Farming Decisions in a Complex and Uncertain World: Nitrogen Management in Midwestern Corn Agriculture

ABSTRACT

Excess agricultural nitrogen in the environment is a persistent problem in the US and other regions of the world, contributing to water and air pollution as well as climate change. Efforts to reduce nitrogen from agricultural sources largely rely on voluntary efforts by farmers to reduce inputs and improve uptake by crops, yet research has failed to comprehensively depict farmers' nitrogen decision making processes, particularly as it engages with uncertainty. Through analysis of in-depth interviews with US corn growers, this study reveals how farmers experience and process numerous uncertainties associated with nitrogen management, such as weather variability, crop and input price volatility, lack of knowledge about biophysical systems, and the possibility of under- or over-applying. Farmers used one of two general decision making management strategies to address these uncertainties: heuristic-based or data-intensive decision making. Heuristic-based decision making involves minimizing sources of uncertainty and reliance on heuristics and personal previous experiences, while data-intensive decision making is the increased use of field- and farm-scale data collection and management, as well as increased management effort within a given growing season.

Keywords: heuristic; nutrient management; agro-ecosystems; risk; weather

INTRODUCTION

Synthetic nitrogen (N) fertilizer is a crucial chemical input of modern industrial agriculture. Global inputs of N have grown dramatically in the past century, to more than three times pre-industrial inputs (Galloway et al. 2008; Vitousek et al. 2012). Due in part to the rapid increases in input levels, excess N in the environment now ranks among the most severe environmental consequences of industrial agriculture (Conley et al. 2009; Davidson et al. 2012; Davidson et al. 2015). Excess environmental N contributes to impairment of water quality in freshwater and coastal zones (Conley et al. 2009), and climate change through the production of N_2O gas (IPCC 2007; Robertson 2012).

Researchers, conservation practitioners, and policy makers have long sought to ameliorate these intractable environmental challenges. Policy based efforts include, for instance, USDA's "avoid, control, and trap" strategy (Osmond et al. 2015) and recent state-based efforts, such as Iowa's Nutrient Reduction Strategy, which set nutrient reduction targets and provide voluntary tools to farmers to meet those targets (Lawrence 2014). The private sector has also taken a larger role, with agricultural firms offering a growing range of fertilizer products, additives, and management tools. The most notable of these efforts is the 4Rs of Nutrient Stewardship strategy—right place, right time, right amount, right rate—developed by the fertilizer industry, which promotes nutrient management strategies to improve overall N use efficiency (NUE; IFA 2009). Researchers have encouraged methods to increase NUE—the proportion of total N applied taken up by the crop produced—and offered perspectives on their potential implementation in cropping and livestock systems (Galloway et al. 2004; Robertson and Vitousek 2009).

Although efforts to improve system-wide NUE have met with varying levels of success (Davidson et al. 2012), given inherent complexity of modern farming systems and the role of fertilizers within those systems, improved management of N could significantly reduce the negative environmental externalities of N fertilizer application (Davidson et al. 2012). Despite these benefits, Ribaudo et al. (2011) report that nearly two thirds of U.S. cropland does not meet the three criteria for optimal N management: (1) the use of appropriate fertilizer rate, (2) timing of application close to greatest crop need, (3) and incorporation of fertilizer into soil.

In response to the persistent state of low NUE, a growing number of studies have attempted to characterize and understand farmer adoption of nutrient management practices, particularly focused on how farmer or farm level characteristics influence adoption (Osmond et al. 2015; Weber and McCann 2015). This literature may benefit from a broader understanding of how farmers make N management decisions, especially farmers' cognitive process of sorting and synthesizing information, as few studies have attempted to depict farmer nutrient decision-making in this way. Such a depiction is especially fruitful to offer a more nuanced understanding of Midwestern farmers' N management decision-making processes.

The research we present here provides such a description. We explore N management decisions using 148 interviews with corn growers in the U.S. Midwest. Corn production is the primary target of N fertilizer use in the U.S., particularly in the Midwest (Robertson and Vitousek 2009; Millar and Robertson 2015). We focus on the social and ecological factors producing uncertainties associated with determining appropriate N input levels in their operations and how farmers navigate these uncertainties. After reviewing past literature, we outline forms of uncertainty likely to be influential during farmers' decision making processes. Next, we introduce our data sources and analysis methods, followed by the major forms of uncertainty that emerged from interviews with farmers. We then provide a discussion of two major strategies farmers use for addressing uncertainty inherent to N management: heuristic (or hands-on) and data-intensive. Last, we offer some concluding thoughts about how our findings impact outcomes of on-farm N management and potential outreach and education strategies.

Past Literature on N Management Decision-making

Farmers have many decisions to make regarding N use. These decisions include determining when in the season N should be applied, where it should be applied relative to the corn plant, the type of N fertilizer to apply, and the rate at which the N is applied (Robertson et al. 2012). There are numerous options for all of these decision points. For instance, farmers can choose to apply N once a season or multiple times including fall, spring and mid-summer. Many farmers split their N application between planting and post-emergence, targeting part of their N application to match the period of rapid crop growth (Robertson and Vitousek 2009). USDA data indicate that in 2013, nearly 32% of crop acres received some nitrogen application post-planting (USDA 2018). Numerous chemical additives can be added to N fertilizers to slow biophysical processes that result in loss or conversion of N in soil, including nitrification and urease inhibitors (Ribaudo et al. 2011). These additives extend the timeframe in which N is available for uptake by plants, reducing loss to the environment. Application rates can vary across each time period in the crop growth cycle, or with the use of variable rate technology (VRT) farmers can choose to use multiple rates within or across their fields. Improved data collection and management technologies can also assist farmers in understanding the nutrient dynamics within their fields. Yield monitors, soil testing, plant and tissue testing, in-field sensors, and remote sensing technologies ; all increase the amount of data available to farmers (Gebbers and Adamchuck 2010; Mulla 2013; Shaver et al. 2011; Zhang and Kovacs 2012). However, it remains unclear to what extent these technologies have been incorporated into crop production systems and how the information gathered feeds back into decision making (Tey and Brindal 2012).

A seasonal N management strategy emerges through farmers' selection and adoption of a given set of practices from these options. Much of the literature examining farmer decision-making focuses on how demographic factors like farmer's age, education level, tenure and income and farm characteristics like farm size influence the adoption of given practices from these options (Baumgart-getz et al. 2012; Caswell 2001; Weber and McCann 2015). The directional influence of these variables is mixed; for example, age and educational attainment are often found to be correlated with practice adoption (negatively and positively, respectively), though in some studies there are inverse relationships, or no relationship (Baumgart-getz et al. 2012). Other studies find social-psychological factors, such as farmers' environmental and risk attitudes, to matter, with positive environmental attitudes often associated with greater adoption of nutrient conservation practices (Reimer et al., 2012), though farmers' attitude-informed behavior might be limited by external processes is noted in other work (e.g. Stuart and Gillon 2013). Some scholarship has emphasized economic dimensions of farmers' decisions (Babcock 1992; Sheriff, 2005; Osmond et al. 2015), including input and crop prices (Davidson et al. 2015; Williamson 2011) and the competitive economic nature of contemporary agriculture (Stuart et al. 2014). This work has generally emphasized that the low price of N relative to corn encourages farmers to apply in excess to 'insure' profitable crop yield (e.g. Sherriff 2005), with some research indicating that high N prices reduce how much farmers apply (Williamson 2011). Finally, a growing literature examines the influence of farmers' information sources, such as university extension or fertilizer dealers, related to N management (Stuart et al. 2014; Osmond et al. 2015; Weber and McCann 2015). These studies have largely demonstrated that farmers seek information on N management from private sector sources, including crop advisors and retailers, potentially leading to higher N application rates (Stuart et al. 2014).

Along with these social factors, biophysical processes also likely influence farmers' N decision-making (Stuart et al. 2015). For instance, N cycling within soil and cropping systems is influenced by biophysical factors including precipitation, temperature, and microbial action (Millar and Robertson 2015). To ensure profitable crop yields, it is likely that farmers' N management strategies occur both in reaction to or in anticipation of these biophysical processes, although relatively little research to date has focused on how biophysical factors influence farmers' decisions. One recent study highlights the complex interactions of corn farmers' values, attitudes, and dynamic biophysical environment with regard to views of soil management (Roesch-McNally et al. 2018). Similarly, other studies have demonstrated that uncertainty over the direction and magnitude of climate change and climate variability is influenced by lack of information and undermines adaptive action (Morton et al. 2017). Uncertainty and risk associated with complex socio-ecological feedbacks then has significant implications for medium- and long-term farm management (including soil and nutrient management domains) and how farmers respond to climate change-related risks.

The above evidence indicates numerous psychological, social, economic and biophysical factors influence farmers' seasonal N management decisions. However, to date the literature has largely focused on the influence of these factors on what decisions farmers make. How farmers make management decisions has yet to be depicted. This literature does indicate that this decision-making process takes place in the context of complex socio-ecological systems with significant uncertainty and risk. Our primary concern in this study is to offer exploratory insight into farmers' decision making related to addressing these social and biophysical processes, especially given significant uncertainty associated with the biophysical dimension of farm management. Consequently, we specifically analyze two questions: (1) how do social, economic and biophysical factors contribute to uncertainty in farmers' N management decision-making; and (2) in what ways do farmers engage with these uncertainties to determine a seasonal N management strategy? Through exploring answers to these questions, we draw from work on uncertainty to offer a depiction of farmers' N management decision-making pathways. Our goal is to identify and describe farmer perceptions of uncertainty and decision-making strategies to address these uncertainties. This analysis uses qualitative methods to explore farmers' decision making strategies in a deep and rich way. Qualitative methods have been used in other studies within the human dimensions of agriculture to explore conservation practice adoption (Reimer et al. 2012a) conservation attitudes (Reimer et al. 2012b), cover crop adoption (Arbuckle and Roesch-McNally 2015), and views of soil stewardship (Roesch-McNally et al. 2018). The use of an extensive set of interviews allows for a deep exploration of the perspectives and behaviors of individual farmers regarding nitrogen management, allowing the researcher to go beyond describing what farmers are doing to elaborate on the why's and how's of decision making.

Decision-making under Uncertainty

Many decisions humans make may not result in an intended outcome due to uncertainties. Prior social science work distinguishes two broad categories: *aleatory* and *epistemic uncertainty* (Weber and Johnson 2009)*. Aleatory uncertainty* is the result of inherent uncertainties associated with stochastic dynamics of complex systems, while *epistemic uncertainty* stems from lack of knowledge about the processes or functions associated with the systems involved (Weber and Johnson 2009). Some aspects of systems, especially the types of biophysical systems associated with agriculture, are outside of human control and subject to significant stochasticity. One example is weather, where temperature and precipitation patterns exhibit annual variability and have significant impacts on crop production. As a result, in determining their N management strategies, farmers likely face many *aleatory* (unpredictable) uncertainties, such as weather and other unknowable or unpredictable biophysical processes, which prevent one uniform decision from being appropriate in all contexts but do reflect the unique confluence of events and information for that farmer at that specific time.

There are also uncertainties stemming from a lack of understanding of the biological, chemical, and physical dynamics involved in crop production. For instance, farmers may be unsure about the exact amount of N produced by a bushel of soybeans, or how much N is needed to produce a bushel of corn. These sources of *epistemic uncertainty* are not encountered by farmers alone; there are significant aspects of nutrient cycling, microbial community structure and function, and plant-soil-water interactions that remain subjects of intense empirical scrutiny by scientists (Galloway 2008). These knowable but unknown or misunderstood processes and factors are also likely sources of uncertainty in farmers' N application decisions. The uncertainties associated with decision-making result in unknown probabilities of desired outcomes resulting from a given decision.

Previous research outlines two distinct decision-making pathways based on predetermined factors and experience, one of which is analytical and rule-based and one that is experiential and associative (Weber and Johnson 2009; Kahneman 2003). This dual-processing is particularly relevant in decision-making under uncertainty. Experiential processing and learning is closely tied with strong sentiment, and often plays a larger role in decision-making, especially in uncertain situations (Loewenstein et al. 2001; Slovic et al. 2007). The role of individual risk preferences yields useful insights for this study. First, decision-makers routinely evaluate choices and outcomes relative to each other. In particular, people frequently compare the outcome of their chosen option with the outcome they could have achieved with another possible option (Landman 1993; Kahneman 2003). Given this relative comparison of choices and the powerful motivation of loss aversion (Camerer 2005), individuals will often minimize the potential for regret when making decisions by biasing toward choices with better potential outcomes. Individuals also show a preference for reduced uncertainty where individuals will selectively process information (i.e. 'edit' it) by eliminating or ignoring aspects of the choices to reduce complexity in decision-making. Importantly, however, precisely how people use these cognitive processes to simplify decisions is not well understood (Weber and Johnson 2009).

The complexity of the biophysical systems at work in converting N into crop yield, along with social and economic factors, complicates choices about fertilizer, including application rate, timing, and placement. This discussion suggests that these factors produce multiple types of uncertainty in farmers' N management decision processes, and that farmers will inevitably encounter ambiguity in decision-making. We anticipate that farmers use multiple strategies for addressing uncertainty, including use of shortcuts or heuristics to streamline decision-making by incorporating multiple experiences and decision factors into single guidelines, information seeking behavior that seek to reduce *epistemic* uncertainties, and more intense incorporation of data in management efforts to exert more control over *aleatory* (i.e., unpredictable environmental) uncertainties. How farmers respond to uncertainty is also likely to result in different decisions with regard to on-farm fertilizer practices, as decision-making may become more analytical or experiential. In the N management context, analytical decision-making is likely to result in information seeking and management intensification, while experiential decision-making relies more heavily on past experience and selective processing of certain forms of uncertainty (such as weather or prices outside of the farmer's control). Moreover, it is likely that farmers do not exclusively follow an experiential or analytical decision-making pathway for all decisions, but rather choose from a range of strategies based on social or biophysical context.

METHODS

We investigate uncertainty in farmer decision-making through analysis of qualitative data. Between May and December 2014, we conducted interviews that focused on N application decision-making with farmers in three states located in the U.S. Midwest: Indiana, Iowa, and Michigan. These states contain extensive lands devoted to row-crop agriculture, though this amount differs from state to state, with over 65% of Iowa planted in either corn or soybeans, while only 12% of Michigan is devoted to these crops. Cumulatively, these three states reflect over a quarter of U.S. corn production in 2015 (USDA-NASS 2016). Our data presented here comes from interviews with 148 farmers, with 51 Iowa farmers, 51 from Indiana, and 46 in Michigan[1]. Interviews were conducted in-person with the farm's primary decision-maker by a member of our research team.

To gather participants for these interviews, we sought initial contact information for farmers through university extension offices in each state, as well through other farmer organizations. Of the

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[1] Six farmers either were not asked this question (for various reasons) or their answer could not be transcribed. In consequence, our total responses equal 148.

154 interviewed farmers, 48% were recruited through university extension and another 16% of our contacts came from other state resource professionals including voluntary conservation associations. The remainder of contacts comprising the sample (35%) were recruited via snow-ball sampling technique (Coleman 1958), where the initial respondents recruit secondary participants by recommending acquaintances as contacts. Snowball sampling is appropriate for contacting interview subjects, such as farmers, who may be difficult to access (Faugier and Sargeant 1997). Farmers in our sample typically grew at least 100 acres of corn per year (range from 170 to 14,000 acres). Average farm sizes of farmers we interviewed in each state are 1,236 acres in Iowa, 1,529 acres in Indiana, and 2,216 acres in Michigan. These farm sizes are substantially larger than the mean farm size according to US Department of Agriculture statistics (Table 1). These wide differences are possibly due to our sampling efforts targeting full-time, commercial corn growers, which operate larger size farms. Iowa farms were located primarily in the eastern and central parts of the state. Indiana farms were primarily located in the northwest, northeast, and central regions, while Michigan farms were concentrated in south-central Michigan, with a few farms in the southwest and southeast parts of the state. While we did not specifically ask participants their age or when they began farming, the majority indicated through the interviews that they had been farming for multiple decades.

Qualitative methods are ideal at providing insights into little studied topics (Kreuger and Casey 2009) and these methodological benefits have been noted in past work in the agricultural context (Prokopy et al. 2017). Accordingly, we used interviews to capture in detail the range of decision-making processes of full-time commercial corn producers, and our results should therefore be viewed as providing exploratory insight into this yet to be well-documented process. The sample size in this research represents a small fraction of the overall farm population in the study states (less than 0.5%, Table 1), but is in line with previous qualitative research studies (e.g. Arbuckle and Roesch-McNally, 2015; Reimer et al., 2012a). Our techniques to gather contacts for these interviews may lead to a sample that over-represents farmers who use university extension or other agricultural organizations in their nutrient decision-making. Previous research has demonstrated that farmers rely more heavily on university extension for information about conservation practices (Mase et al., 2015), so farmers in our study could be more conservation-oriented in their management decisions. Our analyses of interviews show that farmers in our sample expressed diverse opinions on N management, particularly related to where they sought information to inform their decisions on this matter.

We used a semi-structured interview guide for our interviews, which included prompts and opportunities for open-ended responses on defined topics. Participants were asked to provide basic information about their farm operations and use of N fertilizers. In addition, farmers were asked about their use of N efficiency practices, sources of information about N fertilizers, influence of policy and market drivers, the influence of private companies, views of climate change, and perceptions of environmental problems related to use of N fertilizers. Informed consent was obtained from all individual research participants included in this study, and all interviews were recorded with permission of the respondent. Upon completion, interviews were transcribed verbatim and analyzed via NVivo software (QSR 2018).

Qualitative data analysis methods have been developed extensively in many social science fields (Corbin and Strauss 2008). Qualitative research approaches value rich forms of data to develop theory that are “grounded” in the data (Charmaz 2006). As with quantitative research, methods exist for ensuring reliability and validity (Whittemore et al. 2001). Whittemore et al. (2001) highlight several aspects of validity in qualitative research that are important: credibility, authenticity, criticality, and integrity. Findings should come from an accurate interpretation of the data (credibility), which in turn accurately reflect the experience and views of participants (authenticity). Research should involve a systematic approach that critically evaluates data (criticality) and ensure the integrity of the researcher as an impartial observer. For clarity, we have quantified responses in each theme to support our qualitative findings (table 2).

In this study, we used Braun and Clarke's (2006) thematic analysis approach, providing criticality and integrity to the research approach. Initial coding of interviews was done by question category.[2] Coded question-categories most relevant to the N decision-making processes were discussed and determined among members of the research team in a subsequent round of analysis (e.g. questions pertaining to use of various efficiency practices, sources of information about N management, and the difficulty of making management decisions with regard to N). Within these determined question-categories, we identified emergent themes representing phenomena that spanned the selected interview questions. These themes encompassed (1) the factors that imposed uncertainty and risk in N management and (2) how farmers discussed strategies for addressing these factors. Thematic groupings for these factors and strategies were determined between coders. In the Results and Discussion, we provide supporting quotes for each theme elaborated, providing authenticity from our data.

RESULTS AND DISCUSSION

Uncertainty in N Management

Farmers' N management decisions are made in response to many social and ecological factors. The sources of uncertainty were the most clear cross-cutting themes represented in responses to questions throughout the interviews, from farmer perceptions and use of decision support tools, external sources of information, and spatial and annual variation in management practices. How farmers perceive these uncertainties influenced decision-making strategies and on-farm practices. In this section

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[2] To establish a strategy for coding interviewees' responses that varied considerably from the question category, or were perceived as more applicable to another question category, a small sample of interviews were coded by three team members independently. Upon completion of coding, the interviews were checked for consistency. When inconsistency in coding emerged, they were discussed until a question category could be mutually agreed upon. This strategy established the boundaries of particular question categories that were used throughout the remainder of the coding process.

we outline factors farmers commonly deemed important in determining an N management strategy and describe how these factors contributed difficulty and uncertainty to the decision process. The sources of uncertainty we describe below are not mutually exclusive and farmers often mentioned multiple. Table 2 includes counts of the number of farmers who made statements reflecting a given uncertainty theme, as well as a categorization by decision-making process (more on this below). This quantification does not reflect an exhaustive representation of farmer views of these themes. Rather, the count data in table 2 are presented to support the qualitative findings and reflect the general emphasis interviewed farmers place on each theme in decision making.

[Table 2]

Weather: The most commonly mentioned factor in farmers' N decision-making was seasonal weather (79/148, or 53% of respondents; table 2). Farmers frequently discussed the inherent variance of weather, often in response to interview questions concerning the difficulty of determining application rates. As one Iowa farmer said: "*You don't know what the weather is going to be like during the growing season*." Weather's variability created uncertainty in farmers' seasonal N management decisions in three aspects: 1) application rate, 2) application method, and 3) timing of application.

Agro-ecological research has demonstrated that the variability and stochasticity in weather patterns increases the challenge for farmers of matching N application to crop needs throughout the growing season (Millar and Robertson 2015). Suboptimal conditions could reduce yield potential, as heavy rainfall post-application of N can increase denitrification and N soil leaching, consequently reducing N available for crop needs (Robertson and Groffman 2007; Robertson et al. 2012). Weather conditions can also create optimal growing conditions for the crop, leading to high yield-potential conditions that increase crop need for N. However, since a farmer cannot predict the exact seasonal weather they will experience, this unknowable variability contributed to uncertainty in farmers' N application rate decisions, since an ideal rate could not be predetermined. For instance, an Iowa farmer discussed ideal N application as a “moving target” because, in his words, “*[N application] is dependent on the kind of weather you’ve had*.”

In addition to application rate, farmers’ determination of the appropriate method and timing of their N applications was related to another weather-based complexity. One farmer commented on how the effectiveness of pre-plant application method depends on rain: *“Our biggest concern is when you put the pre-plant [N] on it can lay on top of the ground, before it rains, and we can lose some of it from volatilization.”* Farmers in our sample did not perceive a single solution as correct, or even the “best choice” for addressing this issue. For instance, in response to weather variability one farmer had abandoned side-dress N application (in which fertilizer is applied during the growing season alongside the plant post emergence): *“When you want to be doing it [applying N], you’re doing other things; or the weather turns against you and you get a few days of rain and then it gets too big on you and then you’re making a mess. So I’ve pretty much abandoned side-dressing on corn.”* Other farmers, like one from Michigan, considered side-dress as a solution to the issue: *“We try [to apply N] half pre-plant and half side-dress just to help get the acres covered, but this year it was mostly side dress because it was too wet earlier on.”* Many farmers expressed the complex effect of weather on the timing and method (e.g., broadcast vs. incorporation or injection) of N application.

It should be noted that these complexities related to weather often come together simultaneously in farmers’ N management decisions. That is, they must choose N application rates alongside timing and method of application, all of which weather’s variable influence makes more complex and uncertain. As one Indiana farmer described:

> *“The most difficult decision to make on nitrogen is what the crop is going to . . . end up being. If you’ve got a 120-bushel corn crop and you put it [N fertilizer] on in May and said well, we were hoping for a 200 [bushel yield], well you lost money really on that, you spent more money than you should have, and that’s what I like about our crop decision [with side-dressing], we can still*

> *go and put an application of [N] on if we think we need it. So I think the main thing we have to look at is the timing and what you feel like Mother Nature is going to give us for the year. That's the biggest decision we have to make."*

This quote illustrates how seasonal weather's variability, especially related to precipitation, creates uncertainty in two ways. First, it affects when and how N is available to plants and farmers' capacity to operate machinery in fields, which affects timing and method of application. Second, it impacts crop growth, which impacts how much total N is needed to maximize yield given growing conditions in a given year. As seasonal weather is inherently variable, farmers can make no single "right" decision in response to or anticipation of it. The biophysical contexts that define "right" shift with the variations in weather. Consequently, weather represents a source of *aleatory* or random uncertainty in farmers' N management decisions.

Time Lags*:* In addition to weather's *aleatory* (or random) uncertainty, several farmers (n=7, 5% of sample) expressed the impact of time lags on decision-making. Crop production occurs over the course of several months and is influenced by weather, N application rate and timing, and agronomic decisions (e.g. seed selection, tillage, and soil management practices). Most decisions influencing that season's yield are made at the beginning of the production year, or even the preceding year. In this sense, crop yield is "locked in" well ahead of harvest, meaning farmers have made all management decisions with regard to nitrogen well ahead of harvest. As one Iowa famer put it: *"Nitrogen is probably one of the most complicated things we do. Nobody knows in April what we should do and in October it would be fairly easy to know what you should have done."* Another similarly said: *"[N management is] a shot in the dark. You never know until 9 months later what you should have done"*. In other words, the effectiveness of given N management decision relies on pre- and in-season variables. Many of these factors, like weather, are outside of a farmer's control and temporally distant from when a management decision must be made. Consequently, the time-lag between decision points and important variables influencing the effectiveness of said decision adds another layer of unpredictability and thus further contributes to *aleatory* uncertainty in decision-making. Mentions of time-lags by interviewed farmers were limited. This is in part because of the use of in-season N application equipment among farmers in our sample (e.g. side-dress) that enables them to adjust N management in response to weather shifts (see more below). However, our results suggest that time-lags between decisions and outcomes contribute increased difficulty in making initial management decisions for some, especially those that apply N only prior to the season.

Crop and Input Prices: As economic operations, farms are subject to market forces, including the cost of inputs such as N fertilizers and the price they can receive for commodities produced. Prices for both fluctuate within a season and between seasons, which introduced additional ambiguity to farmer management decisions. Prices had an influence on farmers' decisions about how much fertilizer to apply in a given growing season (n=35, 23.6% of sample). Both high and low crop prices also influenced decisions. For instance, when crop prices are high, there can be increased incentive to push yields by adding more fertilizer. Several farmers expressed this motivation. When talking about what helps him make decisions about how much to apply, an Iowa farmer said: *"Well, economics. If corn is $8 (per bushel), you put a lot of N on. If corn is $4, you may not make the most money by putting the [same amount on]."* An Indiana farmer more directly expressed the relationship between crop price and N rate: "*When you're talking five-dollar corn, you can't dicker around and short yourself on nitrogen."* Others noted how fluctuations in crop and input prices (e.g. N) across seasons leads to uncertainty: *"The market is so volatile between fertilizer prices and crop inputs versus commodity prices; it's so volatile between up and down and backwards and forwards it's harder to predict, it's harder to make [N management] plans."*

When the price ratio between input and crop prices are low, margins on crop production are squeezed. Some farmers reduced N application rate in response. As one Iowa farmer said: "*Sometimes* *it's dollars and cents . . . if your margins are minimal, the one thing you can probably cut is your fertility. Long term you'll have a problem, but for a year or two, you're gonna chop something.*" Others saw maintaining their N rate as necessary and instead opted for changing application method. An Indiana farmer put it this way: *"If the corn price is where it's at [i.e. low] and the inputs are staying up there, yeah, you've got to cut back somewhere,"* emphasizing a moment later that application method, rather than rate, must be what is changed, *"I mean, as the yields keep increasing you really can't back down your nitrogen. You just gotta find a more economical way to go about getting it on."*

While fluctuations in crop and input prices impacted many farmers' N management decisions, a few indicated their management was not highly price-dependent. One Indiana farmer said: *"Corn takes so much nitrogen to raise a bushel and that's what I apply."* Though prices were a concern for many, some farmers were far more price sensitive than others when it comes to affecting management decisions. For those who did attempt to respond to them, crop price changes seemed to influence decision-making between seasons or over multiple years, rather than to inspire management changes within a season. Farmers were more likely to make changes from year to year based on anticipated price changes rather than modifying decisions within a growing season. While farmers make pre-season decisions in reaction to expected future crop prices, expectations do not always match actualities. Therefore, changing crop prices introduce some *aleatory* uncertainty to the decision-making process; there is no correct anticipatory N management response to unknowable end-of-season corn prices. Consequently, fluctuating crop prices tended to introduce challenges to the decision process of determining the most appropriate seasonal N management, as farmers risked failing to maximize their potential profits.

Balancing Economic and Environmental Risks: Failure to achieve consistent profitability could lead to losing one's farm, or a significant portion of it, thus having major implications for their livelihoods greater than their bottom line of profitability. As N has been relatively cheap when compared to potential profits per bushel for corn, high application rates are a common means to mitigate economic-related risks—often referred to as an “insurance” N application rates (Sheriff 2005; Stuart et al. 2014). The tendency to apply high rates to reduce the chances of insufficiently profitable yields was reflected among farmers in our sample (n=15, 10.1% of sample). Farmers wanted to ensure they were not under-applying N, clearly stating that having enough N to achieve the desired yield was the most important consideration. One farmer in Iowa put it this way: “*I never want to be short on nitrogen, let's put it that way. You don't want nitrogen to be your limiting factor, you want something else to be your limiting factor. And I know that's not a good answer, but it's a truthful answer*.” For most farmers, success in N management was determined primarily on the basis of ensuring sufficient supply; as one Indiana farmer put it: *“We haven't really seen too many signs of nitrogen deficiency showing up, so we feel like we're getting enough on.”* High application rates, then, are a means of insuring sufficient profitability and thus reducing the risk of losing your farm.

However, this means of mitigating the risk of incurring significant financial losses and potentially losing one’s farm increases the chance of incurring another risk. If the application was more than needed given growing conditions, then the farmer over-applied, meaning the farmer over-spent on fertilizer and increased the chances of causing unintended pollution. An Indiana farmer expressed this potential of high N rates: “*[N management is] definitely difficult because put on too much and you've wasted a lot of money, sent nitrogen down the creek that doesn't need to be. Don't put on enough, your yields suffer*.” Farmers cannot afford to be short on N due to the financial consequences, nor do they wish to contribute to environmental pollution by using “insurance” N rates. These dual negative consequences associated with either low or high N rates contribute the element of risk to farmers’ N management decisions: their decisions are made in response to the potential for negative consequences. Though not specific to uncertainty, these risks are embedded within uncertain processes. The thresholds defining unprofitably low- or environmentally harmful high-application rates are in part based on the uncertain processes discussed above: weather and crop prices. The uncertainty of these processes limits the potential for a prescribed N rate, thus creating the potential for over- and under-application and the risks associated with these dimensions of N use. As farmers consider these risks and their relationship to uncertain economic and biophysical processes when determining N management strategies, they appear to be highly relevant dimensions of farmers' decision-making under uncertainty.

Information Sources: Previous studies have shown farmers utilize numerous venues and means to gather information and recommendations for how to manage N fertilizer application (Daberkow and McBride 1997; Weber and McCann 2015; Stuart et al. 2018). In line with prior work, almost every farmer in our sample indicated they utilized information sources to gather recommendations for how to manage their N application (8 farmers relied only on personal experience). *Information sources* refer to social sources who directly recommend management strategies to farmers, such as university extension, private sector crop advisors, and seed and fertilizer dealers (Stuart et al. 2018). Most interviewees (n=103, 69.6% of sample) were actively using two or more sources to make seasonal N decisions, especially with regard to fertilizer rate and the mean number of sources used across our sample was 2.2. The types of recommendations offered and how farmers use different sources is outside the scope of this paper, but generally aligns with recent research on this topic (Stuart et al. 2018).

Farmers differed, however, in which sources were perceived as credible. For instance, an Iowa farmer expressed a common sentiment that sources associated with fertilizer dealers were untrustworthy: *"What the guy selling my anhydrous tells me, I give that all the weight its worth knowing that he's trying to sell me something…"* Others trusted their dealer's information: *"I feel very trustful of our local [fertilizer dealer's] guy. A lot of people say 'I'm not going to use my fertilizer guy's agronomist. Well, frankly we don't feel that way."* Farmers' opinions differed similarly on the reliability of another common source of recommendations, universities. Some farmers perceived universities' pace of releasing novel information as old-fashioned: "*People sometimes say 'Oh you know the university is too* *slow getting [new information out].*" Others expressed alternative positions: "*I place a lot of value in those university research trials. They're not trying to sell anything.*"

Rarely, if ever, did recommendations from these various sources converge into a comprehensive and coherent management strategy, however. Consultation of multiple information sources among farmers in our sample was common practice but did not necessarily reduce the challenges or uncertainty inherent in N management decisions. Indeed, farmers often realized that due to the complexity of the biophysical factors that influence N use, information sources themselves suffer from *epistemic* uncertainty; even the "experts" cannot have all the answers. As one Iowa farmer put it: *"This whole soil science thing, we just don't understand how the soil works."* Overall, farmers appeared to be deeply aware that there may be no single "right answer" due to lack of knowledge of the complex processes at work in N cycling in crop production systems (*epistemic* uncertainty), but rather that decisions may be appropriate or not in a given circumstance based on a wide range of biophysical and agronomic factors. In short, farmers' use of information sources provided knowledge related to making annual N management decisions, but these information sources offered farmers no conclusive long-term answer to N management.

Decision-Making Practices

The findings presented above suggest that farmers encounter numerous factors that increase the difficulty and uncertainty in determining the optimal N management strategy given economic and biophysical considerations. While farmers widely agreed that there is much uncertainty in N management, and the inherent risk involved when making decisions on such an important aspect of crop production, farmers we interviewed diverged in their assessment of the difficulty of making N management decisions. How farmers respond to both the uncertainties inherent to management decisions and a decision-making space with an overwhelming amount of information also diverged. We found that when faced with uncertainty, farmers generally followed one of two routes: heuristic-based decision-making and data-intensive decision-making (figure 1). We see the divergence of these strategies as related to two fundamentally distinct (but not mutually exclusive) manners of cognitively processing the numerous uncertainties associated with N management decisions, which can be understood in the context of experiential and analytical pathways of decision-making (Weber and Johnson 2009). It is important to note that the reliance on certain tools that characterize one pathway (e.g., application rate heuristics) does not necessarily preclude the use of tools that characterize the other pathway (e.g., use of side-dress application), and that farmers may also use different decision-making pathways for addressing diverse sources of uncertainty. Below we outline these two conceptually interlinked strategies.

Heuristic-based decision-making: When reflecting on the difficulty of determining an appropriate N application rate, most farmers indicated they did not find determining application rates to be difficult (N=104, 70.3% of sample). This often came directly after the farmer had talked at length about the uncertainties associated with weather, prices, and conflicting recommendations, reflecting an important insight into how farmers perceive and incorporate uncertainty in decision-making. Despite acknowledging the inherent uncertainties associated with N management in their farm operations, most farmers had incorporated strategies that alleviated the difficulties in decision-making. Roughly two thirds of those interviewed largely relied on three primary interrelated factors for decision-making: use of heuristics, reliance on past experience, and minimizing sources of uncertainty when making decisions.

Many farmers we interviewed relied heavily on heuristic decision making tools, especially with regard to determining their application rate. Many farmers expressed that their corn crop needed N at a certain ratio of N to corn yield, commonly expressed in terms of pounds of N per bushel of corn yield. For instance, if a farmer was aiming for a yield goal of 200 bushels of corn per acre on a given field, and were relying on a 1:1 ratio, they would apply 200 lbs of N/acre. These heuristic rates or rules of thumb were prevalent throughout many of our interviews, with many expressing these as common knowledge. As one from Indiana put it: *"I'm well convinced from what I've read over the years, it's going to take 1.1 pounds of nitrogen to make a bushel of corn."* Given other variables involved in determining actual crop need, including uncertainties associated with weather, the effects of timing, formulation, and placement, it is difficult to say that there is an agronomically "correct" rate. Many farmers used these simple heuristics when making decisions, however, though the heuristics they used differed widely. Some used ratios as high as 1.2:1 (which could potentially result in greater loss of N into the environment), while others used far smaller ratios (e.g. 0.8:1).

The reliance on heuristics allowed farmers to be confident in their nitrogen management decisions, despite the inherent uncertainties. For these farmers, there was a "right" rate they had figured out based on past experience. Those who relied on heuristics did not follow them exactly; the ratios would be used to determine a general application target, which the farmer would adjust up or down slightly based on past experience, field conditions, and other management decisions like use of inhibitor additives designed to slow loss of N in soil, etc. While certainly analytical, many farmers also attached affective elements and emotive language to their decisions, including emphasizing the role of "gut-feelings."

Farmers relied on ratio heuristics to simplify decision-making, particularly related to how much uncertainty farmers expressed surrounded application decisions. Farm management requires numerous decisions, which have attending levels of risk and uncertainty associated with them; nutrient management decisions are important for any crop production decision but are not the only choices that farmers must make. To balance the cognitive burden of making these numerous decisions, farmers must find ways to make decision-making more efficient. Heuristics are one of the main tools that farmers rely on to ease this cognitive burden and allow farmers to reduce ambiguity and complexity in decision-making. However, while these heuristics simplify the decision-making process at the point of making an individual decision-making, they are often derived through complex and lengthy processes of observation and reflection. These heuristics serve as a lens through which farmers can view years of experience and information, including external recommendations and the impact of various practices they have trialed. For many farmers, these observations, often made holistically, are incorporated into operations through heuristic tools.

Past personal experience and observation played a large role in helping many farmers make decisions about N management. Many indicated that they had largely used the same application rates year after year. As one Michigan farmer said: *"Well, it's not a difficult decision. I think it becomes easier every year. I mean, you might change things a little bit... but it's pretty straightforward if you've got years of good information to work with."* Similar sentiments were expressed by many farmers we interviewed, who felt that after years of following similar practices, they had largely "figured out" what the correct management strategy was for their operations. Indeed, many responded to a question about what information influenced their N management decisions with responses indicating that their personal experience was the most important factor.

Although all farmers identified sources of uncertainty in N management, many indicated they largely ignored these when making decisions, particularly regarding weather. While variability in weather can have significant ramifications for N uptake by crops and cycling within the soil, many farmers simply did not attempt to account for weather when determining application rates and other aspects of management. As one farmer in Iowa said: "*You gotta put so much out there*," indicating that his fertilizer rates did not vary much from year to year based on weather predictions. People are often averse to ambiguity and react differently when situations are perceived to be risky or uncertain (Kahneman 2003; Weber and Johnson 2009). In such situations, many farmers may seek to reduce uncertainty by minimizing important sources of *aleatory* uncertainty, sources outside of their control.

The reliance on heuristics and their own past experience may have ramifications for decision-making. Heuristics can lead to sub-optimal decision-making, though this is not always the case (Gigerenzer and Gaissmaier 2011). With N management, this may or may not be the case. Further, U.S. corn farmers using no sources of information are less likely to adopt a number of best management practices (Weber and McCann 2015), which implies that relying on personal experience may reduce NUE. Generally, evidence indicates Midwestern corn farmers are not efficiently applying N (Ribaudo et al. 2011), but determining the appropriateness of the application rates used by research participants is outside the scope of this study. As farmers themselves emphasize in our interviews, N needs in cropping systems are incredibly complex and affected by numerous variables. Without extensive soil and crop testing and agronomic modeling of each farm field, which is outside of the capacities of most farmers, it is not possible to determine exact crop nutrient needs. Even then, the effect of unpredictable weather and time lags between decisions and outcomes make it nearly impossible to determine exact needs in a given growing season. Reliance on heuristics and/or continual reuse of the past-season's practices allows farmers to minimize or even largely ignore this complexity and uncertainty and more rapidly arrive at a cognitively efficient decision.

Data-intensive decision making: While a large number of farmers interviewed used strategies to simplify their decision-making around N management, some farmers took a different approach. Some farmers (N=44, 29.7% of sample) indicated that they found N management decisions difficult. This position may be exemplified by one Iowa farmer's comment: "*To me, [determining N management strategies] is just about next to being an ulcer type of decision*." Another, speaking somewhat hyperbolically, stated that making the annual N management decision is "impossible." Such farmers engaged fully with the wide range of potential economic, political and ecological variables that could influence their annual crop production and N requirements and consequently employed agricultural techniques. Where farmers using a heuristics-based strategy ignored sources of uncertainty, relied on past experience, and used heuristics for decision-making, farmers following a data-intensive decision making pathway relied on two key strategies: increasing information collected and increasing the number of decision points. To accomplish these, data-based managers commonly discussed two key tools: 1) improved data collection and management and 2) increasing the number of N applications they were using in their operations. Both strategies can decrease the uncertainty associated with N management.

Data-intensive decision makers acknowledge uncertainty and seek to better understand the N cycling processes that create this uncertainty. Compared with farmers who relied on heuristics, data-based farmers were focused on increasing their use of information collected and incorporated in their operations. One Michigan farmer collected a wide range of information about N in his farm management, including nutrient analysis of applied hog manure, pre-sidedress nitrate testing, yield monitoring, and extensive use of test plots to trial new fertilizer formulations and additives. This farmer said that intensifying data collection had reduced the uncertainty out of N management: *"I would say it's not difficult because we have all that information available . . . when you've got a lot of data it kind of makes it easier; we're not guessing. So in that respect it doesn't seem hard as far as what to use."* Where a heuristic simplifies an application rate to a ratio of fertilizer to anticipated yield, increased data collection allows this group of information-seeking farmers to better estimate nutrient availability within their fields. Due to improvements in technology and nutrient cycling models, farmers can collect data on crops, soil, and N availability at increasingly fine spatial and temporal scales. Such data can help farmers reduce the uncertainty in crop nutrient needs throughout the growing season.

Data collection also allowed some farmers to utilize variable rate N application, where N is applied in different amounts across a given field based on yield potential, soil quality, and other agronomic conditions. Although this practice was not commonly used among our interview participants, it was generally viewed as an emerging technology. Farmers who were utilizing variable rate application tended to be data-intensive nutrient managers, collecting yield data, soil and plant tissue tests, practicing mid-season (side-dress) application, and high population rate planting (using a larger amount of seed in a given area). Variable rate management was often done on a zone management system, where fields were categorized into management zones based on past yield data and soil testing. Often these farmers had used these management zones to manage other nutrients (phosphorus, potassium, lime, etc.) and seeding rate and had recently begun using these zones for nitrogen management. In this sense, zone management and variable rate application are practices that can be trialed before being fully adopted in an operation, which can be an important characteristic leading to increased adoption of conservation practices (Reimer et al. 2012a).

The amount of data available for farmers to collect was also seen by some as another form of complexity, leading to increased difficulty in making decisions. One Iowa farmer reflected on the difficulties brought by data management: *"[N management is] hard since we have the variable rate technology, you do all of this reading, all of this research, have your maps and then you're sitting in the fields and you say, I think we'll put a little less on here, or maybe we'll put a little more on. So it is very hard, and you've really got to trust, when you're sitting in the field, that your research up until then is sound."* Recent advances in decision support systems (DSS) have the potential to alleviate some of this complexity. For example, the Adapt N system developed at Cornell University uses soil and management data along with local weather data to generate recommendations for within-season nitrogen application. Field trials have shown the Adapt N tool to be very effective at reducing total nitrogen application without decreases in yield (Sela et al. 2016). These types of DSS tools are potentially more effective than regionally based tools or generalized management strategies (such as the 4Rs approach) because they include inputs specific to the farmer's location and provide dynamic support for decision making (Sela and van Es 2018). In our sample however, only a few farmers were actively using some form of DSS like the Adapt N program. The farmers using these tools were enthusiastic about their impact on nitrogen management, but the majority were not currently using these systems. For farmers seeking to use data-intensive strategies, these DSS tools have the potential to both reduce uncertainty while reducing the time and effort needed to incorporate various forms of information into management decisions.

Splitting N application allows farmers to adjust N levels during the growing season to account for weather. Mid-season application in the form of side-dress application reduces the chances of losing N from the soil profile due to leaching or denitrification processes, an important source of uncertainty in N management. An Iowa farmer talked about the benefits of using side-dress application compared with fall application: *"I think you'll see more split applications, cause to put on 100 percent of your nitrogen in the fall, when you don't even need half of it until the corn tassels, that's a long time for that nitrogen to sit there."* Side-dress application does have associated costs however, including increased time and effort required of farmers for being in the field and determining how much and when to apply, as well as the need for appropriate equipment. Despite associated costs, side-dress was one of the more popular management practices used by those wanting to decrease the uncertainty in N management. For these farmers, the costs of split application were paid back in greater yields and decreased input costs. As one Indiana farmer remarked: *"I like spoon feeding it, getting at the three or four times on there, or two or three, and so that's… I feel that's the best way and with my yields I think I've proven that, they've been increasing consistently."*

While split application can reduce the uncertainty associated with weather variability, it is only one tool. Farmers using side-dress application often use this practice in conjunction with other practices, including data management technologies. One Iowa farmer talked about the interplay of data collection, in his case optical sensors that assess vegetative condition from the applicator equipment, and side-dress application: *"If we have time, if we have the environmental conditions of rainfall or lack of rainfall, we could adjust our side-dressing, but generally on the fields we can, we just let these, the optics run* *through there and decide."* This farmer also expressed that side-dress does not eliminate the uncertainty associated with weather but just reduces it: *"Typically side-dressing is a little early to make a final determination on where you want to be. This buys us more time to get later in the season and get a better handle on where we're at… [but] you don't know what's gonna happen."*

Farm structural variables, especially farm size, did appear to have some impact on use of data-intensive management strategies. Mid-sized (1,000-1,800 acres) appear to be somewhat more likely to rely on more data collection and timing modification practices (35% of mid-sized farms) than smaller (24%) or larger farmers (30%) in our sample. Many of the farmers using split application and more adaptive application within the growing season had operations between 1,000 and 1,800 acres, though a few farmers with smaller or larger operations were also using data-intensive strategies. In contrast, the smallest farm operators seem to rely more on heuristics, in particular rate recommendations and past experience. These trends are likely do to timing and financial barriers, including off-farm jobs, which make it difficult for smaller farm operators to take advantage of more intensive management strategies. Large acreages under management create management challenges as well, creating barriers to the use of some more intensive management practices, especially sidedress application.

While data intensification strategies cannot completely eliminate uncertainty, they serve as valuable tools for dealing with the wide range of *aleatory* and *epistemic* uncertainty in N management. Data-intensifying farmers were focused on increasing control and the ability to adjust practices mid-season. These farmers appeared to be more technology-oriented in other aspects of their operations as well, and many were implementing data collection and management systems throughout their operations. Farmer personality traits and competencies may drive their decision-making into these two pathways. Previous research has demonstrated that competency and cognitive ability can lead to greater reliance on analytical decision making processes (Weber and Johnson 2009). Risk preferences also vary between individuals and situations, which could influence how farmers view the risks associated with various management practices and affect their decisions. More simply, farmers with greater knowledge of the biophysical aspects of N management (less *epistemic* uncertainty) and greater comfort with technology are more likely to feel comfortable increasing management intensity to reduce *aleatory* uncertainty. While a few producers spoke about how they began using certain tools or data-intensive methods, it is unclear from our cross-sectional study approach how or if farmers have transitioned from heuristics to more data-intensive strategies. The producers relying most heavily on data-intensive strategies may have at one time relied more on heuristics, or may have always been predisposed to relying on data-intensive strategies, even if the various tools or technologies have changed over time.

Many producers fell along a spectrum with their use of data-intensive strategies. Some incorporated some form of soil or plant tissue testing (such as a pre-sidedress nitrate test) within a growing season but still relied on a basic ratio heuristic to arrive at their desired application rate. For these producers, soil testing reduced some uncertainty and helped them make more informed decisions but did not fully replace the heuristic-based approach. Many farmers were using some mixture of data-informed decision making and heuristics, either based on past experiences or recommendations from external sources. These past experiences in particular were powerful guides for farmers as a way to reduce decision-making time and perceived uncertainties, even if these past experiences were being supplemented by data-based tools.

CONCLUSIONS

Farm management is complex, involving interactions of overlapping biological, chemical, and social systems. This complexity can lead to high levels of uncertainty and create associated risks, which are perceived by farmers and, in turn, affect their decisions. Nitrogen management provides a key example of this complexity and uncertainty. There are high levels of *epistemic* uncertainty associated with soil and biogeochemical sciences, and the complexity of interacting systems leads to high cognitive load for farmers trying to analyze available information and make decisions. This complexity can lead to decision-making with incomplete information, especially in the terms of attempts to minimize the environmental impact of a farming operation while maintaining profitability. Farmer nutrient management decisions can be appropriate or inappropriate depending on the specific context (i.e. soil characteristics and weather in a given growing season), though we did not evaluate the appropriateness of individual decisions in this research. Rather, we sought to improve understanding of farmer decision-making in situations of high uncertainty.

Farmers widely acknowledge the primary sources of uncertainty, including their own lack of knowledge about the biophysical processes involved in N cycling through cropping systems. Farmers appear to diverge, however, in how they address these uncertainties. In our sample, about two thirds of farmers streamline the decision-making process by discounting or minimizing sources of uncertainty in planning, relying on previous experience and heuristics. These represent cognitive editing of the variables involved in N management, which leads to more efficient and less burdensome decision-making (regardless of whether the actual decisions are optimal from an agronomic or economic perspective). Other farmers more actively account for uncertainty by intensifying their N management through increased data collection and decision focus, though less than a third of our sample generally fall in this category. This data-informed decision-model involves increasing information in the decision-making process to reduce *epistemic* uncertainty and increasing the number of decision-making points throughout the production cycle to reduce *aleatory* uncertainty associated with weather and soil conditions.

These findings have implications for outreach and education on N management. Many farmers rely heavily on heuristics in decision-making, especially application rate ratios. These rate heuristics serve as a useful common language, through which researchers and advisors can communicate with farmers. While these heuristics greatly simplify complex biophysical systems and may be overly reductionist, changing farmer reliance upon them is unlikely in the short term. Outreach professionals should recognize the importance of these heuristics and use them as a launching point for improving farmer understanding of complex biophysical processes. For example, explanations for nutrient cycling and nutrient use efficiency could be framed in terms of their impact on key heuristics, such as application rate to yield percentages.

Outreach professionals should also recognize that not all farmers appear willing or able to intensify management, not only for technological or knowledge reasons, but due to cognitive burdens associated with decision-making in a complex area such as N management. Decision support system (DSS) tools that simplify natural processes and provide recommendations that account for both *aleatory* and *epistemic* uncertainty are potentially useful but may be met with skepticism by farmers who rely heavily on their own personal experience for management decisions. Despite this potential skepticism, these dynamic tools allow farmers to incorporate data specific to their situation to inform nitrogen decisions in ways that account for variable and uncertain local conditions, while also offering the potential for reducing management effort, an important consideration for the farmers we interviewed. As researchers, outreach professionals, and commercial advisors continue to develop these tools, it is important to recognize how farmers make decisions and how information is incorporated into decision-making. Decision support tools should distinguish between types of uncertainties (e.g. *aleatory* or random and *epistemic* or relating to knowledge), use language and information with which farmers are familiar, and offer multiple options, so farmers can weigh choices against each other and their previous experiences.

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Figure Captions

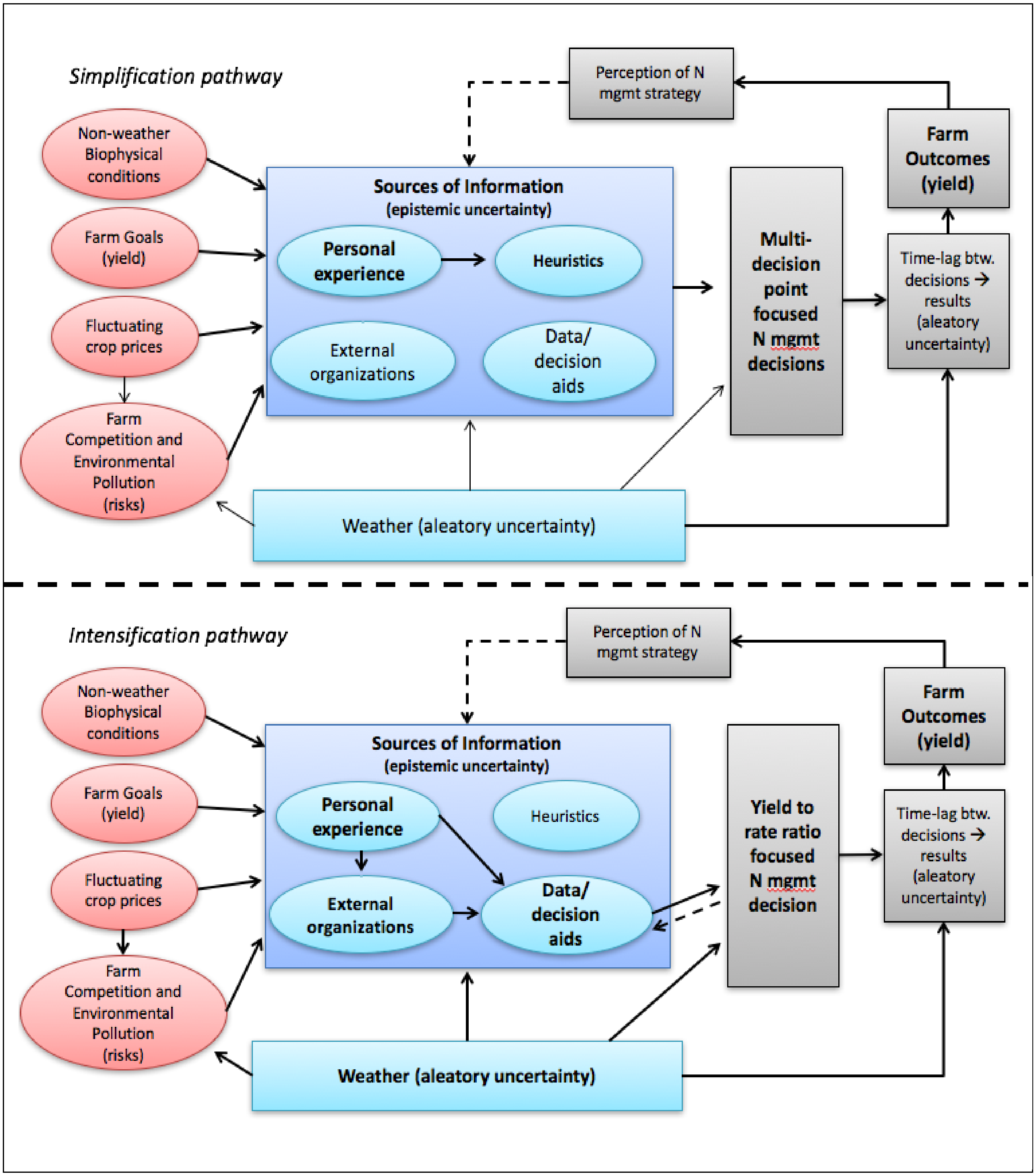
Fig. 1: Two primary pathways through which farmers make decisions for complex and uncertain nutrient management.

Table 1. Farms and mean farm size in the interview sample compared with state level statistics (USDA-NASS 2016)

State	**Sample**		**AgCensus**	
	Number of Farms	Average Farm Size	Number of Corn Farms	Average Farm Size
IA	51	1,236	47,477	345
IN	51	1,529	22,985	215
MI	46	2,216	13,907	191

Table 2. Farmer expression of uncertainty themes and N decision making processes. Note: each cell presents the number of farmers who made at least one statement on a given theme, or the categorization of farmer by decision process (as coded by the researchers).

	Farm Size (acres)							
Uncertainty Theme	**170-999**	**Proportion of Sample**	**1,000-1,799**	**Proportion of Sample**	**1,800-14,000**	**Proportion of Sample**	**Total**	**Proportion of Sample**
Weather	23	15.5%	24	16.2%	33	23.3%	79	53.4%
Time lags	2	1.4%	1	0.7%	4	2.7%	7	4.7%
Crop Prices	11	7.4%	9	6.1%	15	10.1%	35	23.6%
Balancing Econ & Environmental Risks	2	1.4%	3	2.0%	10	6.8%	15	10.1%
				Farm Size (acres)				
Decision Processes	**170-999**		**1,000-1,799**		**1,800-14,000**		**Total**	
Heuristic-based	35	23.6%	30	20.3%	39	26.4%	104	70.3%
Data-intensive	11	7.4%	16	10.8%	17	11.5%	44	29.7%
Combined	46	31.1%	46	31.1%	56	37.8%	148	100.0%


Simplification pathway
Non-weather Biophysical conditions
Farm Goals (yield)
Fluctuating crop prices
Farm Competition and Environmental Pollution (risks)
Sources of Information
(epistemic uncertainty)
Personal experience
Heuristics
External organizations
Data/ decision aids
Weather (aleatory uncertainty)
Perception of N mgmt strategy
Multi-decision point focused N mgmt decisions
Time-lag btw. decisions → results (aleatory uncertainty)
Farm Outcomes (yield)
Intensification pathway
Non-weather Biophysical conditions
Farm Goals (yield)
Fluctuating crop prices
Farm Competition and Environmental Pollution (risks)
Sources of Information
(epistemic uncertainty)
Personal experience
Heuristics
External organizations
Data/ decision aids
Weather (aleatory uncertainty)
Perception of N mgmt strategy
Yield to rate ratio focused N mgmt decision
Time-lag btw. decisions → results (aleatory uncertainty)
Farm Outcomes (yield)