Long Title: Farmer motivations for excess nitrogen use in the US Corn Belt

Short Title: A case study of farmers' over-application of nitrogen

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Abstract: Improving the use efficiency of nitrogen fertilizer is one of the most effective ways to mitigate agriculture's contributions to climate change and water-quality degradation. However, studies suggest that many farmers worldwide are exceeding annual-profitable nitrogen rates and thus "over-applying" nitrogen. This paper utilizes a case study to understand over-application at the individual level, focusing on (1) prevalence and severity of over-application as defined by maximum profitable thresholds and (2) gaining an understanding of what factors limit over-applying farmers desire and capacity to lower their rates. Using a sample of 132 interviews with row-crop farmers in three states in the midwestern US, I find that 37% of interviewed farmers over-applied nitrogen by 5 lbs./acre or more, with few farmers adjusting rates annually and the largest farmers being most likely to over-apply. When asked what prevented them from reducing their rates, over-applying farmers felt their current rates were appropriate or profitable and thus they did not desire to reduce them. Of these farmers, some assumed they could not be over-applying, some used more N to achieve maximized production, while others intentionally over-applied as a risk-mitigation strategy. I conclude by offering recommendations for policy and future research to build on this case study.

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1. INTRODUCTION

When lost to the environmental from agricultural fields, synthetic nitrogen (N) fertilizer is a potent environmental pollutant, contributing significantly to water quality degradation and climate change (Baron et al., 2013; Ribaudo et al., 2011). The rate at which N is applied to agricultural fields is considered one of the most important factors determining the amount of N lost to the environment (Robertson et al., 2013; Ribaudo et al., 2011). Higher N rates are positively associated with nitrous oxide (N_2O) emissions, a powerful greenhouse gas, and runoff to water bodies (Gardner and Drinkwater, 2009), but when application rate exceeds crop yield thresholds, N_2O increases at a rate more than proportional to the amount of N applied, meaning over-application even in modest amounts dramatically increases contributions to climate change (Hoben et al., 2011; McSwiney & Robertson, 2005). Despite the environmental and potential economic costs (Pannel, 2017), over-application (and inefficient N use generally) is frequently observed in agricultural systems across the globe (Cui et al. 2018; Zhang et al. 2015). In light of this context, scholars and policy makers are increasingly calling for the need to reduce the occurrence of over-application in order to mitigate agriculture's contributions to environmental degradation (Davidson et al., 2015; Kanter, 2018; Millar et al., 2010; Robertson et al., 2013). Efforts toward achieving this goal would be helped by a firmer understanding of the factors shaping farmers' decision-making and barriers to more appropriate application rates.

A growing body of literature has offered informed hypotheses as to why over-application occurs. Farmers may intentionally over-use N, referred to as "insurance N." Insurance N application is done to ensure (i.e., "insure") maximized yield and profit-potential from the crop, either for rare-optimal growing conditions where extra N provides a key boost or as a risk-management approach for sub-optimal conditions when N losses occur and would otherwise

reduce yields (Arbuckle & Rosman, 2014; Babcock, 1992; Osmond et al., 2015; Stuart et al., 2012). Research in the agricultural economics literature shows that over-applying N can be economically rational. Over-applying may at times lead to profit-booms due to optimal growing conditions where yields are exceptionally high, which can offset prior years losses from the over-use of N (Rajsic et al., 2009). Similarly, insurance N application for sub-optimal conditions wastes a bit of money each year but can "pay off" in farmers feeling assured that their yield potential is maximized and by enabling farmers to be less concerned about the spatial and temporal dimensions of N use (when and where to apply to reduce over-use) (Arbuckle & Rosman, 2014; Pannel, 2017). Additionally, misinformation or misperceptions could lead farmers to feel their current (high) rates are appropriate. For instance, Huang et al. (2015) points to this factor, as they found farmers reduced their N rates post in-field training. This suggests that the incorrect assumption that they are not over-applying (for multiple reasons) is another potential factor.

While this work suggests several potential drivers of farmers' over-use of N, little research has empirically examined the over-application of N at the level of farmers' decision-making (Arbuckle & Rosman, 2014). Toward beginning to address this gap, I use a case study of farmers decision-making in three Midwestern states to offer preliminary empirical insight into how farmers view their N management and what factors contribute to the occurrence of over-application. For the purpose of this study, I define over-application based on an economic threshold, called Maximum Return to Nitrogen (MRTN). Farmers apply N to increase their crop's yield, but at a given tipping point, the cost of applying more N exceeds the profits generated from higher yields, especially as a crop's yield potential begins to plateau. When that

happens farmers are losing money by applying more N, which is the tipping point that I define as "over-application" (see the methods for a further discussion).

Drawing on this definition, I use qualitative interviews to address two research questions that extend past work: (1) Are, to what extent, and which farmers are over-applying N? (2) What factors are limiting over-applying farmers desire/capacity to lower their N rates? Related to the latter, I find that farmers perceive their N rates to be profitable and in their interest. Farmers offered distinct justification for this perspective: (1) over-application is not possible given market conditions; (2) over-application ensures maximum yields/profits in ideal or optimal conditions; (3) over-application prevents yield/profit losses in poor or suboptimal conditions. This research can be seen to extend the growing body of research on N management more generally (Bosch et al. 2014; Denny et al., 2019; Lemke et al., 2010; Osmond et al., 2015; Weber & McCann, 2015; Stuart et al. 2014) and to answer calls for more research on the topic (Davidson et al., 2015; Stuart et al., 2015).

2. CASE EXAMINATION

2.1 Case study area

Over-application occurs in regions and countries across the world (Zhang et al. 2015). This study examines N over-application in the context of midwestern United States (US) corn agriculture. Most N lost to the environment in the US comes from states in the 'corn belt' region (NASS, 2015). Corn in the region receives exceptionally high N rates (Vitousek et al., 2009) and even when applied in optimum amounts, approximately 15 to 65% of the N applied is typically lost to the environment as pollution (Basso et al., 2016; Randall and Mulla, 2001). Past studies suggest that N is over-applied on nearly 30% of all corn acres in the region (Ribaudo et al., 2012). Excess N lost from Midwest farms is responsible for 60-80% of the hypoxic or "dead" zone in

the Gulf of Mexico that stretches over 6,000 square miles (UCS, 2020; NOAA, 2021), while the recent rise in global N_2O emissions is largely attributable to increasing agricultural N rates (Park et al., 2012). With its concentration of farmland and high N use, the Midwest contributes significantly to global agricultural N_2O emissions (Eckl et al. 2021; Miller et al. 2010).

Given the importance of N rate in determining N pollution levels (Gardner and Drinkwater, 2007), research offering insight into the barriers to reducing the occurrence of over-application contributes toward efforts to mitigate agricultural GHG emissions in the US Midwest, as well as N's contributions to water-quality degradation. I focus in particular on the Midwest states of Indiana, Iowa, and Michigan. These three sample states grow a considerable portion the US's total corn. The year of the interviews, Iowa, Indiana and Michigan ranked 1st, 5th, and 10th in terms of total corn production by US state (NASS 2015). These states also face similar financial and climatic conditions as the rest of the region, and farmers in these states over-use N at similar rates to those in other Midwestern states (NASS, 2015; Ribuado et al., 2012).

2.2 Sampling

Interviews with farmers were used to assess their N management decisions and determine why they may over-apply N. Interviews provide in-depth detail on farmers' practice use and perceptions of these practices. They serve as a good means to explore farmers' over-application and their perception of this practice then, particularly given the limited amount of empirical work on the topic (Kreuger & Casey, 2009; Doll et al., 2017; Prokopy et al., 2017).

Interview data was gathered via one-on-one, semi-structured interviews with 154 corn farmers in: Indiana (n=51), Iowa (n=53) and Michigan (n=50). Farmer recruitment for these

interviews was primarily conducted in spring and early summer, with interviews beginning in May 2014 and mostly taking place on farms. Interviews concluded in mid-November 2014.

Initially a purposive sample design was used (Lavrakas, 2008), where farmers who grew at least 100 acres of corn annually were sought out to ensure those farmers whose actions were viewed as having a large impact on the environment were included. This sample of interview participants was primarily recruited through university extension and other state resource professionals, with a reliance on snowball sampling thereafter to enable an expansion of the original sample size and maintaining the +100 acres criterion. Snowball sampling is considered a good method to contact subjects who are difficult to access (Faugier & Sargeant, 1997). Total farm sizes ranged from 170 acres to 14,000 with an average acreage operated of 1,615. All interviews were done in English, recorded and transcribed verbatim.

This sample may over-represent the number of farmers aware of and using university recommended N application rates like those from Maximum Return to Nitrogen (see below). Past analysis of this sample has shown that interviewed farmers consulted numerous agricultural information sources and often preferred private sector sources (e.g., fertilizer dealers) to University Extension (Stuart et al. 2018). Overall sample bias from engagement to university sources is possible, but likely limited. If present, the number of farmers' over-applying in this sample will likely be a conservative estimate for its occurrence across the true population.

2.3 Analysis

I first examine farmers' actual N application rate to explore if farmers are applying N at rates that exceed optimal economic thresholds. Each of the 154-interviewed farmers was asked about their N application rate, along with a suite of questions about their N management. Each discussion about N started out by asking farmers to describe their N management generally and

the interview followed up with specific prompts as necessary. In response to questions about N rate, some farmers gave unclear responses to this question, others choose not to answer and some, particularly in Michigan, grew multiple crops and used crop rotations for which estimates of maximum profitable thresholds are unavailable. In consequence, I analyze 132 farmer interviews in total.

I follow past work advocating for the use of Maximum Return to Nitrogen (MRTN) rates concept (Sawyer et al., 2006) to assess over-application and N use that significantly contributions to N_2O emissions (Millar et al., 2010). Beyond the science surrounding MRTN, there are other reasons this concept makes for a good measure of over-application. It is also widely accessible, and increasingly promoted by Extension services across the Midwest (Nowatzke and Arbuckle 2018).

MRTN rates are defined by economic tipping points. There are *low* and *high* profitable rate thresholds. If rates exceed the *high profitable rates*, farmers are "over-applying" N, as the cost of additional N exceeds returns from minimal gains in yield, leading to net financial losses. In other words, corn yields go only so high each year. At some point adding *more* N will no longer significantly increase yields, and eventually the cost of N exceeds the returns or financial benefits from higher corn yields—hence the name "maximum return to N." The exact tipping point where more N becomes "unprofitable" depends on crop yield potentials, the sale price of the crop, and the purchase price of N (see Figure 1). Research done across the Midwest has suggested long-term and stable yield potentials for corn across a variety of growing conditions (see ISUAEO, 2022).

< Figure 1 about here, with caption >

In consequence, as defined here, over-application of N is economically unnecessary and contributes needlessly to N pollution, such as N_2O emission and water quality degradation. However, MRTN over-application is not an absolute measure—at some-times (e.g., specific, "ideal" seasonal conditions), actual yield potentials can exceed established norms built into the MRTN calculation. In these instances, applying N above MRTN maximum rates is profitable because of higher-than-normal corn yields. In most years, however, MRTN annual rates accurately reflecting profitable thresholds for N use.

To define high profitable rate thresholds for this study, average annual prices for anhydrous ammonia and corn between the years 2009-2014 were used to determine the five-year average N-to-corn price ratio for this time period (see notes for prices).[1] By using annual prices across this time span, I dampen the potential impact of price variability that may lead some farmers to accidently over-apply. Additionally, anhydrous ammonia is the least expensive form of N (ERS, 2017). In consequence, these measures represent very conservative estimates of "over-application" for the 2014 season.

Across the five years calculated, a ratio of .09 was determined, which is conservatively .01 lower than the .10 annual N-to-corn ratio for the 2014 season in which interviews took place. Using the Iowa State University MRTN calculator (available at: http://cnrc.agron.iastate.edu/), I then calculated MRTN rates for a corn-soy rotation in my sample. Yield potentials vary within state, resulting in both inter- and intra-state differences in high profitable rate thresholds (see

[1] Anhydrous prices were drawn from Schnitkey (2017) and annual corn prices are an average calculated from data drawn from macro-trends.net This data is available at: http://www.macrotrends.net/2532/corn-prices-historical-chart-data. Schnitkey (2017) is available at: https://farmdocdaily.illinois.edu/2017/07/fertilizer-costs-in-2017-and-2018.html

details in the note's section). Using these as threshold rates, I examine whether farmers in each state and within each region of each state are "over-applying" N in the 2014 season.

In the second stage of analysis, I explore barriers to reducing N rates among over-applying farmers. The analysis was done by a single coder. Toward transparency, a very high percentage of farmer quotes are included in tables below. Notably, no interviewed farmer felt they were "over-applying." However, given the literature showing inefficient use of agricultural N fertilizer (Ribaudo et al., 2012), I undertook a more careful examination of farmers' reported N rate in light of calculated MRTN rates. This revealed that a substantial number of farmers who were applying N at rates that exceeded MRTN. Focusing on this sub-sample, I examine what they felt limited them from being able to lower their current N rates, primarily exploring their response to a standard interview question: If you wanted to apply less nitrogen fertilizer, what might stop you from being able to do so? Most farmers essentially argued that their current N rates were appropriate in some fashion, primarily referencing their profitability. Using thematic analysis, I offer a deeper understanding of how, or through what rationalization, farmers justify their (over) use of N as appropriate/profitable.

3. RESULTS

3.1 Are farmers applying N at rates that exceed optimal economic thresholds?

Across the 132 interviewed farmers who gave N rate application responses, five used variable N rates across fields and only one farmer variable rate applied within and across fields. Rather than applying a specific rate to each field (or zones within each field), most farmers who varied their rate discussed using two different rates across soil types, management zones (i.e. irrigated versus non-irrigated land, manured versus non-manured ground) or due to stipulations of a conservation reserve program contract on a portion of their land. This dual-rate approach was used by 31

farmers in my sample. Only nine farmers discussed intentionally adjusting N rates every season, based on market price of N or corn, or other seasonal fluctuations. Most tried to keep N management practices and N rate specifically consistent year to year.

Using the N application rate farmers described in interviews, average application rates across the sample and within each state for corn-soybean rotations were calculated. Farmers who varied their N rates significantly were excluded from this calculation and for the farmers who used dichotomous rates across their operation, the average of the two rates was used.

<Table 1 about here>

Indicated in *Table 1*, a significant portion of farmers from the total sample and within each state applied in excess of the MRTN high profitable rate.[2] Even when considering profitable N rates at the lowest N-to-corn price ratio (when profitable N rates are highest) of the 5-year period (.07), 29% of the sample (Iowa: n=19; Indiana: n=11; Michigan: n=15) exceeded profitable N rates. See *Figure 2* for the percent of sampled farmers who would have "over-applied" at the N-to-corn price ratio for each of the five years between 2009-2014.

<Figure 2 about here>

To understand if all farmers are equally prone to over-application, I examined a number of farmer characteristics (e.g. fall versus in-season application only, total number of applications). Most bore little fruit, but a clear connection between over-application and farm size emerged. Among my sample, across farm size categories, the percentage of farmers applying in excess generally increases, this pattern also holding true for applying 5 and 10

[2] Farmers who only applied N at variable rates across their operation were included in this calculation as applying N at or below recommended levels. This assumption is made to ensure the most conservative estimation of the proportion of farmers who apply N above profitable threshold rates.

lbs./acre or more above MRTN rate (see *Figure 3*). The largest category of farmers (>2,000 acres) were particularly prone to over-apply, and when they over-applied, they tended to substantially over-apply. Over 75% farmers over-applying by at least 5 lbs./acre operated farms that were 1,500 acres or more and 1,835 acres was the average farm size of over-applying farmers.

<Figure 3 about here>

3.2 What factors limited over-applying farmers' capacity or willingness to reduce N application rates?

In response to a question about what might prevent them from reducing N rate if they wanted to, *every* farmer felt any immediate reduction in their N rate would lead to yield and profit loss or would increase the chances they would suffer yield and profit loss from variable weather. Even farmers who applied above their respective profitable N rate threshold still deeply believed that their rates were the minimal allowable without sacrificing annual net profits (indicated by the illustrative comments in *Table 2* and further below). This is dramatically illustrated by one Indiana farmer's comment. He applied N at 210 lbs./acre, exceeding the profitable rate threshold for his region and rotation in Indiana by 13 lbs./acre. However, he commented that the only way he would reduce N rates would be if he could no longer afford to buy N:

> *IN43:* I guess if things got bad enough that you couldn't finance it would be the thing, and they would have to be, I mean, pretty bad before you'd have that happen. Because I'd cut [phosphorus] and [potassium] before I cut nitrogen […] that would be kind of a last resort, and if that was the case you might even see a for sale sign out front.
>
> *Interviewer:* So not a realistic thing?

IN43: No, it's not really going to happen.

This farmer's comments indicate that while he felt that he could reduce N rates, he perceived his current *high* application rate to be appropriate given profit concerns. Though his assertion was particularly strong, it must be noted that among farmers who applied above recommended rates, none expressed the opinion that reducing their N rates would be in their financial interest. Rather, almost all believed just the opposite. In short, profit-concern, or the perception that their current rates were profitable, was the dominant barrier farmers identified to reducing current N rates.

<Table 2 about here>

3.3 Considering why farmers perceived over-application as profitable/appropriate

However, there was not a uniform reasoning behind why farmers' saw their current (high) rates as profitable. Instead, upon further questioning during the interview, farmers generally fell into three distinct categories when discussing why they felt their current rates were profitable. This analysis focuses on farmers who were applying N in excess of their profitable N rate by 5 lbs. or more, to ensure minor rounding (e.g., 138 lbs. to 140 lbs.) was not the cause of over-application. As farmers described why they felt their N rates were profitable, three primary themes emerged: (1) they assumed they could not be over-applying, (2) they did not want to lower their N rates because they were using high N rates to "insure" optimal conditions; (3) they intentionally over-applied as a risk-mitigation strategy. I describe each below.

3.3.1 Over-application as not possible

Of the 49 over-applying farmers, 13 denied the possibility of their over-application. Though N was inexpensive relative to corn at the time of the interviews, it still is and was a

significant input cost. This cost, farmers argued, meant they needed to apply N at minimal rates considering maximum profit potential. In this way, the price mechanisms of the market were thought to be dictating economically *and* environmentally efficient N rates. Over-application, farmers argued, was a market-impossibility.

This sentiment is expressed well by one Iowa farmer, who despite applying 9 lbs./acre over profitable rates, strongly believed that the price mechanisms of the market dictated the application of N at minimal rates: "So [I'm] not over applying [N…] now financially it's become necessary to make those applications precise because the inputs are so expensive" (IA38). This farmer believed that the price-mechanisms of the market meant that the profit seeking behavior would lead farmers to necessarily apply N only at maximally profitable rates and not over them. In spite of this view, he was himself exceeding these rates. Other farmers who exceeded profitable rates similarly expressed the opinion that the price mechanisms of the market were dictating minimally profitable N application rates, and thus they could not be over-applying (see Table 3).

<Table 3 about here>

3.3.2 Insurance application for "optimal conditions"

The next group of farmers felt their current N rates were appropriate because they actually were focused on using *more* N to "insure" they did not miss out on rare, but possible optimal conditions. Some of these farmers focused on ensuring they did not miss out on high yield potential given optimal growing season conditions, some focused-on capitalizing on higher corn prices, and, assuming these two conditions worked out, others emphasized their desire to not miss out on the potential yield/profit booms when employing new agronomic techniques (e.g., increasing seeding population). See *Table 4* for example quotes. Their desire to take advantage

of these optimal conditions, and thus their desire to apply more N, rather than less is what groups these farmers together (8/49).

Farmers who expressed the desire to apply more justified this perspective through emphasizing their potential to achieve greater profits and to expand production: "It seems like [more N is] the most controllable and readily available way for the farmer to boost yield" (IA13). Another farmer similarly noted: "Is there much interest in trying to cut nitrogen fertilizer rates? Because I'm wanting to put on more. 200, 220, 240 [lbs. of N] is not out of line when I'm raising 200-bushel corn" (IN14).

Some farmers specifically justified their pursuit of higher yield via more N by referencing existing market-conditions at the time. High corn prices allowed, or even dictated, that farmers go "all out" to secure maximum yields and thus profits. In response to the question about what might prevent him from reducing N rates, one Indiana farmer colorfully illustrates this:

> "My personal opinion is, since 2008 everything changed as far as the farm, because 2008 is when we went from consistently selling $2 or $2.50 corn to consistently selling $5 corn. At that time, we went from being a farm to a business, and when you're talking $5 corn, you can't dicker around and short yourself on nitrogen. I know a lot of these people think they're going to save their way to prosperity and that's bull crap… Anyway, we don't screw around with nitrogen. We, a lot of times, we'll wind up with 200 or 250 pounds of nitrogen [per acre], and if I mention that to some people, they go crazy and they want to call the cops on me, you know, or like the nitrogen police or something" (IN15).

The profitable rate threshold for this farmer's region was 192 lbs./acre for corn-soy rotations. In

2014, this farmer exceeded this by up to 58 lbs./acre. While he was clearly aware that some concerns exist regarding high N rates— "nitrogen police"—he ultimately found this issue wanting in merit compared to the desire to expand production via high rates. In particular, he wanted to capitalize on potentially high-corn prices and ensure he did not "short" his corn by under-applying N and miss out on this potential. Consequently, he felt his current application rates were appropriate (if not too low).

As these comments suggest, a portion of over-apply farmers did not desire to reduce their N rates because they were intentionally using more N to capitalize on optimal conditions. These farmers were unlikely to consider over-application as a serious issue, or even a problem. Really, the potential issue of N application to them was under-application and they wanted to ensure this did not occur.

<Table 4 about here>

3.3.4 Insurance application for "sub-optimal conditions"

The final group of farmers felt their N rates were appropriate because they intentionally over-applied to reduce the chances they would have low yields/profits due to sub-optimal seasonal conditions (5/49). These farmers focused on how "a little extra N" prevented yield loss and thus also significant profit loss due to poor seasonal conditions. One over-applying Indiana farmer put it in terms of "insurance application, simply stating: "It's a type of insurance" against sub-optimal conditions (IN03). Additional comments reflecting the intentional use of insurance N are displayed in *Table 5*.

While farmers recognized that they were using insurance N rates for sub-optimal conditions, and thus wasting some N, as well as contributing to increased levels of N pollution,

none felt like they could reduce their current N rates (noted above). Even though they are likely often losing some profits through over-application of N, the perceived financial benefits of yield maintenance, especially in sub-optimal conditions, lead this to be seen as a reasonable decision: "We may over apply a little bit more than necessary, but a year like this [with lots of extreme weather] it's better to do it than not do it" (IA34). Some farmers specifically discussed how insurance application was done knowingly at the expense of environmental quality: "This is an age-old question [about] nitrogen. 'Are we getting too much [N] in the Gulf of Mexico because we're putting too much on? Blah, blah, blah.' And every time I've thought: 'You know I can cut this back 10, 15 pounds an acre,' [but] before the year is over with, I'm wishing I hadn't. It shows up," meaning in his profits (IN30).

Notably, farmers were not oblivious to environmental consequences they just felt they could not prioritize them. They saw too little N to put them at risk of serious profit losses, from yield declines. These concerns were not trivial to farmers. One farmer captured the sentiment many others held in defending his high use of N by saying, "Am I going to be able to pay my bills with less nitrogen… Is my corn going to be able to produce with less nitrogen to pay the bills? I guess that's what will really influence me" (IN48).

As these quotes indicate, farmers undertaking insurance application against sub-optimal conditions viewed this practice as a means to achieve the economic security of consistent yields and did not focus on, or could not prioritize the environmental costs associated with their intentionally high N rates.

<Table 5 about here>

4. DISCUSSION

While it has been suggested that midwestern corn farmers are over-applying N (Sheriff, 2005; Stuart et al., 2012), few recent studies have focused on the occurrence of this at the individual-level, showing by how much farmers are over-applying, and what factors shape this practice. Through analysis of farmers' detailed descriptions of their N use, I show that a substantial proportion of interviewed farmers applied N on corn following soybeans at rates that exceeded high profitable thresholds. The percent of farmers found to be exceeding rates in this sample may be inflated. Corn prices were high in the spring of 2014, the time period that most interviews took place. Past work has demonstrated that N rates increase when the N-to-corn price ratio is highly in corn's favor (Ribaudo et al., 2012). This may suggest that this portion of farmers exceeding N rates is a result of temporally defined circumstances; though the results displayed in *Figure 1* above indicate that a substantial portion (>29%) of this sample would have over-applied at any price-ratio between 2009-2014. This proportion is roughly equal to that found in a regional-level survey of over-application (Ribaudo et al., 2012). Moreover, I use high-profitable rates, whereas past literature has suggested farmers should be applying at low-profitable MRTN rates for the greatest environmental benefits without harming profits (Millar et al., 2010). The low-profitable rates were about 20 lbs./acre less across regions than the high profitable rates used in this study. Almost every interviewee exceeded these rates. At least in 2014, many farmers in our sample were not using economically minimum N rates, and were instead hovering around or exceeding the high profitable N rate thresholds.

Operating larger farms appeared to encourage over-application among respondents. This counters past studies that have suggested larger farmers may be more efficient users of N, due to greater technology adoption (Caswell, 2001; Lasley et al., 1990; Weber & McCann,

2015). I cannot assess if lack of N decision-making technology is behind this finding, as not every farmer was asked if they used it. It does, however, confirm more recent work that has shown that despite being more likely to adopt~~ion~~ more efficient N application technology, larger farmers also tend to apply N at higher rates (Houser, 2021). This may be because of the difficulty of precisely managing N across such large swaths of variable ground (Reimer et al., 2020). Given that this study relies on qualitative methods and a relatively small sample size, these results should be seen as preliminary. Future work should continue to explore this relationship between N rate and farm size, especially using large scale surveys and statistical analysis.

All over-applying farmers perceived their rates to be appropriate and profitable. My results suggest three primary reasons why farmers may feel this way. The first group of farmers thought they could not be over-applying as they assumed price mechanisms of the market ensured they were not. In many ways, these farmers' perspectives reflected what has been referred to as "market-fundamentalism" or "the free-market ideology" (Gladwin, Newburry, & Reiskin, 1997). In past work, high levels of belief in the "free-market ideology" has been found to reduce belief in humans' contribution to environmental issues and in this way discourages the desire to act to address them (Heath & Gifford, 2006). Similarly, farmers in this study expressed the free-market position to deny the existence of their over-application—they saw it as a market impossibility. This suggests, as other studies have too, that ideological positions—relatively stable and widely shared sets of values and beliefs—shape farmers' management practice decision-making (Dentzman et al., 2016; Houser et al., 2020).

Beyond being influenced by this ideological position, it is possible that many of these farmers were using an older measure of "efficient" N application rates, like yield-goal

maximization ratios. Further, they may not be widely deploying N decision-making tests that would indicate over-use of N (e.g. pre-side dress nitrate tests). Again, as not all farmers were asked about decision-aid use, I cannot assess this impact. It is possible that in assuming market-signals would indicate over-application, these farmers are less likely to critically explore their N use, by using N tissue-tests for instance. Should these factors be truly explanatory, it would suggest misinformation and misperceptions are indeed encouraging farmers to see over-application as appropriate (Huang et al., 2015). However, it does bear mentioning that these farmers could truly apply above MRTN established rates without harming their profits. While I have used very conservative estimates of over-application to ensure this is not a widespread issue, it still could be that some farmers have unique access to corn or N prices and/or operate on uniquely positioned lands that yield above well-established regional averages. Future research should continue to examine this potential.

Reflecting past work that has argued farmers over-applying N for "insurance" purposes (Babock, 1992; Sherriff, 2005), farmers in this sample believed their over-use of N was appropriate or justified because they used (1) insurance N rates in a hopeful search to "insure" expanded production given optimal conditions or those who viewed (2) insurance N applications in case of sub-optimal conditions as appropriate purely for economic reasons. Among optimal condition insurance applicators, they did not desire to reduce rates because they desired to increase them. This finding empirically confirms past studies that have asserted this optimistic approach likely motivates farmers to apply above economic thresholds (Rajsic et al., 2009). Among sub-optimal condition insurance applicators, they over-applied intentionally to insure stable yield and/or economic outcomes given poor seasonal environmental conditions. Past

studies have widely asserted that farmers' over-use N to "insure" economic stability (Sheriff, 2005; Stuart et al., 2012).

In both cases of insurance N, farmers' justification for over-application—that it can pay to over-apply—is likely correct. Over-applying may at times lead to profit-booms due to optimal conditions, which, if they are large enough, can economically offset prior years losses from the over-use of N (Rajsic et al., 2009). Similarly, though agricultural economics literature has pointed to insurance application for sub-optimal conditions actually increases economic risks to farmers (see Pannel, 2017 for a review), it can "pay off" in non-economic ways (e.g. reduced cognitive difficulty in deciding when and where to apply to reduce over-use (Arbuckle & Rosman, 2014; Sheriff, 2005). As Arbuckle & Rosman (2014: 8) hypothesize, "a reality (for at least some farmers) [is] that the practice of "insurance" over-application is simply a part of staying in business" because of how over-use enables them to not precisely manage the temporal and spatial dimensions of N use. In both cases, as farmers are over-applying, their hopeful search of profit-booms or risk-mitigation is likely leading to relatively high N_2O emissions and other forms of N pollution.

Farmers' over-use of N must be understood in context. Agricultural land in the Midwest is consolidating rapidly (MacDonald et al., 2013) and farmers face considerable pressure to ensure that they are not "lost in the price squeeze" associated with diminishing marginal returns and thus "leave room for their more successful neighbors to expand" (Ashwood et al., 2014; Levins & Cochrane, 1996: 550). In short, Midwest farming is highly competitive, and farmers must act in ways they feel help them to stay in business. Though not a focus of this study, these structural, market-pressures are another important factor shaping farmer decision-making and the reasonableness of their views (Stuart & Gillon, 2013).

I must also give brief attention to how N pricing likely enables farmers to see their over-application of N as appropriate. In 2014, the average annual cost for every 1 lb. of N was around $0.42 (Schnitkey, 2017). At this price, over-applying by 20 lbs./acre costs farmers $8.40 per acre, and they will potentially increase N_2O emissions at an amount equivalent to 0.2 metric tons of CO_2 (Millar et al., 2010). Roughly, 0.2 metric tons of CO_2 equates to the amount of emission reductions expected from moving from conventional to conservation tillage, which is valued as one of the most effective agricultural GHG mitigation strategies (Millar et al., 2010). In terms of profit losses, it is not surprising that nearly 1/3rd of farmers in this sample over-applied by 10 lbs./acre or more yet felt their rates were economically optimal. Generally speaking, 10 lbs. in excess equates economically to little more than losing a bushel of corn an acre (avg. of $4.16 in 2014, macrotrends). There is little economic penalty for over-applying N and the true consequences of over-applying, further spurring on climate change, are external to the pricing of N, relatively temporally distant, or something most midwestern farmers are skeptical of (Arbuckle et al., 2013).

Low N prices likely enabled farmers to feel like they are at their absolute, economic minimum (free market ideology), optimistically over-apply more N toward hoping for further yield growth (insurance application for optimal conditions) or pessimistically perceive excess N as a normal, and thus "minimal" application strategies (insurance application for sub-optimal conditions). Particular to the latter two groups of farmers, low N prices lead these justifications to not only be acceptable, but to be economically rational—why not over-apply if it will cost you very little, may lead to profit-booms, and can provide the cognitive relief that comes from perceiving one's economic risk to be diminished?

Policy options that increase the economic cost of N may be necessary to reduce over-use. Options like taxing N may be unpopular, but necessary to reduce over-use of N. This approach has been effective where adopted (Hamblin, 2009). Other policy research suggests novel options aimed at non-farmer actors, which should also be considered (Kanter et al., 2015). In the long-term, it may be most effective to focus on developing policy and programs that incentivize transitions to greater production of organic N, especially when coupled with higher soil carbon, for instance, via incorporation of more leguminous crops and returning organic wastes to agricultural systems, and/or more diverse crop rotations (Blesh and Drinkwater 2014). This latter approach may be the more difficult to achieve, as it would require a massive transformation of the Midwest row-crop system to a more diverse, agroecological system. However, such a transition could provide numerous social and economic benefits to farmers and rural communities (Davis et al., 2012), is one of the most effective ways to reduce N loss to the environment (Drinkwater & Snapp, 2009) and may be supported by midwestern farmers given declining profit margins and the expected rise in fertilizer costs (Schnitkey, 2018). Future work may also benefit from examining the impact of other external factors, such as crop insurance, which has been shown to promote higher N rates in past work (Houser & Stuart 2020). In any case, while we must immediately reduce N_2O emissions and thus the prevalence of the over-application of N, the impact policy will have on farmers should be carefully considered.

Finally, it must be noted that this work relies on a qualitative, case study of Midwestern farmers in three states and at a time period of particularly high-corn prices. It is ultimately introductory and exploratory then. Future work is needed to develop a fuller and wider depiction of farmers' motivations for over-applying N and the above discussion suggests a number of possibilities—e.g. lack of information source use. Most notably, future research should focus on

gaining a more representative and generalizable understanding of the scope and drivers of farmers' over-use of N. This work would be well served by employing large-scale survey efforts and inferential statistical models.

5. CONCLUSION

Though previous work has assumed and hypothesized that corn farmers over-apply N, this study takes an important step in empirically examining this practice. I focused particularly on answering if and why farmers' felt comfortable in their over-application, under the position that this acts as a significant barrier to voluntarily reducing the prevalence of the over-use of N (Ribaudo et al., 2012). I offer key preliminary evidence that many over-applying farmers feel their current rates are appropriate and suggest this occurs because farmers either assume they cannot be over-applying or are unconcerned about over-application and instead want to "insure" they are not under-applying.

This case study makes important inroads toward understanding farmers' over-use of N, but it is introductory. Toward future work, studies may fruitfully build on these findings through quantitative analysis using MRTN rate thresholds. Further, as this study examined farmers who were over-applying N, it neglected farmers who were applying N at economically appropriate rates. Future analysis focusing on farmers who apply N at or below MRTN rates may reveal the characteristics and circumstances that motivate and enable farmers to reduce their N application rate. Finally, studies to examine over-application at the individual level in other geographic cases (especially in countries where over-use is more severe) and in other temporal circumstance, such as when corn prices are very low. Though limited in some ways, this case study takes a key step forward in addressing a gap in our understanding of the barriers to reducing the over-use of N

(Arbuckle & Rosman, 2014) and contributes toward better understanding the role farmer decision-making plays in the widespread loss of N from agricultural systems (Stuart et al., 2015).

CASE STUDY QUESTIONS:

1. What are the consequences of over-applying nitrogen fertilizer?

2. How is over-application defined in this study? What are the benefits and negatives of defining over-application in this manner?

3. How prevalent was over-application of N? Based on farmers' comments, what contributed to over-application? How might these contributing factors differ across different cases?

4. What factors limited over-applying farmers' desire to lower their N application rates? Are these factors likely generalizable to other cases, both geographically and temporally?

5. How might the interview questions or farmers' own biases have shaped their responses to questions about what limits their capacity to lower their N rates?

AUTHOR CONTRIBUTIONS:
MH: data collection, conceptualization, analysis, initial draft, editing/proofing.

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There are no conflicts of interest.

NOTES:

1. Corn and N prices were as follows for each year: 2009 (N=$808 per ton; Corn=$3.75 per bushel); 2010 (N=$506 per ton; Corn=$4.31 per bushel); 2011 (N=773 per ton; Corn=$6.8 per bushel) 2012 (N=$846 per ton; Corn=$6.92 per bushel); 2013 (N=879 per ton; Corn=$5.69 per bushel); 2014 (N=691 per ton; Corn=$4.16 per bushel).
2. For Iowa, the maximum profitable "upper limit" MRTN rates for a corn-soybean ratio system were 151 (main region) and 167 lbs/acre (S. East IA region). For Indiana, 197 (North West and N. Central regions), 216 (Central region); 235 (E. Central region); 240 (N. East region); and 192 lbs./acre (W. Central, S. West, S. Central & S. East regions). Finally, only a single MRTN rate is available for the corn growing region of Michigan: 161 lbs./acre.

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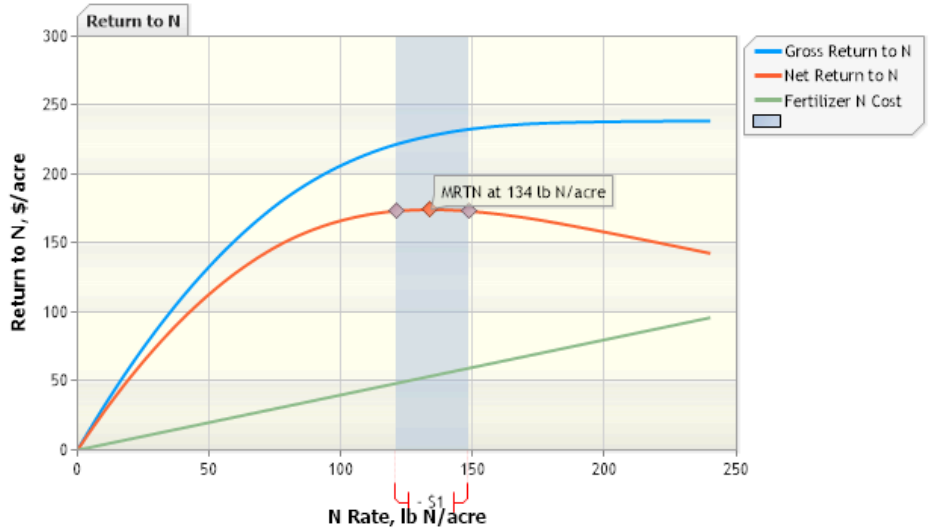
FIGURES

Figure 1: MRTN Example Tipping Point



*Source: ISUAEO, 2022; A calculated MRTN curve and tipping point, using hypothetical corn and N prices. The return line depicts the economic returns from applying higher rates of N, accounting for corn prices and yield. Based on the price ratio of N to corn used here (N =.40 $/lbs.; Corn = 3.40 $/bu; Price ratio= .12) the "right" or MRTN rate depicted here is 134 lbs. of N per acre (center diamond) The "high profitable rate" (right diamond) is 148 lbs. of N per acre, after which returns begin to decline dramatically. For this paper, I define over-application as rates that exceed this upper-most threshold.

Figure 2: N To Corn Price Ratios Between 2009-2014

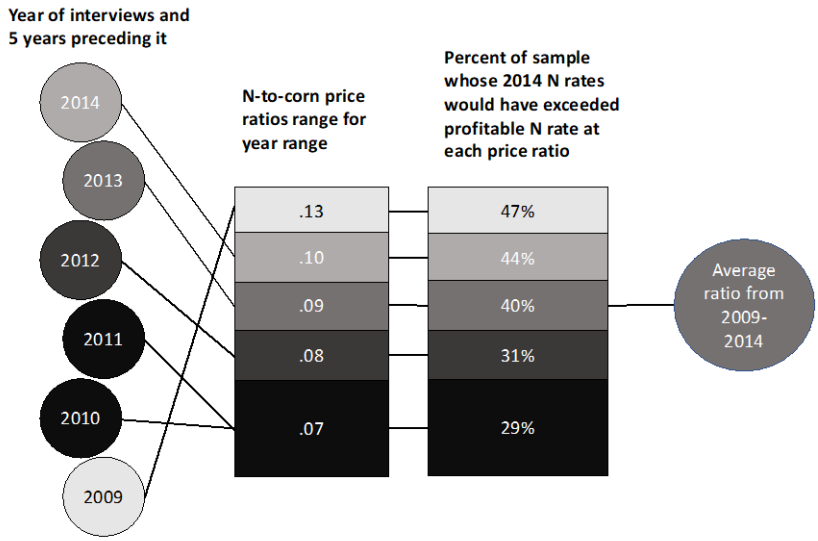
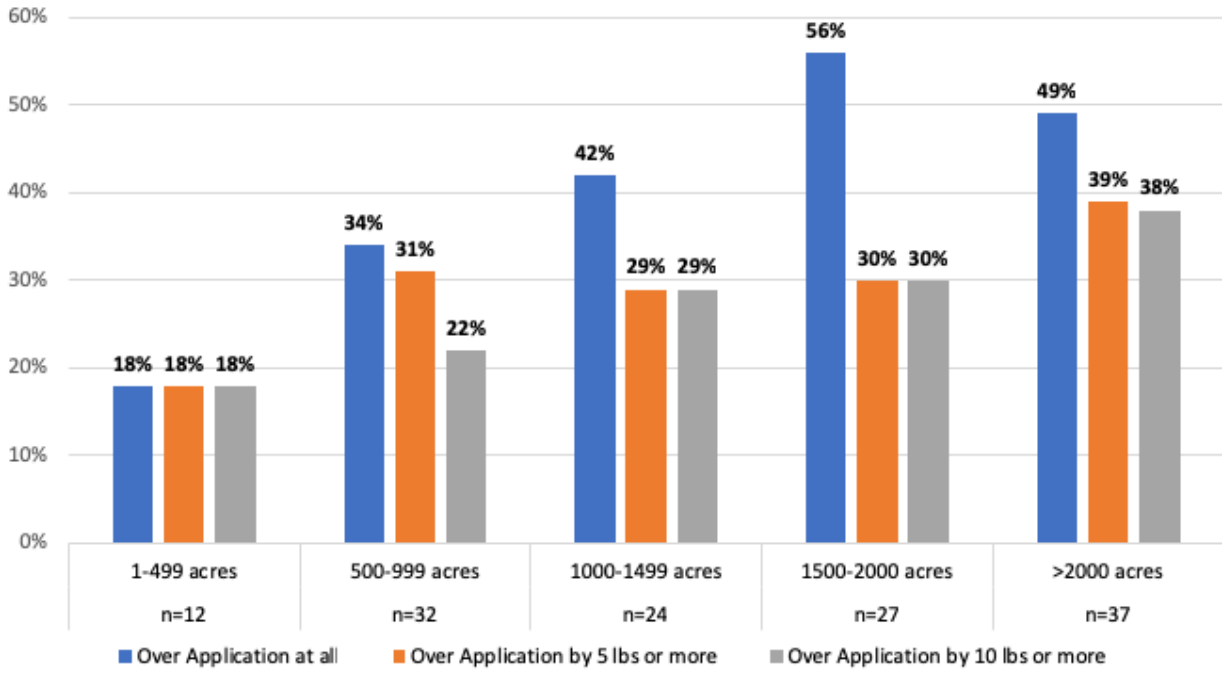


Figure 3: Percent of farmers over-applying N by farm size category



TABLES

Table 1: Descriptive results for N application rate of farmers in a corn-soy rotation

State	High-profitable MRTN rate range across regions (lbs. of N/acre)	Farmers' mean lbs. of N /acre[1]	Farmers' N rate range in lbs./acre[1]	Applying above high-profitable rate	>5 lbs./acre above high-profitable rate	>10 lbs./acre above high-profitable rate	Sample Size
Indiana	192-240	196	140-270	32%	26%	16%	43
Iowa	151-167	160	120-240	53%	49%	14%	47
Michigan	161	163	72-245	47%	38%	36%	42
Total	NA	173	72-270	44%	37%	29%	132

1. Due to six farmers using variable rates of N, these figures are drawn from 126 interviews

Table 2: Yield loss as indicator of farmers' perception of their minimal application

Farmers' Applying Above Profitable Rates Responses to the question: What would stop you from reducing N rates? Example quotes.

"Lack of yield; lack of income" (IN46).

"If you're short of nitrogen you're going to hurt your yield. You can cheat the others a bit but not the nitrogen" (MI47).

"Concern about dropping our economics enough; sacrificing net profit" (IA14).

Table 3: Farmers who applied N above profitable rates commenting on the role of the market in dictating minimal N rates

"And like I said, the fertilizer and seed is so expensive that, you know, we don't want to… We're not out here… This isn't a charity, we want to make money, you know, we don't have unlimited resources to throw out there, we just want to, you know, get the bang for our buck so to speak" (MI17).

"I don't know that anything would stop us from [applying less], I mean, honestly that's the goal, to try to get a product, you know, that we can generate more revenue with less [N], get better utilization out of the units we do put on, so to me that's a goal every year, off the top" (IN35).

"Economically, we don't want to be spending more money for the product than we really have to. So you kinda have to find that sweet spot, as to where what is the right amount on your soil type for the maximum return. And I don't think the general public understands, when they start pointing their finger at us that we're to blame for the dead zone and the nutrients and water, this is my land. This is my livelihood. I'm not going to

something that is not proper or is going to damage that (IA20).

"If it leaves your field, then you've thrown money away. I think we get blamed for it, but the motivation would be to keep what you put on. No one is out there putting [N] on hoping that it goes away. You spent money on it. You buy it hoping it ends up in a lake somewhere? It's counter-intuitive. It doesn't make any sense. The perception is that they're just out here putting fertilizer on willy nilly and I do not believe that to be the case at all" (IA62).

"I tend to stick pretty close to yield goals with nitrogen application. Cause it's a huge expense" (IA64).

"To me it's a financial one. I don't want what I paid for getting off the property [i.e. losing N]. That would be the higher priority piece of it, but it also has the secondary benefit not polluting downstream" (IA33).

"Why put on 400 pounds of nitrogen if you're crop is only going to take up 200? Why waste the money? So that's the other thing, the money factor comes into effect" (IN42).

Table 4: Farmer comments illustrating profit seeking behavior encouraging higher N rates for optimal conditions

"Is there much interest in trying to cut nitrogen fertilizer rates? Because I'm wanting to put on more. 200, 220, 240 [lbs. of N] is not out of line when I'm raising 200-bushel corn" (IN14).

"I've been increasing [N rate] a little bit the last couple years" (IA48).

"And our goal is 200 plus corn. We plant 37,000 [corn] population, so we're looking for good yields (as justification for high N rate)" (IA40).

"If I wanted to apply less? Oh…I guess possibly the fear of not having enough. Not maximizing the potential of your crop […] you hate to give up the potential of [yield]…that's what tends to make you vulnerable [to poor conditions]. You go 55 gallons [of N] instead of 52, you think, 'Oh it's pretty nice [the yield potential], maybe I ought to put a little more on.'" (IN02).

Table 5: Farmers illustrating the use of "insurance" N application rates to ensure yield maximization in sub-optimal conditions

"The uncertainty and the reduction in the yield would be the only thing [stopping me from reducing N rates]. If you were gonna tell me that I needed to cut 50 pounds of nitrogen

you'd have to prove it to me that you could do it on a more than one-year basis because there is flukes when the weather is just perfect, yes you could" (MI45).

"[We apply based on] probably whatever's in the checkbook. And part of that goes out to if you can afford to put on a pound or 1.2 [pounds per] bushel, we will [to help insure yields]" (MI27).