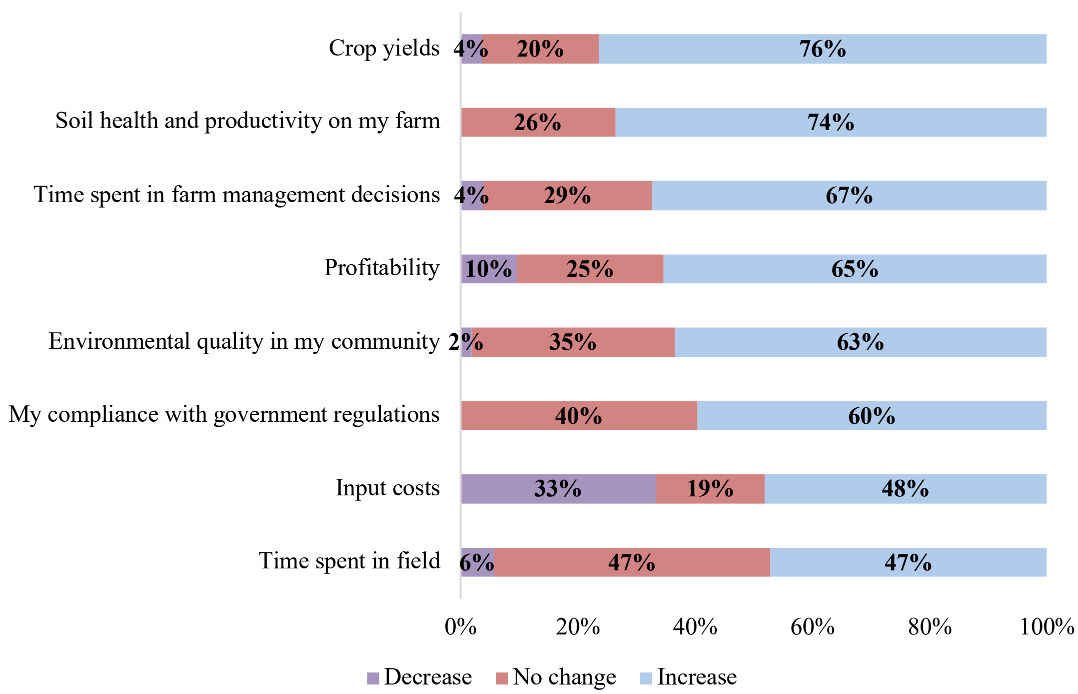

Figure 4: Farmer perception of the impact of NMT on factors (currently using categories)

A more detailed breakdown of the farmer's perception of the importance of each factor and the impact of NMT on each factor by adoption status can be found in Appendix A (Tables A3-A26).

4.2 Factor Analysis Results

Before conducting factor analysis, we evaluated the data using "*factortest*" in Stata, which gave the determinant of the correlation matrix, Bartlett test of sphericity, and the Kaiser-Meyer-Olkin test. Results of the factor test are presented in Table 8.

Table 8: Results and interpretation of factor test

Test	Result	Interpretation
Perceived Important factor		
Determinant of correlation matrix	0.017	The determinant of correlation matrix is greater than 0.00001 so there is not multicollinearity problem.
Bartlett test of sphericity	p-value = 0.000	Reject the null hypothesis that the correlation matrix is an identity matrix and states that variables are intercorrelated which is required for factor analysis.
KMO measure of sampling adequacy	0.807	The value falls on meritorious labels given by (Kaiser 1974) and is greater than 0.6 which is acceptable value
Perceived barriers		
Determinant of correlation matrix	0.008	The determinant of correlation matrix is greater than 0.00001 so there is not a multicollinearity problem.
Bartlett test of sphericity	p-value = 0.000	Reject the null hypothesis that the correlation matrix is an identity matrix and states that variables are intercorrelated which is required for factor analysis.
KMO measure of sampling adequacy	0.734	The value falls on middling labels given by (Kaiser 1974) and is greater than 0.6 which is acceptable value.

The information in Table 8 confirms that the data does not have a multicollinearity problem, variables are sufficiently intercorrelated with each other, and the KMO value is above the acceptable value. Since the data met all the criteria, the data are suitable for factor analysis. We conducted a factor analysis using "*factor*" in Stata.

Results of the factor analysis are presented in Table 9-12 and Figures 5-8.

Table 9: Factor analysis of perceived important factors

Factor	Eigenvalue	Difference	Proportion	Cumulative
Factor1	3.668	2.901	0.826	0.826
Factor2	0.768	0.195	0.173	0.999
Factor3	0.572	0.568	0.129	1.128
Factor4	0.005	0.082	0.001	1.129
Factor5	-0.077	0.051	-0.017	1.111
Factor6	-0.128	0.047	-0.029	1.083
Factor7	-0.175	0.017	-0.039	1.043
Factor8	-0.191		-0.043	1.000

Table 10: Factor analysis of perceived barriers

Factor	Eigenvalue	Difference	Proportion	Cumulative
Factor1	3.695	2.545	0.644	0.644
Factor2	1.150	0.382	0.200	0.844
Factor3	0.767	0.203	0.134	0.978
Factor4	0.564	0.267	0.098	1.076
Factor5	0.298	0.057	0.052	1.128
Factor6	0.241	0.179	0.042	1.170
Factor7	0.062	0.101	0.011	1.181
Factor8	-0.039	0.086	-0.007	1.174
Factor9	-0.125	0.041	-0.022	1.152
Factor10	-0.167	0.021	-0.029	1.123
Factor11	-0.187	0.042	-0.033	1.091
Factor12	-0.229	0.063	-0.040	1.051
Factor13	-0.292		-0.051	1.000

The eigenvalues in Table 9 and Table 10 show the amount of variance explained by each factor, and proportion represents the relative weight of each factor in the total variance. The results show a small number of factors (one from important variables and two from barriers) with an eigenvalue of more than one (Table 9 and Table 10). This could be because we used the PF method for factor analysis. In PCF analysis, all variances are explained, and the sum of eigenvalues for all possible components is the number of items; therefore, a component with an eigenvalue less than 1 is not useful as it explains less variance than a single item, whereas, in PF analysis, the sum of eigenvalues is less than the number of items, making the eigenvalue interpretation complex (Acock 2016). Therefore, for selecting the number of factors to retain, we used scree plots and parallel analysis rather than eigenvalues alone. Scree plots and parallel analysis are presented in Figures 5 through Figure 8.

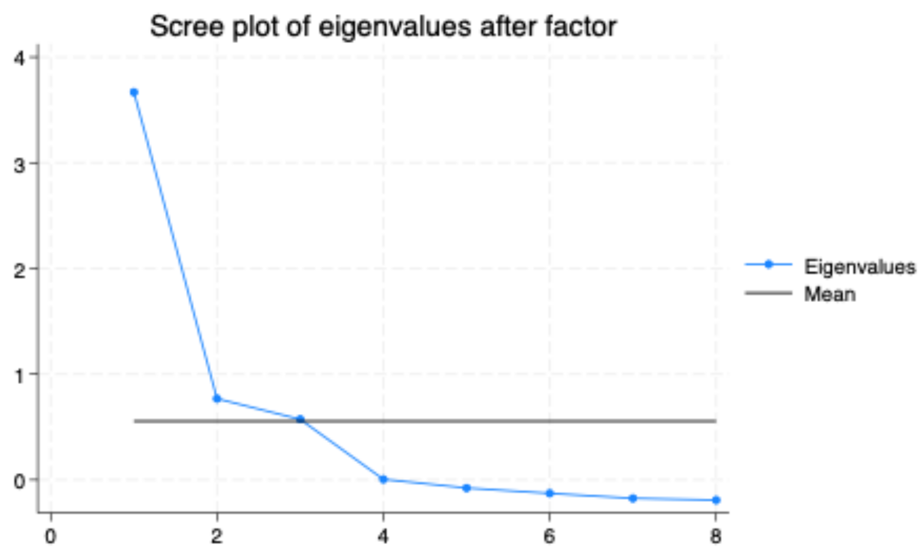

Figure 5: Scree plot of perceived important factors

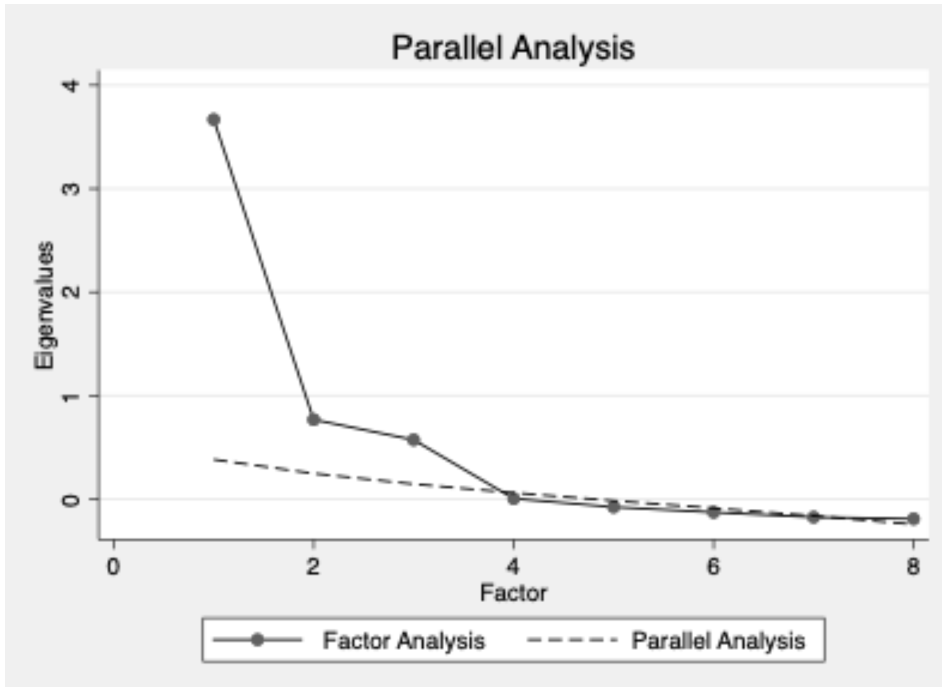

Figure 6: Parallel analysis of perceived important factors

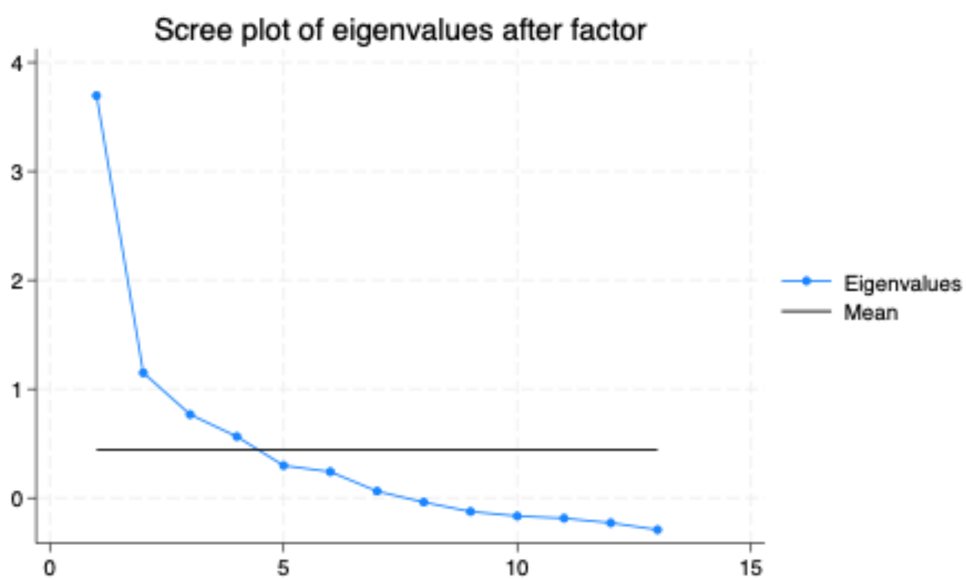

Figure 7: Scree plot of perceived barriers

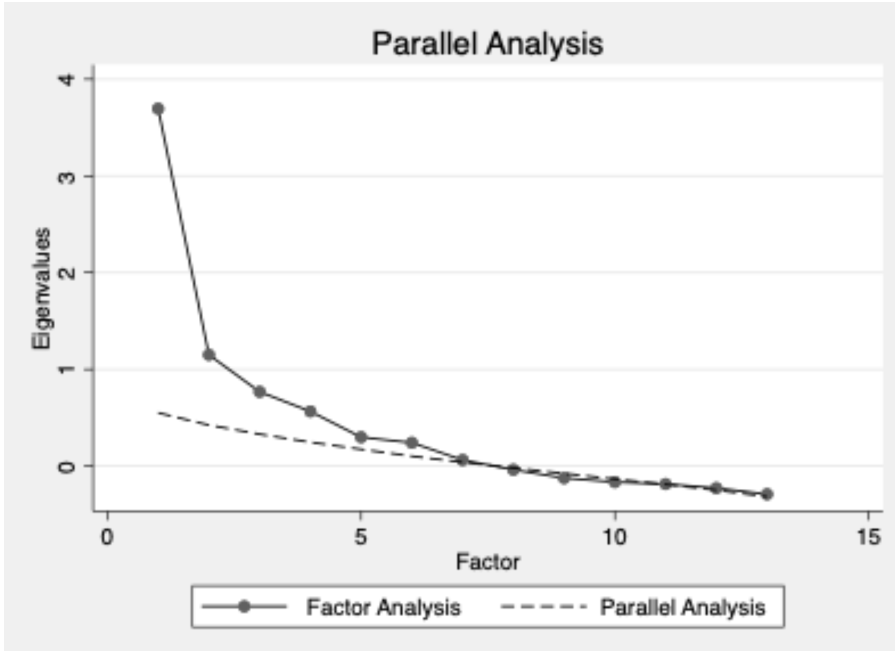

Figure 8: Parallel analysis of perceived barriers

For perceived important factors, both scree plots and parallel analysis suggest three factors (Figure 5 and Figure 6). In the scree plot, the graph shows a significant drop at the fourth factor, after which it flattens, indicating that three factors should be retained. (Figure 5) Similarly, in the parallel analysis, only for the first three factors, the eigenvalue of real data (factor analysis) is larger than the eigenvalue from the random data (parallel analysis) (Figure 6), further supporting the retention of three factors. Therefore, we retained three factors for perceived important factors.

For the perceived barriers, the scree plot suggests four factors, while parallel analysis suggests seven factors (Figure 7 and Figure 8). In the scree plot, the graph significantly drops and becomes flattened from factor 5, with four factors preceding this point (Figure 7). The parallel analysis shows that the real data eigenvalue is higher than that of the eigenvalue of random data for seven factors (Figure 8). Watkins

(2021) suggested sequentially evaluating the interpretability and theoretical meaningfulness when different methods suggest different numbers of factors. Therefore, we evaluated the interpretability of models with four and seven factors at last and found that the four-factor model is more theoretically meaningful and interpretable. Additionally, we evaluated the total variance explained by retained factors, which is greater than 75%, as suggested by (Mooi et al. 2018). Therefore, we retained four factors for perceived barriers.

Table 11 and Table 12 show the factor loading for retained perceived important factors and perceived barriers, which was obtained from conducting factor rotation in Stata.

Table 11: Factor loading of perceived important factors

Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Uniqueness**
Crop yields	**0.652**	0.083	0.025	0.490
Input costs	**0.770**	-0.050	0.126	0.331
Profitability	**0.755**	0.024	-0.011	0.420
Time spent in the field	0.093	-0.071	**0.799**	0.322
Time spent on farm management decisions	-0.006	0.112	**0.789**	0.299
Soil health and productivity on my farm	**0.460**	**0.488**	-0.030	0.338
Environmental quality in my community	0.104	**0.761**	-0.007	0.330
My compliance with government regulations	-0.123	**0.770**	0.057	0.462

Table 12: Factor loading of perceived barriers

Variable	Factor1	Factor2	Factor3	Factor4	Uniqueness
Finding information about the practice	0.007	-0.038	**0.815**	-0.086	0.416
Having enough time to learn about the practice	0.008	-0.015	**0.780**	-0.012	0.408
Getting a return on investment from the practice	-0.012	**0.800**	-0.021	-0.100	0.432
Cost of the practice	0.086	**0.709**	-0.032	0.015	0.440
Difficulty implementing the practice because of timing and weather	0.257	**0.410**	0.073	0.049	0.594
Having the right equipment to implement the practice	**0.866**	0.088	-0.053	-0.001	0.216
Having the right technology to implement the practice	**0.883**	-0.069	0.065	0.020	0.219
Finding services related to the practice (e.g. crop advisor, custom applicator, soil testing)	0.282	0.140	0.029	0.008	0.739
Believing the practice is better suited for larger operations	0.114	-0.145	0.022	**0.596**	0.631
Difficulty implementing the practice on leased land	0.067	0.062	-0.046	**0.329**	0.789
Having a previous negative experience trying the practice	-0.257	0.196	0.077	0.272	0.805
Preferring to use practices they are more familiar with	-0.034	0.123	-0.014	**0.651**	0.568
Believing that new technologies are too difficult to use	0.001	-0.109	-0.008	**0.712**	0.568

Uniqueness in Table 11 and Table 12 represents the variance that is not shared by the common factors. For one of the importance factors and two of the barrier factors, we have only two variables with a threshold level of 0.32 (Table 11 and Table 12 respectively); however, the factors are theoretically important and variables within the factors are highly correlated with each other (r > 0.70) while exhibiting low correlation with other variables except for the correlation between "finding the information about the practice" and "having enough time to learn about the practice" which is 0.68 (Appendix A–Table A27-A28). Yet, we retained the factor with these two variables since it is theoretically important. Thus, even with two variables, factors are considered reliable when the variables within the factors are highly correlated and less correlated with other variables that are not included in that factor, as suggested by Yong and Pearce (2013), and the variables are theoretically important. Greiner and Gregg (2011) and Lambert et al. (2015) also retained the factor with two variables in their study. The "soil health and productivity" variable of the important statement is found loaded significantly on two factors, called cross-loading; however, we retained this variable since it is theoretically justifiable, as recommended by (Yong and Pearce 2013).

Based on the results of the factor analysis (scree plot, parallel analysis, and factor loadings), we identified three factors from the perceptions of the importance of factors in adoption: Factor 1 – "economic importance", Factor 2 – "environmental awareness and compliance importance" and Factor 3 – "time investment importance" (Table 11). Results of factor analysis of perceived barriers to adoption suggest four factors: Factor 1 – "equipment and technology barriers", Factor 2 – "economic and biological barriers", Factor 3 – "information barriers", and Factor 4 – "farmer belief barriers" (Table 12).

4.3 Ordered Logit Regression Results

We incorporated the perceived important factors and perceived barriers that we obtained from the factor analysis as independent variables in the ordered logit regressions to determine how these factors influence current and future NMT adoption, respectively.

Table 13 presents the odds ratios of ordered logit models assessing the drivers of the current adoption status of NMT. It primarily determines how the identified perceived important factors and perceived barriers influence the current adoption status of NMT. This tested the hypothesis that identified perceived important factors and perceived barriers are significantly correlated with the current adoption status of NMT.

In the case of farmers' attitudes toward the importance of factors, a marginally significant ($p<0.1$) result was obtained for *Time Investment Importance*. The importance farmers place on time requirements by NMT was positively correlated with the current adoption status of NMT. For every one-unit increase in the importance of time spent on the field and management, the odds of being in a higher category of current adoption (compared to a lower category) increased by 1.890 times, holding all other variables constant, suggesting that as the farmer placed more importance on time spent on the field and farm management decision, the likelihood of being in higher current adoption status increased. Contrary to our hypothesis, *Economic Importance* and *Environmental Awareness and Compliance Importance* were not significantly associated with current adoption status. Overall, the results suggest that farmer attitudes toward the importance of time investment importance factor had a marginally significant effect on the current adoption status of NMT, whereas farmer attitudes toward the importance of economic importance and environmental awareness and compliance did not have a significant effect on the current adoption status as predicted.

In the case of farmer attitude toward barriers, contrary to our hypothesis, the odds ratio of all the barrier variables (*Equipment and Technology Barrier*, *Economic and Biological Barriers*, *Information Barriers*, and *Farmer Belief Barriers*) was insignificant which indicates that these perceived barriers variables did not significantly influence the current adoption level of NMT. Furthermore, the odds ratio for the adoption of *Other NMPs* was not significant, suggesting that the adoption of at least one of the other similar NMPs, i.e., grid soil sampling, liquid manure injection, commercial nitrogen fertilizer, cover crop, split N application, and VRT, had no influence on the current adoption status of NMT.

In the category of farm characteristics, the *Total Cropland* had a significant odds ratio ($p<0.1$). The result suggests that for every 100 acres increased in the total cropland area, the odds of being in a higher current adoption category (compared to a lower category) increased by 1.051 times, holding all the other variables constant, implying that farmers with higher total acres of the farm were more likely to have a higher level of current adoption status. On the other hand, the proportion of total cropland leased was found to have an insignificant influence on the current adoption status. In addition, the location of the cropland (State) did not have a significant influence on the current adoption status (*State: DE, MD, VA, and PA*).

Farmer characteristics – age of primary decision maker (*Age*), farmer having a college degree as the highest level of education (*College Degree*), and farmer with more than 50% of household income from farming (*Farm Income*)– had no significant association with the current adoption status.

Regarding enrollment in the environmental or cost-share programs, farmers who were enrolled in CRP had 0.291 times the odds of being in the higher current adoption category (vs. the lower category) compared to the farmers who were not enrolled ($p<0.1$). However, no significant influence was observed with the enrollment of CREP, CSP, EQIP, and ACP.

A separate model (Model 2 shown in Table 13) was estimated with the addition of interaction variables (total cropland area interacted with perceived important factors and perceived barriers) to check whether the impact of the perceived important factors and perceived barriers on current adoption status varies by farm size. We obtained less than one odds ratio (0.876) for the *TotalCropland* × *Environmental Awareness and Compliance Importance* ($p<0.05$). This implies that farmer with larger cropland areas who consider soil health and productivity, environmental quality, and compliance with government regulations more important in their decision to use NMT were less likely to be in a higher current adoption status. The odds ratio of *TotalCropland* × *Time Investment Importance* was significant ($p<0.05$) and greater than one (1.112) which suggests that farmers with larger cropland areas who consider the time spent on the field and on-farm management decisions more important in their decision to use NMT were more likely to be in a higher current adoption status. Likewise, we obtained a marginally significant ($p<0.1$) but less than one odds ratio (0.928) for the *TotalCropland* × *Farmer Belief Barrier*. This illustrates that farmers with larger cropland areas who perceive farmer belief barriers (such as the belief that NMT is better suited for larger operations, NMT is difficult to implement on leased land, preference for familiar practice and technologies are too difficult to use) highly limit the use of NMT were less likely to be in higher current adoption level. In other words, the more a large-scale farmer perceived belief-related barriers as significant, the lower their likelihood of being in a higher current adoption category for NMT.

However, when we compared the goodness of fit of the two models, we found that additional parameters in Model 2 (including interaction variables) did not significantly improve model fit. We compared two model specifications using the Likelihood ratio test and AIC/BIC. From the Likelihood ratio test, we obtained a p-value of 0.146 ($p>0.1$), which illustrates full model (model 2) did not significantly improve the model compared to model 1 (restricted model) (Appendix A–Table A29). Additionally, both AIC and BIC in model 1 are lower than those of model 2, indicating that model 1 performed better.

Table 13: Ordered logit regression results for current adoption level of NMT

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	**P-value**	**Odds ratio with standard errors**	**P-value**
Farmer attitudes toward importance of factors	*Economic Importance*	0.563 (0.237)	0.172	0.528 (0.292)	0.248
	Environmental Awareness and Compliance Importance	1.352 (0.504)	0.419	2.551** (1.166)	0.040
	Time Investment Importance	1.890* (0.677)	0.076	0.995 (0.476)	0.992
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	0.785 (0.282)	0.499	0.715 (0.301)	0.426
	Economic and Biological Barrier	1.809 (0.731)	0.142	1.670 (0.787)	0.277
	Information Barrier	1.025 (0.439)	0.953	0.831 (0.428)	0.720
	Farmer Belief Barriers	0.672 (0.216)	0.216	1.051 (0.450)	0.907
Adoption of other NMP	*Other NMP*	2.719 (2.954)	0.357	1.350 (1.515)	0.790
Farm characteristics	*Total Cropland* (100 acres)	1.051* (0.028)	0.056	1.055 (0.035)	0.100
	Land Lease (>50% of total cropland)	0.601 (0.295)	0.299	0.684 (0.358)	0.468
Farmer characteristics	*Age*	1.009 (0.016)	0.596	1.007 (0.018)	0.708
	College Degree	0.678 (0.289)	0.361	0.766 (0.351)	0.560
	Farm Income	0.596 (0.308)	0.317	0.540 (0.290)	0.250

Table 13 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	0.291* (0.187)	0.054	0.328 (0.231)	0.113
	CREP (Conservation Reserve Enhancement Program)	2.218 (1.494)	0.237	3.053 (2.249)	0.130
	CSP (Conservation Stewardship Program)	2.608 (1.532)	0.103	2.319 (1.503)	0.194
	EQIP (Environmental Quality Incentives Program)	1.165 (0.610)	0.770	1.268 (0.712)	0.672
	ACP (State Agriculture Cost-Share Program)	1.265 (0.617)	0.630	1.511 (0.795)	0.432
State	*DE* (Delaware)				
	MD (Maryland)	0.851 (0.471)	0.770	0.831 (0.481)	0.748
	PA (Pennsylvania)	1.208 (0.820)	0.781	1.083 (0.753)	0.909
	VA (Virginia)	1.018 (0.705)	0.980	1.108 (0.837)	0.892

Table 13 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Interaction of cropland area and important factors	*TotalCropland* × *Economic Importance*			1.065 (0.061)	0.273
	TotalCropland × *Environmental Awareness and Compliance Importance*			0.876 ** (0.048)	0.016
	TotalCropland × *Time Investment Importance*			1.112** (0.059)	0.044
Interaction of cropland area and barriers	*TotalCropland* × *Equipment and Technology Barrier*			0.999 (0.034)	0.990
	TotalCropland × *Economic and Biological Barrier*			0.992 (0.046)	0.853
	TotalCropland × *Information Barrier*			1.052 (0.081)	0.511
	TotalCropland × *Farmer Belief Barrier*			0.928* (0.038)	0.068

Table 13 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
	cut1	1.997 (1.544)		1.456 (1.622)	
	cut2	2.771* (1.557)		2.310 (1.634)	
	Log likelihood	-98.258		-92.844	
	Pseudo R^2	0.111		0.162	
	Akaike information criteria (AIC)	242.515		245.687	
	Bayesian information criteria (BIC)	308.820		332.171	
	N	132		132	

Table 14 presents the odds ratios of ordered logit models assessing the drivers of the farmer's future likelihood of starting or expanding the use of NMT. This result focused on the respondents other than those who have adopted this tool on at least half of their total acres. It specifically examined how the identified perceived important factors and perceived barriers influence the future likelihood of the adoption or expansion of the use of NMT. This tested the hypothesis that identified important factors and perceived barriers are significantly correlated with the future adoption decision of farmers for NMT.

We observed similar results for future likelihood of adoption decisions as we observed in the current adoption status in the case of farmer attitudes toward the importance of factors. The marginally significant ($p<0.1$) and positively correlated relationship was obtained for the *Time Investment Importance*. Every one-unit increased in the importance of time spent on the field and farm management decision increased the odds of being in a higher category of future likelihood of adoption of NMT (compared to lower category) by 2.036 times, holding all other variables constant, inferring that as the farmer placed more importance on time spent on the field and farm management decision, farmer's likelihood of adopting or expanding the use of NMT in next three year increased. Contrary to our hypothesis, *Economic Importance and Environmental Awareness and Compliance Importance* were not found to be significantly associated with the future likelihood of the adoption decision of farmers.

Similar to the result of the current adoption status, the odds ratio of all the potential perceived barriers (*Equipment and Technology Barrier*, *Economic and Biological Barrier*, *Information Barrier*, and *Farmer Belief Barrier*) was insignificant, which is contrary to our hypothesis. This suggests that these potential barrier variables did not significantly influence the future likelihood of adoption decisions for NMT as well. Further, the odds ratio of *Other NMP* was not significant, which suggests that the adoption of at least one of the other similar NMPs, i.e., grid soil sampling, liquid manure injection, commercial nitrogen fertilizer, cover crop, split N application, and VRT, etc., did not influence the future likelihood of adoption decision for NMT.

A similar result, as in the current adoption status, was observed in the category of farmer characteristics for the future likelihood of adoption decision for NMT. The *Total Cropland* had a marginally significant and positively correlated odds ratio (<0.1). The result suggests that for every 100 acres increased in the total cropland area, the odds of being in a higher future likelihood of adoption category (compared to a lower category) increased by 1.050 times, holding all the other variables constant, which shows farmers with higher total acres of the farm were more likely to adopt NMT in next three years. On the other hand, we observed an insignificant influence of the proportion of total cropland leased (*Land Lease*) on future adoption decisions of farmers. Likewise, the location of the cropland (*State: DE, MD, PA, and VA*), either in Delaware, Maryland, Pennsylvania, or Virginia, did not have a significant effect on the future likelihood of the adoption decision of the farmer.

The result shows a similar insignificant odds ratio for all the variables of farmer characteristics. The age of the primary decision maker (*Age*), the highest level of education as a college degree (*College Degree*), and more than 50% of household income from farming (*Farm Income*) had no significant association with the future adoption decision of farmers for NMT.

Regarding enrollment in the environmental or cost-share program, positively correlated and marginally significant odds ratios were observed in the enrollment of CSP and ACP programs. For farmers who were enrolled in CSP, the odds of being more likely to adopt NMT in the next three years were 3.689 times that of farmers who were not enrolled in this program. Similarly, farmers who were enrolled in the ACP program had 2.787 times the odds of being very likely to adopt NMT in the next three years (vs. somewhat or unlikely) compared to farmers who were not enrolled in this program. However, no significant influence was observed with the enrollment of CRP, CREP, and EQIP.

Model 2 (shown in Table 14) was estimated with the addition of interaction variables (total cropland area interacted with perceived important factors and perceived barrier) to check whether the effect of perceived important factors and perceived barrier on future likelihood of adoption decision for NMT varies by farm size. The result shows a significant ($p<0.05$) and less than one odds ratio for the *TotalCropland* × *Equipment and Technology Barrier* variable (0.879). This implies that farmers with larger cropland areas who perceived that the equipment and technology barrier highly limit the use of NMT were less likely to adopt NMT in the future.

When comparing the goodness of fit between the two models, we found that additional parameters in model 2 (including interaction variables) did not significantly improve model fit. We assessed and compared the two model specifications using the Likelihood ratio test and AIC/BIC. The LR test resulted in a p-value of 0.304 ($p>0.1$), indicating that the full model (model 2) did not significantly improve upon model 1 (restricted model) (Appendix A–Table A29). Additionally, both AIC and BIC values for model 1 are lower than those for model 2, further suggesting model 1 as a better model fit.

Table 14: Ordered logit model results for future likelihood of adoption or expansion of NMT

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Farmer attitudes toward importance of factors	*Economic Importance*	0.876 (0.364)	0.750	0.800 (0.452)	0.692
	Environmental Awareness and Compliance Importance	1.441 (0.538)	0.328	1.004 (0.523)	0.994
	Time Investment Importance	2.036* (0.745)	0.052	1.814 (0.864)	0.211
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	1.057 (0.411)	0.886	2.197 (1.152)	0.133
	Economic and Biological Barrier	0.791 (0.344)	0.591	0.562 (0.296)	0.274
	Information Barrier	1.686 (0.818)	0.281	1.903 (1.123)	0.276
	Farmer Belief Barriers	1.058 (0.352)	0.866	0.698 (0.351)	0.474
Adoption of other NMP	*Other NMP*	1.611 (1.765)	0.663	2.583 (3.054)	0.422
Farm characteristics	*Total Cropland* (100 acres)	1.050* (0.030)	0.092	1.057 (0.047)	0.208
	Land Lease (>50% of total cropland)	0.905 (0.434)	0.834	0.840 (0.438)	0.738
Farmer characteristics	*Age*	0.974 (0.019)	0.164	0.973 (0.020)	0.169
	College Degree	0.566 (0.260)	0.215	0.544 (0.278)	0.234
	Farm Income	0.642 (0.344)	0.408	0.625 (0.353)	0.406

Table 14 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	1.296 (0.834)	0.687	1.451 (1.059)	0.610
	CREP (Conservation Reserve Enhancement Program)	0.750 (0.520)	0.679	0.500 (0.404)	0.390
	CSP (Conservation Stewardship Program)	3.689* (2.694)	0.074	6.246** (5.726)	0.046
	EQIP (Environmental Quality Incentives Program)	0.472 (0.274)	0.196	0.403 (0.253)	0.148
	ACP (State Agriculture Cost-Share Program)	2.787* (1.461)	0.051	2.900* (1.584)	0.051
Location of most of the cropland	*DE* (Delaware)				
	MD (Maryland)	1.103 (0.658)	0.869	1.027 (0.626)	0.966
	PA (Pennsylvania)	1.067 (0.764)	0.928	1.135 (0.886)	0.871
	VA (Virginia)	0.832 (0.625)	0.807	0.579 (0.508)	0.533

Table 14 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Interaction of cropland area and important factors	*TotalCropland × Economic Importance*			1.007 (0.069)	0.914
	TotalCropland × Environmental Awareness and Compliance Importance			1.063 (0.083)	0.432
	TotalCropland × Time Investment Importance			1.063 (0.071)	0.362
Interaction of cropland area and barriers	*TotalCropland × Equipment and Technology Barrier*			0.879** (0.049)	0.021
	TotalCropland × Economic and Biological Barrier			1.086 (0.056)	0.112
	TotalCropland × Information Barrier			0.977 (0.092)	0.802
	TotalCropland × Farmer Belief Barrier			1.084 (0.070)	0.212

Table 14 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
	cut1	-0.824 (1.646)		-0.512 (1.806)	
	cut2	1.123 (1.647)		1.550 (1.804)	
	Log likelihood	-88.413		-84.246	
	Pseudo R^2	0.166		0.205	
	Akaike information criteria (AIC)	222.825		228.493	
	Bayesian information criteria (BIC)	284.514		308.946	
	N	108		108	

4.4 Sensitivity Analysis

For the current adoption status in Model 1 and Model 2, we excluded the response “used in the past but not now.” As a sensitivity analysis, we combined the response “used in the past but not now” with “never used” categorizing both as “currently not using NMT”. This allowed us to assess whether including the “used in the past but not now” response changes the results. Though the estimates varied in significance level, we obtained a similar magnitude and direction in the variables in the ordered logit regression results (Appendix A–Table A30).

We observed outliers in total cropland area; therefore, we estimated the regression models after removing the observations with cropland areas that are greater than 2.5 standard deviations away from the mean. Some changes occurred in both the current and future adoption models. The direction of the coefficient remained the same in the significant variable, although the statistical significance changed in some significant variables (Appendix A–Table A31-Table 32).

As an additional sensitivity test, we imputed missing values through a multiple imputation approach. We observed a similar magnitude and direction for the key significant variables in the ordered logit regression results (Table 15 and Table 16), which support no imputation results. We chose no imputation results for the main interpretation because there was less than 10% missing data, and the result wouldn't be biased if not imputed for less than 10% missing data (Bennett 2001).

Table 15 shows the multiple imputation results for the current adoption level of NMT. In Model 1, we found the odds ratio estimated for *Time Investment Importance* and *CRP* was no longer significant; however, the direction and magnitude of the odds ratio remained similar. Whereas the effect of the *Total Cropland* on the current adoption level remained consistent with an even stronger significance level ($P<0.05$).

In Table 15 Model 2, when we included interaction variables (total cropland area interacted with perceived important factors and perceived barrier), we did not obtain a significant odds ratio for *TotalCropland* × *Environmental Awareness and Compliance Importance*, *TotalCropland* × *Time Investment Importance*, and *TotalCropland* × *Farmer Belief Barrier*; however, their direction and magnitude remained consistent. However, the odds ratio of *TotalCropland* × *Equipment and Technology Barrier* became significant and positively correlated with the current adoption level.

Table 15: Ordered logit regression results for current adoption level of NMT (Multiple Imputation)

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Farmer attitudes toward importance of factors	*Economic Importance*	0.633 (0.232)	0.213	0.543 (0.263)	0.208
	Environmental Awareness and Compliance Importance	1.429 (0.472)	0.280	1.998* (0.813)	0.089
	Time Investment Importance	1.512 (0.463)	0.177	1.252 (0.522)	0.589
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	0.676 (0.202)	0.192	0.474** (0.172)	0.040
	Economic and Biological Barrier	1.369 (0.488)	0.378	1.658 (0.733)	0.252
	Information Barrier	1.154 (0.401)	0.679	1.462 (0.669)	0.407
	Farmer Belief Barriers	0.807 (0.221)	0.437	1.058 (0.389)	0.877
Adoption of other NMP	*Other NMP*	3.421 (3.556)	0.237	1.505 (1.616)	0.703
Farm characteristics	*Total Cropland* (100 acres)	1.046** (0.023)	0.045	1.051* (0.030)	0.079
	Land Lease (>50% of total cropland)	0.586 (0.252)	0.214	0.739 (0.340)	0.512
Farmer characteristics	*Age*	1.007 (0.015)	0.609	1.003 (0.016)	0.846
	College Degree	0.546 (0.216)	0.128	0.494* (0.208)	0.095
	Farm Income	0.539 (0.273)	0.223	0.517 (0.269)	0.207

Table 15 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	0.452 (0.262)	0.171	0.556 (0.332)	0.327
	CREP (Conservation Reserve Enhancement Program)	1.825 (1.139)	0.335	1.855 (1.219)	0.347
	CSP (Conservation Stewardship Program)	2.118 (1.130)	0.160	1.718 (0.985)	0.345
	EQIP (Environmental Quality Incentives Program)	0.958 (0.455)	0.928	1.198 (0.595)	0.715
	ACP (State Agriculture Cost-Share Program)	1.431 (0.608)	0.398	1.663 (0.755)	0.263
State	*DE* (Delaware)				
	MD (Maryland)	0.794 (0.403)	0.650	0.904 (0.482)	0.852
	PA (Pennsylvania)	0.616 (0.392)	0.448	0.689 (0.452)	0.571
	VA (Virginia)	1.002 (0.624)	0.997	1.036 (0.672)	0.956

Table 15 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Interaction of cropland area and important factors	*TotalCropland × Economic Importance*			1.023 (0.050)	0.636
	TotalCropland × Environmental Awareness and Compliance Importance			0.939 (0.039)	0.143
	TotalCropland × Time Investment Importance			1.045 (0.040	0.246
Interaction of cropland area and barriers	*TotalCropland × Equipment and Technology Barrier*			1.052* (0.028)	0.060
	TotalCropland × Economic and Biological Barrier			0.966 (0.041)	0.424
	TotalCropland × Information Barrier			0.965 (0.051)	0.512
	TotalCropland × Farmer Belief Barrier			0.962 (0.030)	0.221
	cut1	1.944 (1.471)		1.178 (1.536)	
	cut2	2.630 (1.482)		1.902 (1.544)	
	N	157		157	

Table 16 shows the multiple imputation results of the future likelihood of adoption or expansion of the use of NMT. The imputation of missing values did not change the significance and effect of *Time Investment Importance*, *Total Cropland*, and *ACP* on future adoption decisions for NMT. However, though there was a similar effect, the *CSP* was not significant.

In model 2, when we added interaction variables (total cropland area interacted with perceived important factors and perceived barriers), we found a consistent effect and significance level of *TotalCropland* × *Equipment and Technology Barrier* on future adoption decision for NMT. At the same time, we also observed a significant and positively correlated relationship between *TotalCropland* × *Economic and Biological Barrier* and future adoption decisions for NMT.

Table 16: Ordered logit model results for future likelihood of adoption or expansion of NMT (Multiple Imputation)

Categories	**Independent variable**	**Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years**			
		Model 1		**Model 2**	
		Odds ratio with standard errors	**P-value**	**Odds ratio with standard errors**	**P-value**
Farmer attitudes toward importance of factors	*Economic Importance*	0.868 (0.333)	0.714	0.698 (0.358)	0.485
	Environmental Awareness and Compliance Importance	1.517 (0.506)	0.212	1.413 (0.629)	0.437
	Time Investment Importance	1.793* (0.594)	0.078	1.512 (0.669)	0.349
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	0.945 (0.320)	0.870	1.423 (0.606)	0.407
	Economic and Biological Barrier	0.772 (0.300)	0.508	0.545 (0.260)	0.205
	Information Barrier	1.792 (0.684)	0.126	2.237 (1.182)	0.128
	Farmer Belief Barriers	1.152 (0.333)	0.624	0.805 (0.334)	0.603
Adoption of other NMP	*Other NMP*	1.539 (1.543)	0.667	1.947 (2.054)	0.527
Farm characteristics	*Total Cropland* (100 acres)	1.061* (0.026)	0.018	1.081* (0.044)	0.056
	Land Lease (>50% of total cropland)	0.906 (0.394)	0.822	0.845 (0.407)	0.727
Farmer characteristics	*Age*	0.972 (0.018)	0.139	0.971 (0.019)	0.153
	College Degree	0.680 (0.294)	0.373	0.714 (0.334)	0.473
	Farm Income	0.639 (0.327)	0.382	0.664 (0.354)	0.444

Table 16 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	1.180 (0.738)	0.791	1.230 (0.840)	0.761
	CREP (Conservation Reserve Enhancement Program)	0.859 (0.577)	0.821	0.608 (0.458)	0.510
	CSP (Conservation Stewardship Program)	2.518 (1.581)	0.142	3.387 (2.575)	0.109
	EQIP (Environmental Quality Incentives Program)	0.440 (0.230)	0.118	0.353* (0.198)	0.065
	ACP (State Agriculture Cost-Share Program)	2.569* (1.247)	0.052	2.772** (1.433)	0.049
Location of most of the cropland	*DE* (Delaware)				
	MD (Maryland)	1.231 (0.686)	0.709	1.136 (0.651)	0.824
	PA (Pennsylvania)	1.080 (0.694)	0.904	0.958 (0.653)	0.950
	VA (Virginia)	0.868 (0.628)	0.845	0.711 (0.580)	0.676

Table 16 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Interaction of cropland area and important factors	*TotalCropland × Economic Importance*			1.033 (0.060	0.574
	TotalCropland × Environmental Awareness and Compliance Importance			1.005 (0.066)	0.940
	TotalCropland × Time Investment Importance			1.052 (0.053	0.320
Interaction of cropland area and barriers	*TotalCropland × Equipment and Technology Barrier*			0.912** (0.041)	0.042
	TotalCropland × Economic and Biological Barrier			1.085* (0.052)	0.088
	TotalCropland × Information Barrier			0.957 (0.069)	0.552
	TotalCropland × Farmer Belief Barrier			1.081 (0.055)	0.124
	cut1	-0.718 (1.597)		-0.552 (1.674)	
	cut2	1.275 (1.588)		1.539 (1.661)	
	N	128		128	

4.5 Semi-structured Interview Results

To understand farmers' perceptions of economic importance and time investment factors, we analyzed semi-structured interviews through descriptive statistics and thematic analysis.

Table 17 shows a summary of farmers' responses to the economic importance question, "*Is it most important for you to increase yield and profitability or to reduce/keep input costs low?". The m*ajority of farmers mentioned increasing yield and profitability as the most important factors compared to reducing input costs. Since NMT requires an initial input cost per acre fee, we asked the farmer to report the factors that make the cost increase worthwhile. Figure 9 shows the common factors that were reported by farmers; the majority of farmers reported an increase in profitability, followed by a reduction in nitrogen cost and an increase in yield as factors that could justify spending money on NMT. One of the farmers stated, "*I would like if they will help reduce nitrogen cost and save money and increase yield."* In conclusion, the results suggest that profitability is the most important economic factor, and farmer are willing to invest in NMTs if it reduces other financial cost and increases yield.

Table 17: Farmers' response to economic importance statement

Economic Importance variable	**Most important variable (n)**
Increase yield and profitability	12
Reduce/keep input costs low	1
Both	5

Figure 9: Word cloud showing farmer perception on factors which can justify NMT cost

We analyzed time investment questions of semi-structured interviews to understand why farmers who prioritize time requirements by NMT are more likely to adopt these tools when they believe that these tools increase time spent in the field and farm management decisions. One farmer states the possible reason, "*I would say because it kind of does some of the math and equation for you, so you don't have to sit down and hand write it all out and then try to compute it on your own. I mean, it makes it more accessible, so it's all a time and accuracy efficiency.*" This suggests that even though farmers perceived these tools as time-consuming during implementation, they also recognized their efficiency in saving time and improving accuracy when analyzing the required nutrients for their fields. Table 18 shows the farmers' responses to time investment follow-up questions. The majority of farmers were willing to invest more time in adopting new tools if that investment had a good return. For example, one of the farmers said, "*If it's a tool that will likely give me a 3 to 1 return on investment*." Moreover, one of the farmers at the Delaware Risk Management Conference said, "*Maybe there's a perception of up front time investment but a belief that will pay off later.*" Thus, time could be an important factor in deciding the adoption of NMTs. In addition, farmers showed willingness to invest time in its use if the tool pays off financially.

Table 18: Farmers' response to time investment importance questions

Question	**Agree**	**Disagree**	**May be**	**Don't know**
Do you think NMTs are more time-effective compared to other NMPs?	1	9	4	3
Do you think a practice is more valuable if it requires more time to implement?	5	12	2	0
Are you willing to invest more time to adopt new tools?	14	3	1	0

Chapter 5

DISCUSSION AND CONCLUSION

5.1 Discussion

This study investigated the perceived important factors and barriers associated with current and future adoption decisions of farmers for NMT. The results showed a larger percentage of farmers (65.13%) had never used NMT, 10.77% had used these tools to some extent of cropland (less than half of their total acres of cropland), whereas only 20% of farmers had used this tool on at least half of their total cropland. When we further asked farmers who had never used these tools or who had used them on less than half of total acres of cropland about their likelihood to start using or expand acreage for the use of NMT in the next three years, larger percentage of farmers (65.55%) reported that they are not likely to use these tools and only 26.89% and 7.56% of farmer reported they are somewhat likely and very likely to use or expand the use of this tool in the next three years. A recent study has shown lower adoption of similar technology. For instance, a study conducted by Schimmelpfennig and Lowenberg-DeBoer (2020) among corn farmers in New York, Pennsylvania, Michigan, and Ohio showed 7%, 1%, and 10% adoption rates for soil mapping, remote sensing, and VRT fertilizer technology. Further research should examine the adoption rate of Nitrogen Modeling Tools such as Adapt -N, Climate FieldView, Granular, etc.

The descriptive statistics and ordered logit regression results give additional insight into farmers' perception of the importance of economic implications and how their perception influences current and future adoption decisions for NMT. The majority of farmers stated economic factors such as profitability, soil health and productivity, input cost, and crop yield are the most important factors in the adoption decision of NMT. Further, they believed that the use of NMT has an economic benefit. A similar result was obtained from semi-structured interviews; the majority of farmers stated that an increase in profitability is the most important factor compared to the reduction in input cost, and they further indicated that an increase in profitability, followed by reduction in nitrogen cost and an increase in yield could make the investment in NMT worthwhile. However, in regression analysis, the perceived level of importance of economic factors on current and future adoption decisions of NMT was insignificant. Though insignificant, the direction and magnitude of the result imply that the more importance farmers placed on economic factors, they were less likely they were to adopt NMT both currently and in the future. This insignificant result shows that the farmer's stated importance did not significantly influence their actual adoption behavior. The finding is consistent with Luther et al. (2020), as they found an insignificant relationship between farmer orientation toward optimizing income and adoption of variable-rate nitrogen application. Contrasting findings were observed in other studies (Kolady et al. 2021; Ulrich-Schad et al. 2017). The study suggests that factors other than economic importance might influence the adoption of NMT.

The results of descriptive statistics and ordered logit regression further explore farmers' perception of the importance of environmental concern and government compliance and how it influences current and future adoption decisions of farmers for NMT. For the majority of farmers, environmental awareness and regulatory compliance (factors such as soil health and productivity, environmental quality, and compliance with government regulations) were very or moderately important in their decision to use NMT, however, they believed that the use of NMT will have no change on those factors, which shows farmers unawareness about the environmental benefit of these tools. The regression results have shown an insignificant effect of farmers' perceived importance of environmental awareness and government compliance on current adoption status and their future likelihood of adoption decisions for NMT. This finding is consistent with Ulrich-Schad et al. (2017), who reported the insignificant effect of the importance of evidence of environmental benefit on the adoption of conservation practices such as soil tests, variable rate application, and application timing. They also found an insignificant influence of farmers' attitudes toward water quality pollution from agriculture on the adoption of those conservation practices. However, when we include the interaction variable with farm size, we observed that large-scale farmers who perceive environmental awareness and compliance as highly important in their decision to use NMT were less likely to be in the higher current adoption category. It could be because larger farms might have already adopted other NMPs for environmental conservation, making them less inclined to adopt NMT. This finding is not consistent with Hu et al. (2022) who suggested that farm size does not have an impact on farmers' preference for environmental technologies (i.e., agricultural technology for protecting the environment by reducing energy consumption and pollution emission). Further research should further explore the effect of environmental concern on the adoption of NMT and how this varies by farm size.

Regarding the time investment importance factor, the result shows that while there was a perception that adopting NMT would increase time spent in the field and farm management decisions, approximately half of the respondents considered this factor only moderately important, and around 20% of farmers considered this as not important in their decision to adopt NMT. Reimer et al. (2012) has suggested the time demand of practices as a barrier and McCormack et al. (2022) has shown time-saving characteristics of tools as stronger drivers of technology adoption among farmers. Though many farmers did not view time investment as the most important factor in their adoption decision, the regression results suggest that it was a statistically significant predictor of the NMT adoption decision. As the farmer perceived time spent in the field and farm management decisions as of greater importance in their adoption decision regarding NMT, they were found more likely to be in a higher current adoption status, and they were more likely to adopt or expand the use of this tool in the next three years. Conversations during semi-structured interviews suggest these perceptions could be because of the tool's efficiency in saving time and improving accuracy, or farmers' willingness to invest additional time due to their profitability. Moreover, larger farmers who perceived the time requirement by NMT as a more important factor were more likely to be in the higher current adoption category of NMT. This implied that farm size could be a driver of significant and positively correlated results of the time investment importance factor. The finding is supported by Hu et al. (2022) who found that larger-scale farmers are more willing to spend time to gain agricultural technology information, indicating that they are more willing to spend time on agricultural technology. There could be many reasons behind this result as well, which need to be further investigated. Larger farmers may have more resources and a greater capacity to integrate time-intensive technologies. Or, it could be that when farmers use NMT on larger farms, it could work as a time-saving rather than a time-constraint tool since NMT requires time initially to incorporate soil, crop, and weather data, and once the tool is set, it gives the real-time nitrogen requirement throughout the season which shows time efficiency of the tool (National Oceanic and Atmospheric Administration 2024). This is supported by one quote from a semi-structured interview, i.e., *"I would say because it kind of does some of the math and equation for you, so you don't have to sit down and hand write it all out and then try to compute it on your own. I mean, it makes it more accessible, so it's all a time and accuracy efficiency."*

The ordered logit regression model further tested the hypothesis regarding perceived barriers (equipment and technology barrier, economic and biological barrier variables, information barrier, and farmer belief barriers) and found that these perceived barriers did not significantly influence the current adoption status and future likelihood of adoption decision of farmers for NMT. However, when we interacted them with the total cropland area, we found significant results for some of the interaction variables. The result suggests larger farmers who perceived that belief barriers – such as NMT are better suited for larger operations, difficult to implement on leased land, preference for familiar practices, and new technologies are too difficult to use – highly limit the use of NMT were less likely to adopt NMT currently at higher levels. The finding is supported by existing literature to some extent. Leased land has been identified as a barrier to the adoption of conservation practices or best management practices (Kalcic et al. 2014; Reimer et al. 2012). Similarly, studies have found that farmers who have previously used specific or similar practices are more likely to adopt conservation practices or PATs such as VRNT (Prokopy et al. 2019; Barnes et al. 2019). Furthermore, the result shows that large farmers who stated having the right equipment and technology as a barrier that highly limits the use of NMT were less likely to adopt these tools in the next three years. Previous research has provided evidence that as farmers perceive equipment barriers as highly important, they are less likely to use NMPs such as conducting soil tests (Ulrich-Schad et al. 2017).

The ordered logit regression model (Model 1) regarding current and future adoption decisions identifies the influence of farm and farmer characteristics on the adoption of NMT. Like previous studies (Kolady et al. 2021; Lambert et al. 2015), our result illustrates that farmers with larger cropland areas were more likely to be in a higher current adoption category and were also more likely to adopt these tools in the future. However, our research indicates that the proportion of land leased, age, highest education level, and proportion of farm income did not influence the adoption of NMT. The finding is similar to previous studies (Daberkow and McBride 2003; Castle et al. 2016; Lambert et al. 2015).

Moreover, the result indicates that enrollment in environmental or cost-share programs influences the adoption of NMT. Farmers who were enrolled in the CSP and ACP were more likely to start using or expand the use of NMT in the next three years compared to the farmers who were not enrolled in these programs. The result is in line with the previous literature that concluded that farmers who are enrolled in environmental organizations are more likely to adopt BMPs, such as crop rotation, herbicide control practices, etc. (Ghazalian et al. 2009). On the contrary, farmers who were enrolled in the CRP were less likely to be in a higher current adoption status compared to those who were not enrolled. This could be because CRP encourages farmers to convert highly erodible and environmentally sensitive acreage to vegetative cover, like native grasses, trees, and riparian buffers, which reduces their cropland area. Future research should further examine how and why enrollment in different environmental and cost-share programs influences the adoption of NMT.

Though this study was carefully conducted and analyzed, it has limitations. The first limitation is the sample size; the findings would have been more robust and representative if the sample size were larger. Second, there are several other factors that were not studied in this study, such as labor constraints, access to communication, etc. Third, this study relies on survey responses, which may be subject to social desirability bias, response bias, or self-reported bias. Fourth, the target population of the study was limited to the four states of the Mid-Atlantic region of the US.

Despite the small sample size, we found that the influence of perceived importance of factors and potential barriers varies by farm size. This suggests that future research should be focused on specifying motivational factors and barriers to the adoption of NMT for large, medium, and small farm sizes, using a larger, nationally representative sample. Future research should further explore the gap between stated or self-reported willingness to adopt NMTs and their actual adoption behavior over time. Moreover, further studies should explore whether the provision of information about time benefits, economic benefits, and environmental benefits of NMT use influences farmers' willingness to adopt NMT.

5.2 Conclusion

Agricultural runoff is found to be a significant contributor to nitrogen loading in CBW, which is impairing its water quality and ecosystem. In-season Nitrogen Modeling Tool (NMT), which is recorded to improve Nitrogen Use Efficiency and reduce environmental nitrogen losses, is anecdotally known to have a lower adoption rate among U.S. farmers. This study addresses this issue by investigating farmers' perspectives on the importance of different factors, such as economic implications, environmental concerns, and time use, and examining their relationship with current and future adoption decisions for NMT. This study further explores the farmers' perspectives on the extent of limitation of different potential barriers, such as resource barrier and information barrier, etc., and their influence on the current and future adoption decision for NMT.

The analysis of the results indicates that farmers who placed greater importance on time spent in the field and farm management decisions were more likely to adopt NMT, either currently or in the future. Farmers perceived these tools as time and accuracy-efficient tools, and they were willing to invest additional time if the tools proved profitable. Farmers did report an increase in profitability as the impact of NMT. These suggest that we should emphasize the time- and cost-saving benefits of NMT to promote the adoption rate. Among 13 potential barriers, having the right equipment was identified as a highly limiting perceived constraint in the adoption of NMT. However, perceived barriers did not significantly influence current and future adoption decisions of NMT. Farm size was positively correlated with the NMT adoption, and the effect of environmental awareness and compliance, time investment, belief barriers, and equipment and technology barriers on the adoption of NMT varied by farm size. These highlight that the extension and policy approaches that aim to increase adoption should prioritize the barriers based on the farm size. In addition, participation in the CRP was negatively associated with current adoption, whereas enrollment in the CSP and ACP positively influenced future adoption decisions for NMT.

There are several implications of this study. This is the first study that examined the perceived important factors and barriers and their association with farmer adoption decisions, specifically for the use of NMT. This study might contribute to the literature on technology adoption and behavior by providing insight into NMT and farmer attitudes toward NMT.

The findings inform policymakers and stakeholders, such as the U.S. Départment of Agriculture (USDA), in designing the program that addresses barriers to improve Nitrogen management. By focusing on farm size-specific barriers, they can enhance the adoption of NMT, leading to nitrogen management and a reduction of nitrogen loading in the CBW. Moreover, the findings inform organizations, such as the Mid-Atlantic 4R Alliance, that are promoting the adoption of NMT, to emphasize the cost-saving and time-saving benefits of these tools. The study further suggests selecting the target populations for barrier reduction and motivation programs based on farm size, ensuring that programs are tailored to meet the specific needs and challenges of farmers with different farm sizes.

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Appendix A

DESCRIPTIVE STATISTICS AND MODEL TESTS

Table A1: Total missing observation of independent variables, except the variable of interest

Variable	Missing	Total	Percent Missing
Total Cropland	3	204	1.47
Land Lease	3	204	1.47
Age	20	204	9.80
College Degree	11	204	5.39
Farm Income	12	204	5.88
CRP	21	204	10.29
CREP	21	204	10.29
CSP	21	204	10.29
EQIP	21	204	10.29
ACP	21	204	10.29
DE	0	204	0.00
MD	0	204	0.00
PA	0	204	0.00
VA	0	204	0.00
Other NMP	6	204	2.94
Total	160	3060	5.23

Table A2: Descriptive statistics of future likelihood of adoption and 'never used' NMT category farmer

Current adoption of NMT	**Future likelihood to adopt NMT**			
	Not likely	**Somewhat likely**	**Very likely**	**Total**
Never used NMT	78 (65.55%)	32 (26.89%)	9 (7.56%)	19 (100%)

Table A3: Descriptive statistics of farmers' perceptions regarding yield (never used category)

Perceived impact of NMTs on yield	Importance of yield in farmers' decision regarding NMT adoption			
	1(Not important)	2(Moderately important)	3(Important)	Total
2(No change)	13	11	16	40
3(Increase)	2	27	47	76
Total	15	38	63	116

Table A4: Descriptive statistics of farmers' perceptions regarding input cost (never used category)

Perceived impact of NMTs on input cost	Importance of input cost in farmers' decision regarding NMT adoption			
	1(Not important)	2(Moderately important)	3(Important)	Total
1(Decrease)	0	8	27	35
2(No change)	7	9	8	24
3(Increase)	2	19	36	57
Total	9	36	71	116

Table A5: Descriptive statistics of farmers' perceptions regarding profitability (never used category)

Perceived impact of NMTs on profitability	**Importance of profitability in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	3	5	8
2(No change)	6	8	23	37
3(Increase)	0	18	53	71
Total	6	29	81	116

Table A6: Descriptive statistics of farmers' perceptions regarding time spent on the field (never used category)

Perceived impact of NMTs on time spent on the field	**Importance of time spent on the field in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	2	3
2(No change)	17	16	7	40
3(Increase)	10	37	26	73
Total	27	54	35	116

Table A7: Descriptive statistics of farmers' perceptions regarding time spent on farm management decisions (never used category)

Perceived impact of NMTs on time spent on farm management decision	**Importance of time spent on farm management decision in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	1	1	0	2
2(No change)	18	22	5	45
3(Increase)	3	44	21	68
Total	22	67	26	115

Table A8: Descriptive statistics of farmers' perceptions regarding soil health and productivity (never used category)

Perceived impact of NMTs on soil health and productivity	**Importance of soil health and productivity in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	10	19	24	53
3(Increase)	2	17	42	61
Total	12	36	66	114

Table A9: Descriptive statistics of farmers' perceptions regarding environmental quality (never used category)

Perceived impact of NMTs on environmental quality	**Importance of environmental quality in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	1	2
2(No change)	15	26	20	61
3(Increase)	1	23	29	53
Total	16	50	50	116

Table A10: Descriptive statistics of farmers' perceptions regarding compliance with government regulations (never used category)

Perceived impact of NMTs on compliance with government regulations	**Importance of compliance with government regulations in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	2	1	2	5
2(No change)	20	30	23	73
3(Increase)	5	17	16	38
Total	27	48	41	116

Table A11: Descriptive statistics of farmers' perceptions regarding yield (less than half of total acres category)

Perceived impact of NMTs on yield	**Importance of yield in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	0	1
2(No change)	1	1	2	4
3(Increase)	1	2	10	13
Total	2	4	12	18

Table A12: Descriptive statistics of farmers' perceptions regarding input cost (less than half of total acres category)

Perceived impact of NMTs on input cost	**Importance of input cost in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	2	3	5
2(No change)	0	1	1	2
3(Increase)	1	3	7	11
Total	1	6	11	18

Table A13: Descriptive statistics of farmers’ perceptions regarding profitability (less than half of total acres category)

Perceived impact of NMTs on profitability	**Importance of profitability in farmers’ decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	2	3
2(No change)	1	2	2	5
3(Increase)	1	1	7	9
Total	2	4	11	17

Table A14: Descriptive statistics of farmers’ perceptions regarding time spent on the field (less than half of total acres category)

Perceived impact of NMTs on time spent on the field	**Importance of time spent on the field in farmers’ decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	1	2
2(No change)	1	6	2	9
3(Increase)	2	0	4	6
Total	3	7	7	17

Table A15: Descriptive statistics of farmers' perceptions regarding time spent on farm management decisions (less than half of total acres category)

Perceived impact of NMTs on time spent on farm management decision	**Importance of time spent on farm management decision in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	1	1	2	4
3(Increase)	1	5	7	13
Total	2	6	9	17

Table A16: Descriptive statistics of farmers' perceptions regarding soil health and productivity (less than half of total acres category)

Perceived impact of NMTs on soil health and productivity	**Importance of soil health and productivity in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	2	4	1	7
3(Increase)	1	0	9	10
Total	3	4	10	17

Table A17: Descriptive statistics of farmers' perceptions regarding environmental quality (less than half of total acres category)

Perceived impact of NMTs on environmental quality	**Importance of environmental quality in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	1	0	0	1
2(No change)	4	1	3	8
3(Increase)	0	1	7	8
Total	5	2	10	17

Table A18: Descriptive statistics of farmers' perceptions regarding compliance with government regulations (less than half of total acres category)

Perceived impact of NMTs on compliance with government regulations	**Importance of compliance with government regulations in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	2	4	3	9
3(Increase)	0	2	6	8
Total	2	6	9	17

Table A19: Descriptive statistics of farmers' perceptions regarding yield (more than half of total acres category)

Perceived impact of NMTs on yield	**Importance of yield in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	0	1	1
2(No change)	2	1	2	5
3(Increase)	1	8	19	28
Total	3	9	22	34

Table A20: Descriptive statistics of farmers' perceptions regarding input cost (more than half of total acres category)

Perceived impact of NMTs on input cost	**Importance of input cost in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	4	9	13
2(No change)	2	3	3	8
3(Increase)	1	5	7	13
Total	3	12	19	34

Table A21: Descriptive statistics of farmers' perceptions regarding profitability (more than half of total acres category)

Perceived impact of NMTs on profitability	**Importance of profitability in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
1(Decrease)	0	1	1	2
2(No change)	0	2	5	7
3(Increase)	1	3	19	23
Total	1	6	25	32

Table A22: Descriptive statistics of farmers' perceptions regarding time spent on the field (more than half of total acres category)

Perceived impact of NMTs on time spent on the field	Importance of time spent on the field in farmers' decision regarding NMT adoption			
	1(Not important)	2(Moderately important)	3(Important)	Total
1(Decrease)	0	1	0	1
2(No change)	2	9	4	15
3(Increase)	3	5	10	18
Total	5	15	14	34

Table A23: Descriptive statistics of farmers' perceptions regarding time spent on farm management decisions (more than half of total acres category)

Perceived impact of NMTs on time spent on farm management decision	Importance of time spent on farm management decision in farmers' decision regarding NMT adoption			
	1(Not important)	2(Moderately important)	3(Important)	Total
1(Decrease)	0	1	1	2
2(No change)	3	6	2	11
3(Increase)	4	7	9	20
Total	7	14	12	33

Table A24: Descriptive statistics of farmers' perceptions regarding soil health and productivity (more than half of total acres category)

Perceived impact of NMTs on soil health and productivity	Importance of soil health and productivity in farmers' decision regarding NMT adoption			
	1(Not important)	2(Moderately important)	3(Important)	Total
2(No change)	1	1	4	6
3(Increase)	1	7	20	28
Total	2	8	24	34

Table A25: Descriptive statistics of farmers' perceptions regarding environmental quality (more than half of total acres category)

Perceived impact of NMTs on environmental quality	**Importance of environmental quality in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	4	1	4	9
3(Increase)	1	6	17	24
Total	5	7	21	33

Table A26: Descriptive statistics of farmers' perceptions regarding compliance with government regulations (more than half of total acres category)

Perceived impact of NMTs on compliance with government regulations	**Importance of compliance with government regulations in farmers' decision regarding NMT adoption**			
	1(Not important)	**2(Moderately important)**	**3(Important)**	**Total**
2(No change)	5	5	2	12
3(Increase)	0	5	16	21
Total	5	10	18	33

Table A27: Matrix showing correlation among perceived barriers

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) ***Information***	1.00												
(2) ***EnoughTime***	0.68	1.00											
(3) ***ReturnInvestment***	0.26	0.28	1.00										
(4) ***CostLimitation***	0.29	0.31	0.61	1.00									
(5) ***TimeAndWeather***	0.30	0.32	0.39	0.52	1.00								
(6) ***RightEquipment***	0.26	0.27	0.39	0.43	0.50	1.00							
(7) ***RightTechnology***	0.33	0.33	0.33	0.40	0.40	0.83	1.00						
(8) ***Service***	0.24	0.31	0.35	0.27	0.20	0.38	0.45	1.00					
(9) ***LargeOperation***	0.16	0.22	-0.01	0.19	0.18	0.17	0.21	0.15	1.00				
(10) ***DifficultyLeased***	0.19	0.20	0.14	0.17	0.32	0.23	0.20	0.25	0.33	1.00			
(11) ***NegativeExperience***	0.22	0.19	0.19	0.15	0.05	0.03	0.04	0.18	0.09	0.27	1.00		
(12) ***PreferFamiliar***	0.12	0.23	0.24	0.18	0.19	0.18	0.21	0.15	0.38	0.19	0.25	1.00	
(13) ***NewTechnology***	0.11	0.13	-0.01	0.11	0.10	0.12	0.15	0.03	0.41	0.19	0.23	0.50	1.00

Table A28: Matrix showing correlation among perceived important factors

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) *Yield*	1.00							
(2) *Cost*	0.61	1.00						
(3) *Profit*	0.55	0.66	1.00					
(4) *TimeInField*	0.33	0.48	0.38	1.00				
(5) *TimeInFarmManagement*	0.39	0.45	0.34	0.75	1.00			
(6) *SoilHealthAndProductivity*	0.54	0.58	0.55	0.35	0.40	1.00		
(7) *EnvironmentalQuality*	0.36	0.40	0.43	0.29	0.36	0.66	1.00	
(8) *ComplianceWithGovernment*	0.31	0.23	0.23	0.20	0.35	0.49	0.65	1.00

Table A29: Likelihood ratio test result that compare full and restricted model for current and future adoption of NMT

Model	Stata output (Results)
Current adoption status	lrtest fullmodel restricted Likelihood-ratio test Assumption: restricted nested within fullmodel LR chi2(7) = 10.83 Prob > chi2 = 0.1463
Future likelihood to adopt	lrtest fullmodel restricted Likelihood-ratio test Assumption: restricted nested within fullmodel LR chi2(7) = 8.33 Prob > chi2 = 0.3042

Table A30: Ordered logit regression results for current adoption level of NMT (Combining "never used" and "used on the past but not now" responses as "currently not using")

Categories	Independent variable	Dependent variable: Current adoption status of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	**P-value**	**Odds ratio with standard errors**	**P-value**
Farmer attitudes toward importance of factors	*Economic Importance*	0.563 (0.228)	0.157	0.582 (0.311)	0.312
	Environmental Awareness and Compliance Importance	1.477 (0.528)	0.276	2.357* (1.039)	0.052
	Time Investment Importance	1.590 (0.542)	0.173	0.923 (0.418)	0.860
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	0.791 (0.274)	0.499	0.700 (0.284)	0.381
	Economic and Biological Barrier	1.716 (0.675)	0.169	1.695 (0.772)	0.247
	Information Barrier	1.031 (0.433)	0.940	0.928 (0.470)	0.884
	Farmer Belief Barriers	0.690 (0.212)	0.230	1.002 (0.406)	0.995
Adoption of other NMP	*Other NMP*	2.104 (2.186)	0.474	1.053 (1.125)	0.961
Farm characteristics	*Total Cropland* (100 acres)	1.043* (0.026)	0.094	1.041 (0.032)	0.194
	Land Lease (>50% of total cropland)	0.614 (0.290)	0.303	0.686 (0.346)	0.456

Table A30 continued

Categories	Independent variable	Dependent variable: Current adoption status of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	**P-value**	**Odds ratio with standard errors**	**P-value**
Farmer characteristics	*Age*	1.003 (0.015)	0.839	0.999 (0.017)	0.961
	College Degree	0.695 (0.291)	0.386	0.741 (0.332)	0.504
	Farm Income	0.698 (0.346)	0.470	0.678 (0.348)	0.450
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	0.377 (0.229)	0.110	0.468 (0.306)	0.246
	CREP (Conservation Reserve Enhancement Program)	1.774 (1.139)	0.372	2.066 (1.428)	0.293
	CSP (Conservation Stewardship Program)	2.533 (1.455)	0.106	2.187 (1.384)	0.216
	EQIP (Environmental Quality Incentives Program)	1.190 (0.608)	0.733	1.332 (0.723)	0.597
	ACP (State Agriculture Cost-Share Program)	1.298 (0.611)	0.580	1.458 (0.722)	0.446

Table A30 continued

Categories	Independent variable	Dependent variable: Current adoption status of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Location of most of the cropland	*DE* (Delaware)				
	MD (Maryland)	1.032 (0.561)	0.954	1.089 (0.614)	0.879
	PA (Pennsylvania)	0.995 (0.651)	0.995	0.894 (0.605)	0.870
	VA (Virginia)	1.022 (0.699)	0.974	1.069 (0.797)	0.928
Interaction of cropland area and important factors	*TotalCropland* × *Economic Importance*			1.027 (0.056)	0.622
	TotalCropland × *Environmental Awareness and Compliance Importance*			0.911* (0.044)	0.055
	TotalCropland × *Time Investment Importance*			1.094* (0.052)	0.062
Interaction of cropland area and barriers	*TotalCropland* × *Equipment and Technology Barrier*			1.003 (0.032)	0.905
	TotalCropland × *Economic and Biological Barrier*			0.982 (0.043)	0.700

Table A30 continued

Categories	Independent variable	Dependent variable: Current adoption status of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
	TotalCropland × *Information Barrier*			1.041 (1.076)	0.582
	TotalCropland × *Farmer Belief Barrier*			0.937* (0.035)	0.091
	cut1	1.671 (1.510)		0.989 (1.585)	
	cut2	2.404 (1.519)		1.776 (1.592)	
	Log likelihood	-102.732		-98.755	
	Pseudo R^2	0.094		0.129	
	Akaike information criteria (AIC)	251.464		257.510	
	Bayesian information criteria (BIC)	319.122		345.759	
	N	140		140	

Table A31: Ordered logit regression results for current adoption level of NMT, excluding outliers in total cropland area

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Farmer attitudes toward importance of factors	*Economic Importance*	0.662 (0.291)	0.348	0.427 (0.246)	0.141
	Environmental Awareness and Compliance Importance	1.677 (0.638)	0.174	2.325* (1.128)	0.082
	Time Investment Importance	1.417 (0.531)	0.352	1.241 (0.607)	0.659
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	0.847 (0.320)	0.662	0.652 (0.329)	0.397
	Economic and Biological Barrier	1.637 (0.690)	0.242	1.935 (1.095)	0.243
	Information Barrier	0.894 (0.393)	0.800	0.977 (0.539)	0.967
	Farmer Belief Barriers	0.665 (0.223)	0.225	1.163 (0.550)	0.748
Adoption of other NMP	*Other NMP*	2.010 (2.192)	0.522	1.161 (1.329)	0.896
Farm characteristics	*Total Cropland* (100 acres)	1.079** (0.037)	0.026	1.083 (0.054)	0.114
	Land Lease (>50% of total cropland)	0.488 (0.251)	0.164	0.691 (0.370)	0.491
Farmer characteristics	*Age*	1.004 (0.016)	0.787	1.003 (0.017)	0.839
	College Degree	0.952 (0.420)	0.913	0.836 (0.403)	0.712
	Farm Income	0.565 (0.297)	0.278	0.508 (0.284)	0.226

Table A31 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	0.260* (0.181)	0.053	0.380 (0.279)	0.189
	CREP (Conservation Reserve Enhancement Program)	2.736 (1.946)	0.157	2.807 (2.145)	0.177
	CSP (Conservation Stewardship Program)	3.257* (2.054)	0.061	2.958 (1.996)	0.108
	EQIP (Environmental Quality Incentives Program)	0.942 (0.524)	0.916	1.190 (0.703)	0.769
	ACP (State Agriculture Cost-Share Program)	1.251 (0.631)	0.657	1.406 (0.781)	0.539
State	*DE* (Delaware)				
	MD (Maryland)	0.936 (0.526)	0.908	1.042 (0.627)	0.945
	PA (Pennsylvania)	1.150 (0.801)	0.841	1.223 (0.894)	0.783
	VA (Virginia)	1.038 (0.796)	0.961	1.127 (0.882)	0.878

Table A31 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Interaction of cropland area and important factors	*TotalCropland* × *Economic Importance*			1.120 (0.087)	0.143
	TotalCropland × *Environmental Awareness and Compliance Importance*			0.922 (0.068)	0.273
	TotalCropland × *Time Investment Importance*			1.042 (0.055)	0.436
Interaction of cropland area and barriers	*TotalCropland* × *Equipment and Technology Barrier*			1.069 (0.121)	0.555
	TotalCropland × *Economic and Biological Barrier*			0.923 (0.110)	0.506
	TotalCropland × *Information Barrier*			1.011 (0.111)	0.915
	TotalCropland × *Farmer Belief Barrier*			0.909 (0.058)	0.143

Table A31 continued

Categories	Independent variable	Dependent variable: Current adoption level of NMT			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
	cut1	1.643 (1.563)		1.372 (1.644)	
	cut2	2.494 (1.576)		2.282 (1.656)	
	Log likelihood	-92.349		-88.214	
	Pseudo R^2	0.129		0.168	
	Akaike information criteria (AIC)	230.699		236.429	
	Bayesian information criteria (BIC)	296.115		321.754	
	N	127		127	

Table A32: Ordered logit regression results for future likelihood of adoption or expansion of NMT, excluding outliers in total cropland area

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Farmer attitudes toward importance of factors	*Economic Importance*	0.916 (0.388)	0.837	0.950 (0.583)	0.934
	Environmental Awareness and Compliance Importance	1.468 (0.551)	0.306	0.844 (0.459)	0.756
	Time Investment Importance	1.987* (0.734)	0.063	1.680 (0.828)	0.293
Farmer attitudes toward barriers	*Equipment and Technology Barrier*	1.214 (0.497)	0.636	1.897 (1.151)	0.291
	Economic and Biological Barrier	0.744 (0.340)	0.519	0.390 (0.272)	0.178
	Information Barrier	1.553 (0.752)	0.363	2.220 (1.470)	0.229
	Farmer Belief Barriers	1.080 (0.371)	0.822	0.684 (0.365)	0.477
Adoption of other NMP	*Other NMP*	1.754 (1.956)	0.614	3.030 (3.676)	0.361
Farm characteristics	*Total Cropland* (100 acres)	1.054 (0.042)	0.189	0.994 (0.070)	0.934
	Land Lease (>50% of total cropland)	0.799 (0.403)	0.658	0.853 (0.445)	0.762
Farmer characteristics	*Age*	0.973 (0.019)	0.163	0.974 (0.019)	0.210
	College Degree	0.578 (0.276)	0.252	0.566 (0.306)	0.293
	Farm Income	0.661 (0.353)	0.439	0.786 (0.475)	0.692

Table A32 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
Enrollment in environmental or cost-share programs	*CRP* (Conservation Reserve program)	1.300 (0.858)	0.690	1.379 (1.006)	0.659
	CREP (Conservation Reserve Enhancement Program)	0.754 (0.528)	0.688	0.497 (0.411)	0.399
	CSP (Conservation Stewardship Program)	5.575** (4.549)	0.035	5.025 (4.927)	0.100
	EQIP (Environmental Quality Incentives Program)	0.419 (0.248)	0.142	0.370 (0.234)	0.117
	ACP (State Agriculture Cost-Share Program)	2.652* (1.400)	0.065	2.720 (1.536)	0.076
Location of most of the cropland	*DE* (Delaware)				
	MD (Maryland)	1.008 (0.605)	0.989	1.040 (0.650)	0.950
	PA (Pennsylvania)	0.905 (0.664)	0.892	1.199 (0.940)	0.816
	VA (Virginia)	0.556 (0.469)	0.487	0.608 (0.556)	0.587
Interaction of cropland area and important factors	*TotalCropland* × *Economic Importance*			0.958 (0.106)	0.701
	TotalCropland × *Environmental Awareness and Compliance Importance*			1.124 (0.111)	0.237

Table A32 continued

Categories	Independent variable	Dependent variable: Future likelihood of adoption or expansion of use of NMT in next three years			
		Model 1		Model 2	
		Odds ratio with standard errors	P-value	Odds ratio with standard errors	P-value
	TotalCropland × Time Investment Importance			1.091 (0.091)	0.300
Interaction of cropland area and barriers	*TotalCropland × Equipment and Technology Barrier*			0.895 (0.132)	0.453
	TotalCropland × Economic and Biological Barrier			1.253 (0.231)	0.222
	TotalCropland × Information Barrier			0.887 (0.133)	0.427
	TotalCropland × Farmer Belief Barrier			1.106 (0.088)	0.206
	cut1	-0.862 (1.676)		-0.269 (1.822)	
	cut2	0.974 (1.675)		1.674 (1.822)	
	Log likelihood	-84.989		-81.181	
	Pseudo R^2	0.169		0.206	
	Akaike information criteria (AIC)	215.978		222.363	
	Bayesian information criteria (BIC)	277.019		301.982	
	N	105		105	

Appendix B

QUESTIONNAIRE

Who should complete this survey?

This questionnaire should be completed by the person who is the primary decision-maker for crop management and who is at least 18 years old. If you are not the primary decision-maker, please request that the primary decision-maker complete the survey.

1. Are you the primary decision-maker on your farm?

□ Yes □ No

If you selected "no," we do not need you to complete this survey, but your response is still important to us. Please return the survey in the postage paid envelope.

2. This survey is intended for growers of corn, soybeans, and/or small grains. How many acres of corn, soybeans, and/or small grains did you plant in 2021?

_________ acres of corn _________ acres of soybeans _________ acres of small grains

□ I do not grow corn, soybeans, or small grains.

If you selected "I do not grow corn, soybeans or small grains," we do not need you to complete this survey, but your response is still important to us. Please return the survey in the postage paid envelope.

Thank you for completing this survey. First, we'd like to know a little more about your farm. If you have questions about the practices listed, please see the **glossary at the end of the survey**.

3. How many total acres of cropland do you own? __________ acres

4. How many total acres of cropland do you lease from others? __________ acres

5. Where is most of your cropland that you farm located?

   ____________________ County   _______ State

6. How many years have you been the primary decision-maker on your farm? _______ years

7. Which of the following best describes your tillage system?

   □ Conventional tillage   □ Conservation tillage   □ No-till

8. Do you currently raise poultry or livestock?

   □ Yes   □ No

9. Do you use manure for fertilizer?

   □ Yes   □ No

10. Do you apply your own commercial fertilizer or hire a custom applicator?

   □ Apply own   □ Hire custom applicator   □ Both   □ I do not use commercial fertilizer

11. For each of the following practices:

- Select the response that best describes your current experience with the practice.
- Then, if you are **not** currently using a practice on ***at least half*** of your acres, indicate how likely you are to *start using or expand acreage* for each practice.

	What is your current experience with the practice?				How likely are you to start using or expand acreage for the practice in the next 3 years?			
*all practices are defined in the glossary at the end of the survey	I **currently** use this practice on **at least half** of my acres.	I **currently** use this practice on **less than half** of my acres.	I have used this practice **in the past**, but **no longer use** it.	I have **never** used this practice.	Not likely	Somewhat likely	Very likely	**N/A** I already use this practice on **at least half** of my acres
Follow a written nutrient management plan	☐	☐	☐	☐	☐	☐	☐	☐
Grid/zone soil sampling	☐	☐	☐	☐	☐	☐	☐	☐
Liquid manure injection (low-disturbance)	☐	☐	☐	☐	☐	☐	☐	☐
Injection or incorporation of commercial nitrogen fertilizer	☐	☐	☐	☐	☐	☐	☐	☐
Cover crops	☐	☐	☐	☐	☐	☐	☐	☐
Split nitrogen application (e.g. pre-plant + sidedress, fertigation, split spring application, etc.)	☐	☐	☐	☐	☐	☐	☐	☐
Variable rate nitrogen application (VRT)	☐	☐	☐	☐	☐	☐	☐	☐

In-season nitrogen modeling tools (e.g. Adapt-N, Granular, Encirca, Climate Field View)	☐	☐	☐	☐	☐	☐	☐	☐

12. Consider each of the practices listed in the table below. If an agricultural cost-share program offered you a one-time **40% cost-share** to implement that practice for one year *in addition* to your current practices, would you be willing to adopt or expand acreage for that practice within the next 3 years?

- If you are **currently** using the practice on **less than half** of your acres, check "yes" if you would be willing to adopt the practice for **at least half of your acres**.
- If you are **currently** using the practice on **at least half of your acres**, check "yes" if you would be willing to adopt the practice **for the remainder of your acres**.

Please consider each practice individually and select "Yes" or "No" for that practice. If you already use the practice on all of your acres, please select "N/A."

*all practices are defined in the glossary at the end of the survey	Yes	No	N/A I already use this practice on all of my acres
Follow a written nutrient management plan	□	□	□
Grid/zone soil sampling	□	□	□
Liquid manure injection (low-disturbance)	□	□	□
Injection or incorporation of commercial nitrogen fertilizer	□	□	□
Cover crops	□	□	□
Split nitrogen application (e.g. pre-plant + sidedress, fertigation, split spring application, etc.)	□	□	□
Variable rate nitrogen application (VRT)	□	□	□
In-season nitrogen modeling tools (e.g. Adapt-N, Granular, Encirca, Climate Field View)	□	□	□

13. How sure are you of the answers you gave for each practice?

□ Definitely sure □ Probably sure □ Unsure

14. Do you believe that the results of surveys such as this can influence the design and implementation of agricultural cost-share programs?

□ Yes □ No

Questions 15-20 ask about your perceptions and experience with specific practices. Please answer each question as it relates to the practice indicated in bold font.

15. In the table below:

- Indicate if you think using **in-season nitrogen modeling tools** will cause an increase, no change, or a decrease in each of the following factors. If you are already implementing the practice, answer based on your experience.
- Then, on a scale from 1 to 3, indicate how important each factor was in your decision to implement/not implement **in-season nitrogen modeling tools**.

	Impact of the practice			Importance in decision to implement		
The impact of the practice on	Decrease	No change	Increase	Not important	Moderately important	Very important
…crop yields	□	□	□	1	2	3
…input costs	□	□	□	1	2	3
…profitability	□	□	□	1	2	3
…time spent in the field	□	□	□	1	2	3
…time spent on farm management decisions	□	□	□	1	2	3
…soil health and productivity on my farm	□	□	□	1	2	3
…environmental quality in my community	□	□	□	1	2	3
…my compliance with government regulations	□	□	□	1	2	3
Other (please specify)	□	□	□	1	2	3

16. How much do you think each of the following factors limit farmers' use of **in-season nitrogen modeling tools**? Please rate each factor on a scale from 1 to 5, where 1 is not at all and 5 is very much. Circle your response.

	Limits farmers' use of practice				
	Not at all				Very much
Finding information about the practice.	1	2	3	4	5
Having enough time to learn about the practice.	1	2	3	4	5
Getting a return on investment from the practice.	1	2	3	4	5
Cost of the practice.	1	2	3	4	5
Difficulty implementing the practice because of timing and weather.	1	2	3	4	5
Having the right equipment to implement the practice.	1	2	3	4	5
Having the right technology to implement the practice.	1	2	3	4	5
Finding services related to the practice (e.g. crop advisor, custom applicator, soil testing)	1	2	3	4	5
Believing the practice is better suited for larger operations.	1	2	3	4	5
Difficulty implementing the practice on leased land.	1	2	3	4	5
Having a previous negative experience trying the practice.	1	2	3	4	5
Preferring to use practices they are more familiar with.	1	2	3	4	5
Believing that new technologies are too difficult to use.	1	2	3	4	5
Other (please describe)	1	2	3	4	5

17. In the table below:

- Indicate if you think using **split nitrogen application** will cause an increase, no change, or a decrease in each of the following factors. If you are already implementing the practice, answer based on your experience.
- Then, on a scale from 1 to 3, indicate how important each factor was in your decision to implement/not implement **split nitrogen application.**

	Impact of the practice			Importance in decision to implement		
The impact of the practice on	Decrease	No change	Increase	Not important	Moderately important	Very important
…crop yields	□	□	□	1	2	3
…input costs	□	□	□	1	2	3
…profitability	□	□	□	1	2	3
…time spent in the field	□	□	□	1	2	3
…time spent on farm management decisions	□	□	□	1	2	3
…soil health and productivity on my farm	□	□	□	1	2	3
…environmental quality in my community	□	□	□	1	2	3
…my compliance with government regulations	□	□	□	1	2	3
Other (please specify)	□	□	□	1	2	3

18. How much do you think each of the following factors limit farmers' use of **split nitrogen application**? Please rate each factor on a scale from 1 to 5, where 1 is not at all and 5 is very much. Circle your response.

	Limits farmers' use of practice				
	Not at all				Very Much
Finding information about the practice.	1	2	3	4	5
Having enough time to learn about the practice.	1	2	3	4	5
Getting a return on investment from the practice.	1	2	3	4	5
Cost of the practice.	1	2	3	4	5
Difficulty implementing the practice because of timing and weather.	1	2	3	4	5
Having the right equipment to implement the practice.	1	2	3	4	5
Having the right technology to implement the practice.	1	2	3	4	5
Finding services related to the practice (e.g. crop advisor, custom applicator, soil testing)	1	2	3	4	5
Believing the practice is better suited for larger operations.	1	2	3	4	5
Difficulty implementing the practice on leased land.	1	2	3	4	5
Having a previous negative experience trying the practice.	1	2	3	4	5
Preferring to use practices they are more familiar with.	1	2	3	4	5
Believing that new technologies are too difficult to use.	1	2	3	4	5
Other (please describe)	1	2	3	4	5

19. In the table below:

- Indicate if you think using **variable rate nitrogen application (VRT)** will cause an increase, no change, or a decrease in each of the following factors. If you are already implementing the practice, answer based on your experience.
- Then, on a scale from 1 to 3, indicate how important each factor was in your decision to implement/not implement **variable rate nitrogen application (VRT) .**

	Impact of the practice			Importance in decision to implement		
The impact of the practice on	Decrease	No change	Increase	Not important	Moderately important	Very important
…crop yields	□	□	□	1	2	3
…input costs	□	□	□	1	2	3
…profitability	□	□	□	1	2	3
…time spent in the field	□	□	□	1	2	3
…time spent on farm management decisions	□	□	□	1	2	3
…soil health and productivity on my farm	□	□	□	1	2	3
…environmental quality in my community	□	□	□	1	2	3
…my compliance with government regulations	□	□	□	1	2	3
Other (please specify)	□	□	□	1	2	3

20. How much do you think each of the following factors limit farmers' use of **variable rate nitrogen application (VRT)**? Please rate each factor on a scale from 1 to 5, where 1 is not at all and 5 is very much. Circle your response.

	Limits farmers' use of practice				
	Not at all				Very much
Finding information about the practice.	1	2	3	4	5
Having enough time to learn about the practice.	1	2	3	4	5
Getting a return on investment from the practice.	1	2	3	4	5
Cost of the practice.	1	2	3	4	5
Difficulty implementing the practice because of timing and weather.	1	2	3	4	5
Having the right equipment to implement the practice.	1	2	3	4	5
Having the right technology to implement the practice.	1	2	3	4	5
Finding services related to the practice (e.g. crop advisor, custom applicator, soil testing)	1	2	3	4	5
Believing the practice is better suited for larger operations.	1	2	3	4	5
Difficulty implementing the practice on leased land.	1	2	3	4	5
Having a previous negative experience trying the practice.	1	2	3	4	5
Preferring to use practices they are more familiar with.	1	2	3	4	5
Believing that new technologies are too difficult to use.	1	2	3	4	5
Other (please describe)	1	2	3	4	5

21. What type of assistance would help you make the decision to implement *additional* nutrient management practices (beyond those you currently use)? Select all that apply.

- □ Assistance locating a crop advisor
- □ Consultation on creating a nutrient management plan or a more advanced plan
- □ Guidance on how to take the next step in implementing the practice
- □ Assistance with equipment costs
- □ Economic analysis of implementing a new practice (i.e. calculating return on investment)
- □ Other (please describe) ____
- □ None of the above

22. How important is information from the following sources in your decision to implement nutrient management practices? Please rate each factor on a scale from 1 to 5, where 1 is not influential and 5 is very influential. Circle your response.

	Not influential				Very influential
Family members	1	2	3	4	5
Other farmers (non-family)	1	2	3	4	5
Personal experience with using a practice	1	2	3	4	5
University researchers	1	2	3	4	5
University county extension agents	1	2	3	4	5
Private foundations	1	2	3	4	5
State Department of Agriculture	1	2	3	4	5
Natural Resources Conservation Service (NRCS)	1	2	3	4	5
County Conservation District staff	1	2	3	4	5
Crop consultants for a seed or fertilizer company	1	2	3	4	5
Independent crop consultants	1	2	3	4	5
Farm journals (e.g. Delmarva Farmer)	1	2	3	4	5
Commodity boards and/or trade organizations	1	2	3	4	5
Other (please describe)	1	2	3	4	5

23. What type of information would be most helpful for you to learn about nutrient management practices? Please rate each type of information from 1 to 5, where 1 is not helpful and 5 is most helpful. Circle your response.

	Not helpful				Most helpful
Case studies	1	2	3	4	5
Economic budgets	1	2	3	4	5
On-farm trial opportunities	1	2	3	4	5
Testimonials (short stories) from local farmers	1	2	3	4	5
University research summaries	1	2	3	4	5
Other (please describe)	1	2	3	4	5

24. What methods of communication do you find most helpful for receiving information about nutrient management practices? Please rate each communication method from 1 to 5, where 1 is not helpful and 5 is most helpful. Circle your response.

	Not helpful				Most helpful
Brochures/pamphlets	1	2	3	4	5
Emails	1	2	3	4	5
Farm demonstrations by local farmers	1	2	3	4	5
Field days	1	2	3	4	5
Farm school/training meetings	1	2	3	4	5
Newsletters	1	2	3	4	5
Podcasts	1	2	3	4	5
Social media (e.g. Facebook, Twitter, Instagram)	1	2	3	4	5
Website or blog	1	2	3	4	5
YouTube training videos	1	2	3	4	5
Other (please describe)	1	2	3	4	5

25. Now we'd like to ask you some general questions about your perceptions of nutrient management. Please rate the following statements from 1 to 5, where 1 is strongly disagree and 5 is strongly agree.

	Strongly disagree				Strongly agree
I am concerned that nutrient loss from my farm negatively affects soil health and crop yield.	1	2	3	4	5
I am concerned that nutrient loss from my farm negatively affects farm profitability.	1	2	3	4	5
Nutrient management practices that incorporate technology can help me avoid nutrient loss from my farm.	1	2	3	4	5
I am concerned that nutrient loss from my farm negatively affects water quality.	1	2	3	4	5
I am concerned about water quality on my farm.	1	2	3	4	5
I am concerned about water quality in nearby rivers, streams, and bays.	1	2	3	4	5
The government should regulate farm nutrient management.	1	2	3	4	5
Nutrient losses can be controlled through voluntary measures.	1	2	3	4	5
I am in favor of agricultural cost-share programs that provide financial assistance to farmers who implement nutrient management practices on their farm.	1	2	3	4	5

26. Are you enrolled in any of the following programs? (Select all that apply)

- □ Conservation Reserve Program (CRP)
- □ Conservation Reserve Enhancement Program (CREP)
- □ Conservation Stewardship Program (CSP)
- □ Environmental Quality Incentives Program (EQIP)
- □ State agricultural cost-share program
- □ Other (please describe)___________________________
- □ None of the above

27. Do you participate in water related recreation at least once per year? (e.g. boating, fishing, swimming in a lake, river, stream, etc.)

□ Yes □ No

28. Do you have surface water on your land or flowing through your property under regular non-flooding situations such as a lake, river, stream, brook, creek, pond, etc.?

□ Yes □ No

29. In what year were you born? _________

30. What is the highest level of education you have completed?

- □ Less than 12 years
- □ High school diploma or GED
- □ Some college
- □ Associate's degree and/or technical training
- □ Bachelor's degree
- □ Graduate or professional degree

31. What proportion of your household's gross income in 2020 was earned through farming?

- □ Less than 25%
- □ 25%-50%
- □ 51%-75%
- □ 76%-100%

32. What is your plan for your farm when you retire? (Check the option that best fits your situation. Please select only one response.)

- □ Someone related to me will operate the farm.

- □ Someone who is not related to me will operate the farm.
- □ The farm will be converted into non-farm use or sold for development.
- □ The farm will be enrolled in a farmland preservation program.
- □ I am uncertain.

If there is anything else you would like us to know about your nutrient management decisions, please comment below.

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Thank you for your time completing this survey. <u>Please return the survey in the postage paid envelope.</u> By completing this survey, you are eligible to enter a drawing for a $250 Visa gift card (10 available), a $100 Visa gift card (20 available) or a $50 Visa gift card (99 available). To enter the drawing, please complete the enclosed postcard with your name and address. To be eligible for the drawing, surveys must be returned by January 15, 2022.

GLOSSARY

Conservation tillage: The practice of surface tilling prior to planting to prepare the seedbed for planting but also retain crop residues on the field, including vertical or mulch tillage, ridge tillage, chiseling, or disking.

Conventional tillage: The practice of full width tillage prior to planting to prepare the seedbed for planting using chisels, field cultivators, or disks.

Cost-share: A program that reimburses farmers and other land-managers for a portion of the cost of using certain conservation practices if all guidelines are met.

Cover crop: A crop (e.g., small grains, brassicas, legumes) planted during the winter months in fields that would otherwise be bare or fallow to prevent the loss of soil nutrients, minimize soil erosion, and enhance soil properties; this crop is to benefit the soil and water quality and therefore, is not harvested (although it may be grazed).

Grid soil sampling: A systematic soil sampling methodology that allows for mapping of nutrient variability in the field. A grid of known size (e.g., 2 acres) is superimposed over a field and a composite soil sample of 5 to 10 soil cores is collected at each grid intersection. Each soil sample is submitted separately for soil analysis. Grid sampling is best for large, uniformly shaped fields.

Incorporation: The practice of mixing manure or commercial fertilizer into the soil profile using tillage.

Injection: The application practice of placing manure and/or chemical fertilizer under the soil surface with minimal soil disturbance. Injection is a viable option for liquid manures or commercial fertilizers only. Common injection equipment includes shallow disk or shank injectors with closing disks.

In-season nitrogen modeling tools: Computer modelling systems that use local weather, site, and crop conditions to predict in-season crop nitrogen demands during the season in real time. Several companies offer nitrogen modeling services to guide in-season N applications (e.g. Adapt-N, Granular, Encirca, Climate Field View)

No-till: Plants are established and grown in a field that was not tilled following the previous crop. This tillage management maintains the highest level of crop residue.

Nutrient management plan: A site-specific plan written by a certified consultant that provides guidance for efficient nutrient applications based on University recommendations and/or soil test results. The goal of a nutrient management plan is to improve nutrient use efficiency and reduce nutrient losses to the environment.

Pre-plant fertilization: The application of fertilizer days or weeks prior to planting crop

Split nitrogen application: Applying a small amount of nitrogen early in the season (i.e., pre-plant or at-plant) followed by one or more applications of nitrogen in-season during the period of active plant growth (e.g. sidedress). Most of the nitrogen is applied in-season.

Variable Rate application: A type of application where the material (seed, fertilizer, irrigation, etc.) is applied based on a specific need-based prescription for different areas within a field based on soil or crop characteristics.

Zone soil sampling: A soil sampling methodology that allows areas of known or suspected variability to be sampled individually. Individual composite soil samples are collected from specified field areas by soil type, management history, landscape positioning, drainage type, etc. Each soil sample is submitted separately for analysis. This soil sampling method is best for irregularly shaped or small fields.