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Taming Nitrogen: Recognizing N2O Emissions in Fertilization Practice

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Abstract

Atmospheric nitrous oxide (N2O) is a greenhouse gas resulting from an imbalanced global nitrogen cycle. Although agricultural soils emit the majority of anthropogenic N2O, it is rarely considered in soil management practice. To understand why, this thesis explored the social constructs of nitrogen management through a case study contrasting practices and attitudes from three schools of thought with different approaches to soil fertility management: precision, organic, and no-till with cover crops; and from the perspective of different roles in agriculture from farming and advising to science and industry. Nitrogen management practices were compared using a model from organizational theory in which problems and solutions are inconsistently matched. All schools of thought had approaches to balance yield and nitrogen conservation, and a prominent best practice was maximizing nitrogen use efficiency (NUE) as much as possible within the limits of acceptable yield. By reducing nitrogen flux, this reduces N2O. A sense of minimizing entropy – nitrogen losses inherent in conversions and storage between its many chemical forms – could further reduce N2O emissions. Though how to accomplish this is technologically unclear at present, a future state can be developed from currently evolving fusions between a mainstreaming soil health movement, a maturing practice of intensive cover crops, supportive technologies of soil testing, sensing and modeling which increasingly capture nitrogen dynamics, and the emerging technology of precision nitrogen sensing and management.

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1. INTRODUCTION AND BACKGROUND

THE NITROGEN PROBLEM

NITROGEN AND THE OBJECTIVES OF AGRICULTURE

There is an understood agricultural objective of creating abundance, for the purpose of feeding the community, the city, and now, the world. To meet this goal, the design principle of retaining and building the soil, with its yield-giving ability, has driven cropping systems and fertilizer treatments since agriculture's beginnings. We can look to examples from the early civilized world for successes and failures: from relying on river sediments as in Mesopotamia and Egypt, to battling erosion in the Levant, to recycling wastes and adding organic inputs as in China (Lowdermilk 1939, Ju 2005). Throughout, we expanded to a second design principle: pushing the limits of yield-giving ability. From some of the earliest agricultural systems which harnessed nitrogen-fixing legumes (Delwiche 1978) to the Green Revolution's breeding and cropping systems which utilize industrially-fixed nitrogen which we cite for feeding half the world's population, nitrogen has become one of the most important pivot points around which agricultural methods have developed.

Agriculture contributes to the now-doubled flux of nitrogen through the biosphere, and this increased flux also magnifies naturally-occurring conversions of nitrogen into its chemically reactive forms (Vitousek 1997, Schlesinger 2009). A report put forth by the Stockholm Resilience Centre lists the nitrogen cycle as a planetary system currently pushed beyond its safe operating space – an assessment based on the effects of nitrates on aquatic systems (Steffen 2015). Of the different forms of agricultural nitrogen pollution, nitrates are the most widely recognized and mitigated, followed perhaps by ammonia. A third important form, nitrous oxide, is not widely understood or discussed outside of academia despite being a potent and increasing greenhouse gas, and has as-yet limited technology for study and mitigation.

In this light, nitrogen management is now subject to a new agricultural objective – conservation of nitrogen resources to protect planetary biogeochemical cycles. The now-prevalent best practice to maximize nitrogen use efficiency (NUE) is arguably driven by nitrate mitigation, though by reducing nitrogen flux reduces all forms of reactive nitrogen loss. An emerging complementary design principle is to minimize conversion of nitrogen into reactive forms. Reactive nitrogen is described by Richter (2000) as entropy of the system, which can be reduced by sending nitrogen through energy-efficient pathways between stable forms. This implies keeping nitrogen tied up in the biosphere, for example recycling nutrients on-site, continuous green cover, minimizing soil disturbance, and intercropping (Richter 2000). Where before we harnessed nitrogen for its crop-yielding potential, we now hope to contain it.

Table 1: Nitrogen in agricultural objectives and design principles

Objective	**Design principles**
Abundance	Preserve/build soil and soil fertility. Push limits of available nitrogen.
Conservation	Increase nitrogen use efficiency. Reduce conversion of nitrogen to reactive forms.

NITROGEN AND GLOBAL CYCLES, CARBON AND CLIMATE

Nitrous oxide (N2O) has been receiving increased attention and research in the context of climate change. Anthropogenic N2O emissions have been growing at an increasing rate, and could double between now and 2050 if no changes are made (Davidson 2014). Though the atmosphere contains only 0.000032% N2O, there is about 19% more of it accumulated now than its pre-industrial level. Since N2O has about 300 times the warming potential per molecule as CO2, and stays in the atmosphere a long time, it contributes about 6% to the greenhouse gas warming effect. It is also likely the dominant emission depleting ozone (IPCC 2013). The Environmental Protection Agency (EPA) estimates that 77% of the U.S.'s anthropogenic N2O emissions in 2014 came from agricultural soil management, compared to 6% from combustion and 4% from manure management (EPA 2016).

At the recent COP21 Paris Talks on Climate Change, stakeholders from agriculture for perhaps the first time put forth a scrutiny on agriculture both as a contributor to climate change, and also for its potential to mitigate it. Though much of this discussion has been about carbon sequestration in agricultural soils, a nitrogen focus seems an obvious next step. And in fact, carbon and nitrogen are two pieces of the same emergent systems problem: along with the direct impacts reactive nitrogen has on water systems and the atmosphere, its interactions with carbon, phosphorus, and other nutrient cycles create indirect impacts. The presence and ratio of nitrogen and phosphorus determines productivity and biodiversity of ecosystems, which in turn affects the carbon cycle and climate (Steffen 2015).

WHAT CAUSES N2O EMISSIONS AND HOW TO MANAGE FOR IT

Managing to minimize nitrous oxide emission is complex, but theoretically possible. In agriculture, nitrous oxide is produced by soil microorganisms as a byproduct of the metabolisms nitrification, denitrification, and now being studied, chemo- and nitrifier denitrification. The overall activity of these metabolisms, as well as the percentage of N2O they produce, vary depending on soil conditions including available oxygen, carbon sources and nitrogen substrate, pH, and temperature. Changing conditions may simply shift N2O production from one metabolism mode to another (Liebig 2012). Conditions which could potentially favor nitrous oxide emission also shift from one point in the soil to the next and over time, complicating measurements in research and the vetting of mitigation options (Bakken 2012).

Inputting less nitrogen to cropping systems has been called the most certain way to avoid mineralized nitrogen in excess of plant needs and thus N2O emissions (Ribaudo 2011). Increasing NUE is widely promoted as a strategy to minimize nitrate and ammonia pollution, for example by using the best practices called the 4R's: applying fertilizer in the right time, right place, right amount, and right form (Roberts 2007). The reduction of N2O emissions from improving NUE depends on how nitrogen-efficient a system already is. Although Intergovernmental Panel on Climate Change (IPCC) calculations assume added nitrogen has a linear effect on N2O emissions, in fact, once crop needs have been surpassed, added nitrogen increases N2O exponentially. In N-limited crop systems in less developed countries, adding nitrogen to the system has very little N2O effect (Shcherbak 2014). This underscores the importance of knowing where we are on that curve, and that even being in the "linear" zone warrants exploring other mitigation possibilities.

Options exist to try to control specific forms of reactive nitrogen. The caveat is that practices designed to mitigate one reactive nitrogen species sometimes exacerbate another. For example, a report by the USDA Economic Research Service notes that injecting ammonia below the soil surface to prevent volatilization can increase leaching, or that while switching from Fall to Spring fertilizer application may prevent overwinter leaching, Spring soil conditions favor N2O production. The report cites further technologies which can be used to counter this risk, such as nitrification inhibitors (Ribaudo 2011). Some soil management options have unclear effects on N2O, and have to be evaluated depending on conditions. Choices of whether to adopt no-till to build soil organic matter (Rochette 2008), manage pH, which can have different effects on nitrifier and denitrifier populations (Baggs 2010), or utilize cover crops and crop residues (Basche 2014, Chen 2013, Dietzel 2011) could have different effects on N2O depending on site conditions.

Liebig (2012) presented mitigation options specific to N2O – some of which mirror already-promoted NUE best practices, and others which are outside of that box. These include using less N-demanding crops, absorbing excess nitrates with non-leguminous crops, controlling irrigation to avoid N2O-favoring saturation patterns, manipulating the microbial community, and keeping a high ratio of labile soil carbon to free nitrates so as to provide an energy source for complete denitrification (Liebig 2012).

FITTING N2O MANAGEMENT INTO CURRENT PRACTICE

Any of these options to mitigate nitrous oxide would have to fit into current practice. Shove (2010) has criticized the policy arena for framing climate change as a personal choice issue, favoring psychological behavioral studies over other theories of social change. Complex human activities, Shove says, cannot be shaped by individuals. Even if everyone in agriculture knew how (and perfect technology existed) to mitigate nitrous oxide, all other on-farm aspects of managing the soil, and the off-farm infrastructure and technology supporting that practice, must influence which options are chosen. Policymakers and researchers, Shove says, are obligated to study the wider context of a practice and to consider infrastructural change if it is found to be a problem (Shove 2010). Seppänen also discusses social change theory, applying it to the practice of agriculture. People in agriculture work under long-standing ways of doing things. As they resolve conflicting goals, or question the purpose of some activity, they contribute to shaping the practice over time for themselves and others (Seppänen 2002). These complementary approaches – Shove's being more systemic and Seppänen's more grassroots – both involve studying the whole context of practice rather than individual choice moments.

It is also useful to recognize that farming practice has many schools of thought, with different priorities – so "farming practice" can be thought of as several practices evolving in a common arena.

AREA OF INQUIRY

Wezel (2009) described agroecology as having three approaches to studying and changing the agricultural system – through science, practice, and social movements. The reactive nitrogen problem in agriculture exemplifies how all three approaches are needed:

- Scientifically, the nitrogen cycle is complex, with nitrogen undergoing transformations into many chemical forms. Nitrogen transformations are biologically-driven, thus the nitrogen cycle interacts with other biogeochemical cycles. Nitrous oxide is particularly difficult to measure, predict, and control.
- In practice, nitrogen is a critical element for growing food. It must be managed in coordination with other nutrients, and as part of general soil management and farm business objectives. Nitrogen management practice is shaped by the infrastructure that supports it, such as the inputs industry, developing technology, advising, and environmental regulations.
- Socially, different institutions and schools of thought within agriculture frame choices about best soil and nutrient management practices according to their prioritization of issues and goals. Interactions between these schools of thought are shaped within the arenas of science, economics and politics, and practice.

The area of inquiry for this research was the social side of the nitrogen problem, with science and practice as its context: how best practices are formed regarding soil fertility management, and prioritization of nitrogen losses in its various forms, particularly nitrous oxide. This was exploratory research into the ways in which current thought complicates a transition to agricultural practices which conserve nitrogen in general, and minimize nitrous oxide emissions specifically. The aim of the research was to inform strategies which could support such a transition.

Three schools of thought were identified as having different approaches to nitrogen management: precision agriculture, no-till with cover crops, and organic. Although the nitrogen problem affects all scales and types of farming, this research focused mainly on medium to large scale production of staple crops, such as grains and legumes. In the United States, university extension and the Natural Resources Conservation Service (NRCS) have well-established outreach programs focusing on staple crop farming. Additionally, there are many conferences and field days organized for staple crop farming in all three identified schools of thought. Many of these farmers are important customers of one or several of the following: agricultural supply co-ops, precision agriculture technology, and increasingly, cover crop seed.

Stakeholders were identified for a case study from within the U.S. staple crop system. They are farmers, advisors, scientists, industry professionals and government workers. Representatives were included from each of the three schools of thought identified, as well as general experts on agricultural nitrogen. Rather than statistically random sampling, experts were chosen by theoretical sampling, representing strong viewpoints of the roles and schools of thought described above. This supported building theories of how these groups interact (Eisenhardt 1989).

THEORETICAL FRAMEWORK

To study the handling of nitrous oxide within the context of nitrogen management and food production, and all of that within the context of science and technology support, requires soft systems methodologies. Qualitative information from the case study conducted with expert stakeholders was analyzed with the help of a theoretical framework from organizational theory created for complex and decentralized problem-solving scenarios.

FINDING SOLUTIONS IN A FLUID AND DECENTRALIZED PRACTICE

In the context of agroecology, Bland and Bell (2007) said that rigidly defining a system by listing its current properties and external influences can only identify change opportunities which are predictable from the current situation, but that in reality, unpredictable future states often arise as new emergent properties form. Their proposed approach defines a system by its intention to accomplish something, drawing system boundaries which may overlap and exist at different scales simultaneously. It then examines how those systems understand their own context and decision-making processes as they preserve and transform themselves. They urge agroecologists to continue developing research methods which account for these “soft systems” (Bland 2007).

From organizational theory, Cohen et al. (1972) described a “garbage can” model of decision-making – a metaphor for decision situations in which problems and solutions are chaotically mixed together, considered, and chosen based on chance and context. Such decision-making occurs especially when preferences, technologies, and participation are diverse and changing – scenarios they dubbed “organized anarchies.” Rather than drawing a strict boundary around a set of individuals comprising an organization and assuming they choose rationally as a unit, system boundaries are drawn around decision scenarios wherein problems and solutions are navigated by decision-makers participating at the time. Fioretti (2008) notes this fits the newer term “multi-agent system,” where agents could be decision-makers, or the problems and solutions themselves as they in a sense compete for relevance. Decisions made in these scenarios are said to often fail at solving difficult or important problems. So-called oversights occur when a solution is chosen without considering certain problems at all, while flights may consider the problems but dismiss them because a solution is not reached; in both cases participants may solve a different problem instead (Cohen 1972, Fioretti 2008). Fioretti (2008) suggests expanding the garbage can model by accounting for how decision patterns preserve and transform themselves, rather than treating each decision as a once-only and random phenomenon.

Seeing the similarities between Cohen’s model and soft systems methodology, its theoretical framework was applied to the problem of managing nitrogen in agricultural systems. Elements of the model served as a common framework for overlaying information from multiple sources and scales. Individual farms, research and advisory programs, and schools of thought can all be expressed in terms of which problems and solutions they consider relevant and why, as well as how they reinforce or challenge popular decision patterns. Comparing decision patterns across these groups shed light on problematic decision oversights and flights.

RESEARCH QUESTIONS

What are the characteristics of the organized anarchy of nitrogen management practice which complicate strategies for N2O mitigation?

Regarding nitrogen management in general:

- What nitrogen management practices are promoted by different institutions and schools of thought?
- Which problems do different nitrogen management practices address, and with which solutions?
- What infrastructure and practical considerations influence nitrogen management practices?
- What norms and values influence nitrogen management practices?
- How do the institutions and schools of thought interact to evolve nitrogen management practices?

Regarding N2O specifically:

- In which decision situations is N2O loss considered a relevant problem, and by whom?
- In decision situations where N2O loss is not considered a relevant problem, but perhaps could be, why isn't it? What other factors override its importance?

2. METHODOLOGY

DATA COLLECTION

In accordance with exploratory research, in-depth interviews were chosen to provide qualitative data with rich context. Questions were designed to draw out each person's views, practices, and priorities with nitrogen in the context of their experience, as well as how they perceived their own views, practices, and priorities in relation to others'. The interview was designed for one to one and a half hours. Some busy participants were only able to give half an hour of their time, so in those cases the interview was adapted to discuss the most important or not yet represented topics. Field visits supplemented the interviews with additional observations about practices and norms. These included personal farm tours, public field days, and attending conferences. Eisenhardt (1989) discusses staying flexible in case study work, and that following opportunities of different data collection modes helps triangulate and confirm information.

CHOOSING INTERVIEWEES

Expert stakeholders were chosen to represent farmers, advisors, scientists, industry professionals and government workers; the practices of precision agriculture, no-till with cover crops, and organic agriculture; and general expertise of nitrogen in agriculture. Many had more than one role or affiliation, or had experience with several types of practices. Initial contacts were made through a summer internship, attending conferences and field days, and reaching out to known organizations. Interviewees also recommended further contacts, some of whom were also brought into the study. Interviewees were sought for both expertise and influence in their area, influencing others through leadership, teaching, writing, and speaking. Eighteen interviews were conducted in the United States, and two in Europe.

INTERVIEW GUIDE DESIGN

The interview guide was designed to address the research questions, along with contextual information according to Cohen's model (1972), and the internal and external influences discussed by Seppänen (2002) and Shove (2010). These included which problems and solutions are considered and why, how they are prioritized, and which decisions are relevant to their work. To avoid bias, opening questions were more general and later questions more specific. Where possible, specific nitrogen issues and labels for schools of thought were avoided until mentioned by the interviewee, or asked about later if not mentioned. Several qualitative techniques were utilized in the interview:

- Grand Tour – a detailed narrative of personal experience in order to learn the context and details which are familiar and important to the interviewee. Farmers and advisors were asked to describe their best soil fertility management practice over the course of a growing season, and scientists, industry and government professionals were asked to describe the history of their work in nitrogen, current projects, and their plans for future work.
- Laddering – successively asking why things are important in order to learn about values associated with priorities and choices. This was done after the grand tour, as part of identifying the most important themes discussed.
- Progressive questions about forms of nitrogen loss, if not already mentioned
- Ranking – sorting nitrogen management themes mentioned during the grand tour by order of importance, in order to learn about priorities and pre-requisites. This activity provided some additional context, but was time consuming and seemed to add less value than the other questions. In the case of thirty-minute interviews, ranking was skipped in favor of direct questions about issues considered most important.
- Influences – where information about soil management is sought, both written and interactive, such as conferences. Perceptions about any schools of thought were explored in detail at this stage.
- Projective questions – asking about ideal visions, what-if scenarios, and how they might explain themselves to someone who disagreed with them, in order to learn about how challenges and barriers are perceived or could be overcome.

The interview guide questions are listed in Appendix 1.

ANALYSIS

Analysis was performed in two stages: summarizing the interviews individually, and then combining related themes across all the interviews into conceptual models and a narrative, which follow in the Results and Discussion section.

ANALYSIS STAGE ONE: SUMMARIZING INDIVIDUAL INTERVIEWS

Descriptive quotes from each interview were placed into grids. Each row contained a theme discussed and each column was labeled with a category inspired by Cohen's model: 1) a general overview including history, values issues and context; 2) problems (discussed as considered and not considered), 3) solutions (discussed as considered and not considered), 4) mentions of choice moments or decisionmakers, and 5) any visions expressed. This facilitated combining quotes throughout the conversation when a topic was returned to several times. Parsing out context, problems, solutions, choice scenarios, and visions aided in understanding how each person thought about solving problems within the themes they discussed as important.

Themes were delineated and labeled based on the context of each individual conversation. They were not pre-defined, and no attempt was made to delineate identical themes across multiple interviews. The open-ended interview questions brought forth many themes not directly related to nitrogen. These were all kept in the analysis during stage one, assuming they would provide contextual information. Any preliminary conclusions during stage one were noted in a reflection log.

ANALYSIS STAGE TWO: COMBINING THEMES AND CREATING CONCEPTUAL MODELS

Themes and quotes from the grids from stage one, along with reflections, were organized into common themes and rearranged into a narrative flow based on the research questions. Using Cohen's theory as a guide, examples were identified of problems, solutions, and values converging around choices in nitrogen management, especially where groups took different approaches to similar problems. Possible decision flights and oversights were identified by comparing these approaches. This analysis helped to reveal barriers and complications to reactive nitrogen and nitrous oxide mitigation, and to suggest ways to reframe the issues.

3. RESULTS AND DISCUSSION

The results and discussion are organized into three sections:

3.1 – A narrative of nitrogen practice
3.2 – Complications specific to nitrous oxide management
3.3 – Towards a future of nitrogen and N2O management

The first section discusses current nitrogen practice, how it is reinforced by schools of thought and institutions, and possible directions it was thought to be going in the future. The second section explores why nitrous oxide is or is not included as a part of nitrogen management. The third section synthesizes the qualitative information from the first two sections into conceptual models, suggesting possible ways to shift towards an agriculture with less nitrous oxide emissions.

All statements about nitrogen management are based on conversations with expert stakeholders, unless it is specified that the statement came from field observations or was cited from literature.

3.1 A NARRATIVE OF NITROGEN PRACTICE

The narrative begins with a detailed discussion of nitrogen practice from various schools of thought, and how these groups reinforce and challenge their own nitrogen practice as they interact. Then practices from each school of thought are discussed in terms of the agricultural objectives of yield and conservation, and from direct nitrogen management to ideas about system redesign. Norms and values are explored which reinforce or challenge agricultural objectives. The narrative then turns to how the context of infrastructural support – research, technology development, advising, and provision of services – has shaped nitrogen practice up to this point and where it may go in the future.

NITROGEN MANAGEMENT WITHIN DIFFERENT FARMING PRACTICES

Research questions:

- What nitrogen management practices are promoted by different institutions and schools of thought?
- What norms and values influence nitrogen management practices?

Because the names of farming practices and schools of thought can take on many meanings, their nitrogen management approaches as described by interviewees in this case study are summarized here.

PRECISION AGRICULTURE

The core principle of precision agriculture is that growing conditions vary in space. It rejects basing fertilizer needs on whole-field soil test and yield averages. Instead it measures and calculates nutrients per the smallest areas possible, applying more inputs to high-potential areas, and wasting fewer inputs on low-potential areas. Ideally, doing this increases yield in the best areas while poor to average areas yield the same – raising the average yield above what was previously thought possible. People are reportedly often surprised by how much conditions and yield can vary in a field, and thus conveying this variability can be impressive and convincing to those hesitant to adopt it. Farmers who choose to adopt precision agriculture were described as being more open to trying new technology.

The main challenge with large-scale precision agriculture is it can be complicated and expensive. Still, varying the rate of inputs seems to provide enough economic benefit to justify the practice for those using it. One interviewee suggested precision agriculture is often coupled with expensive high-tech inputs, and so variable-rate application helps control these costs, enabling adoption of both technologies. In many (but not all) cases, farmers rely on service providers to help manage precision agriculture on their operations. All of this suggests that precision agriculture as presented here is targeted to larger-scale operations, with investment being shouldered by service providers and/or the largest farms with sufficient capital.

Precision agriculture also generates huge amounts of data: not only from soil test results interpolated onto a field map and input and yield rates at each point in space, but increasingly from sensors which monitor plant growth. There was a sense this technology can still do more – such as monitoring conditions real-time and making adjustments during the season. Interviewees expressed that it is difficult to interpret all of the data into meaningful decisions. This has stirred an interest from the information technology (IT) industry, creating a rush to fill this gap. This was seen as both an opportunity for technological breakthroughs, and a challenging interaction between two industries which operate very differently from one another.

NO-TILL WITH COVER CROPS

The core principle of this method is that fertility and other benefits can be achieved partly or wholly via intense growth of other plants when the main crop is not growing, which are then killed at an optimal time so that their residues support the next crop and build soil organic matter (SOM). The practitioners generally consider themselves conventional farmers, and the practice as described here is often combined with no-till. This fusion was said to have begun when a small group of farmers and advisors experimented with intensive cover cropping methods which had been presented at a no-till conference series by speakers from South America. It has since gained momentum among a small subset of farmers for whom no-till has been an established practice for decades.

The use of cover crops for building fertility is a departure from their previous purpose within conventional farming, which was primarily erosion control, along with moisture control or preventing nitrate leaching. The prominent newfound use was growing and holding soil carbon and nitrogen, for which the C:N ratio and biomass at the time of killing the cover crop was considered paramount. Roughly one third of the mix was legumes – not more – which is said to optimize their nitrogen fixation. One third grasses and one third broadleaf plants including brassicas were included to capture and hold nitrogen that is mineralized. Other goals considered in designing a cover crop mix were pest, weed, and disease management, improving soil structure, and accessing micronutrients.

The cost of cover crop seeds, and extra planning and management of a crop that will not be harvested, can be barriers to the practice. Some said that it takes a few years to see results, or simply that they cannot achieve good results. Even after planting cover crops, some farmers may feel uncertain and apply the same amount of nitrogen as before, negating the economic benefit. On the other hand, those most enthusiastic and successful using cover crops cite reducing their nitrogen inputs partially or entirely. Enthusiasts said that cover crops must be given the same priority in planning as the main crop, planting them in time to maximize growing degree days, and choosing species that will grow well in that region and time of year. The benefit hinges on the cover crop producing enough biomass to make a difference – providing enough fertility that the next season's input costs are lowered.

ORGANIC

The core principle of organic nitrogen management was said to be enhancing the soil's capacity to mineralize nitrogen, and to time that mineralization to plant needs. Because synthetic nitrogen is not allowed, manures, compost, cover crops, and residues provide nitrogen; but the timing and amount of nitrogen released from these sources is difficult to predict. Accordingly, the primary challenge cited was getting enough mineralized nitrogen when needed.

Many described the organic practice as undergoing changes. As ideas about soil health and soil microbiology are becoming more mainstream, other schools of thought are making developments and disseminating knowledge about these subjects. Some of these technologies are then being applied or adapted back to organic farming.

NATURAL AGRICULTURE, "BEYOND ORGANIC"

A niche but interesting case was a Japanese practice called natural agriculture or nature farming. Its core principle is that fertility needs can be met by supporting a symbiosis between soil microbiology and plants. Many methods from other practices, including organic, were cited as counterproductive to this system. It avoids inputting any nitrogen – including from compost and manure, and avoids seeds adapted to high-input conditions. It refrains from practices which disturb the symbiosis between soil and plant species growing there, avoiding tillage, weeding, rotating crops or even buying new seeds each season. Instead, crops are grown and seeds saved in the same place each year. Fertility is supported by weeds which grow off-season, and if not detrimental, in-season. Though cover crops as described above do not strictly fit the principles of the practice, a kind of concession mentioned was to use the same cover crops each year. Ultimately, however, nitrogen was not treated as a limiting factor, and the nutrient profile in food grown under this practice was seen as beneficial to human health.

SOIL HEALTH

The soil health movement has perhaps become its own school of thought distinct from organic. Its history may stem from organic pioneers in the early 1900's in Europe who linked soil organic matter to continued productivity. They developed farm systems based on composting and cycling nutrients, ideas which were known to intellectual circles from accounts of historic agricultural methods in Asia (Freyer 2014). Their work influenced mid-century organic pioneers, some of whom were named by interviewees: J. I. Rodale in the United States, and Hans and Maria Müller in Switzerland.

"Soil health" in its current sense as described by interviewees emphasizes how nutrients are cycled through plant-microbe interactions in soil. Building soil carbon and soil structure is a primary goal of soil health in order to improve nutrient cycling. There was a trust by many that human health benefits from a soil health approach, illustrated by the often-used phrase "healthy soils for healthy food."

INTERACTIONS BETWEEN SCHOOLS OF THOUGHT

Research questions:

- What norms and values influence nitrogen management practices?
- How do the institutions and schools of thought interact to evolve nitrogen management practices?

There was a sense precision agriculture and no-till with cover crops were distinct groups. From a precision standpoint, the no-till with cover crops method was seen as still being a whole-field approach. While a valid critique – cover crop farms may be at a somewhat smaller scale and level of capital investment than precision agriculture farms – they did report choosing cover crop species mixes to address concerns and goals of each individual field, and one said it would be nice to manage cover crops in zones. Relatively new equipment which can variable-rate seed multiple varieties was presented at a no-till conference as having possible applications for cover crop seeding.

The no-till with cover crops movement seemed to coincide somewhat with the promotion of soil health. Supporting institutions such as the NRCS and some extension programs combine soil health, no-till, and cover crops in their outreach. Perhaps influenced by this, some of the no-till with cover crops farmers set their farms apart from even larger-scale farms relying more on precision and high-tech methods. From their point of view, these larger farms were producing a material commodity, whereas they saw themselves as producing food. This was perhaps influenced by "healthy soil for healthy food" ideal from soil health. Soil health and cover crops concepts have also certainly reached precision farmers and researchers, reportedly through NRCS and extension, the inputs and service providers they sometimes partner with, and increasingly via articles in popular farming magazines and journals. But the adoption of these ideas into precision farming is still tenuous. One precision farmer said that cover crops need to be able to apply to large scale economics and big agriculture, but it was not quite there yet.

No-till and cover crops are now a merged concept for those in the movement. No-till alone has its own history of several decades before that, and became known as chemically intensive because it relied heavily on herbicide in lieu of tillage. This alienated it from organic. Even incorporating cover crops, the no-till with cover crops farmers use chemicals as needed, albeit with the goal of decreased use.

Organic may be undergoing a transition now that some of its core ideas have reached a wider audience under the umbrella of soil health. Groups outside organic are reportedly discussing soil management using biological principles in greater technical detail than can be found in current organic publications. It was said that some organic farmers would seek details about more biologically-based nutrient management from more conventional publications and events, but that others felt an aversion to discussions of chemicals or genetically-modified seeds which might be presented alongside that information. Still, some organic farmers are talking about cover crops with the same species and ideas as promoted by the no-till with cover crops.

Some conferences and publications have changed their name or focus from organic to sustainable, opening the door for other practices to promote their solutions. Reportedly, even some working on precision agriculture technologies are finding a place at these conferences, to see if the technology can find applications there. This convergence was said to be in a very early stage, however, and is meeting both skepticism – "figuring out better ways to use your chemicals" – and a sense of opportunity for helping sustainable agriculture.

Soil health was simultaneously distanced from thinking about nitrogen directly, and trusted to solve any reactive nitrogen problems as a side benefit. Soil health and nitrogen management were said to be in different tracks at conferences. Several discussing soil health said we are too focused on nitrogen, or that research and outreach efforts have to be about soil health first, with nutrients and nitrogen as a subtopic within that context. An explanation from a scientist illustrates why this separation might exist, but also why soil health and nitrogen should be viewed as a fused concept:

> "We'd been focusing for many decades on managing our nutrients, and that's done us a lot of good. But if you look at a nutrient in a vacuum, for example nitrogen, you're missing a huge part of the picture. Because the physical and biological processes in soil are really what drive the nitrogen cycle. Especially the biological processes, but of course those are influenced by the physical state of the soil."

A SPECTRUM OF NITROGEN MANAGEMENT OBJECTIVES

Research questions:

- Which problems do different nitrogen management practices address, and with which solutions?
- What norms and values influence nitrogen management practices?

Nitrogen management practices discussed in the interviews strove for a balance between the agricultural objectives of abundance or maximizing yield on one end, and conservation, NUE, and minimizing nitrogen loss on the other. This did not necessarily depend on which school of thought was being followed; each gave examples on all parts of this spectrum, even if their approaches were different. Many example practices directly managed soil nitrogen, and through compromises between yield and NUE, impacted the amount of nitrogen ultimately added to the system – nitrogen flux. Others went beyond direct nitrogen management to systematic re-designs which had indirect but important effects on nitrogen.

Table 2: Practices and system redesign ideas along a spectrum of abundance and conservation.

Objective		**Highest priority / design principle**
Directly managing soil nitrogen		
Decreased N applied? ↓	Abundance	Maximize Yield
↓		Maximize Economic Return
↓		Maximize use of alternative nitrogen sources
↓	Conservation/ Regeneration	Maximize NUE within yield constraints
↓		Maximize NUE absolutely, Minimize losses
Beyond directly managing soil nitrogen		
Balancing abundance and conservation		Improve global NUE through food system design and diet: sociology, economics
		Cropping system design, soil health, modes of animal production: biology, ecology

MAXIMIZING YIELD

There were example practices from each school of thought chosen to maximize yield, except perhaps in natural agriculture. Yield was balanced with other priorities in different ways by each approach. Yield was seen as critical to making money and staying in business, and some also discussed feeding the world's population. Beyond these utilitarian incentives, there may also be an enthusiasm for pushing limits – achieving more of something than previously thought possible – that manifests into system design in different ways.

Yield drove the early development of precision agriculture, and is a primary metric for judging success from the system. Early precision agriculture experiments in the 1980's sought to answer the questions: do nutrients vary in the soil, and can we manage for it? Results were judged by yield maps and whole-field yield improvement. A self-taught precision farmer also described studying yield maps at the end of every season to see what worked well, and checking a database of compiled yield data across the region to see which varieties yielded best, and under what treatments.

Achieving high yield may be seen from a precision standpoint as a perfect mastery of variables, with weather as the only unknown. A farmer described precision-planting two varieties within the same field: on high-potential areas using a variety which could "flex," producing more kernels per ear if the weather was just right. Additional fertilizer and other treatments were then applied later in the season if the payoff was judged worthwhile. New equipment such as high-clearance tractors and Y-drops make it possible to apply products to crops which are already very tall. Another gave an account of achieving extremely high wheat yields with closely planted high-yield seeds, precision-applied nitrogen, and products to prevent lodging and disease in this stand of denser-than-usual biomass.

In organic agriculture, several said that achieving high yields is more difficult, but a high priority for the same economic reasons as for any farm. Contrasting viewpoints were given about how strictly nitrogen is controlled for yield in organic systems. As a researcher said, the association with nitrogen is different in organic farming. On one hand, it was mentioned that organic farmers tend to rely less on standard nitrogen, phosphorous and potassium (NPK) soil tests and their recommendations. On the other hand, many associated with organic farming spoke of adding the correct amount of nitrogen for crop needs.

Organic practices to assure yield took two routes: increasing the amount of organic inputs to be on the safe side, or assuring mineralized forms of nitrogen would be present at the right time. Regarding the first, organic inputs were for some constrained by local availability, cost and labor of applying bulk materials, rather than concerns over nitrogen loss. Regarding the second, several practices were used to assure mineralized nitrogen was available when needed. Some mentioned jump-starting mineralization by adding microbial food sources, using cover crops known to release nitrogen quickly, or with tillage right before planting. Some also described using high-nitrogen sources such as feather or blood meal or Chilean nitrate at critical stages, such as in early Spring or when wheat produces tillers in the Fall. In these cases, it was felt that leaving mineralized nitrogen to chance risked yield loss.

The no-till with cover crops practice changes the yield objective in some interesting ways. The most successful cover crop farmers boast as good or better yields on their main crop as achieved previously with conventional no-till. But yield goals were not limited to the main crop: a high biomass yield of the cover crop is also needed to provide fertility. Like organic, the association between nitrogen and yield is different for no-till with cover crops, but nitrogen is perhaps more deliberately emphasized. No-till cover crop farmers and advisors calculate nitrogen from a hybrid of residue and soil sources, and supplement any gap with synthetic nitrogen. Nitrogen contents may be easier to predict and control in cover crop mixes selected for a specific C:N ratio than in animal manures or compost.

How yield is achieved under a no-till with cover crops system may also have different implications for plant breeding. Some mentioned that modern high-yielding varieties have less stalk, returning less organic matter to the system whether as cover crop or main crop residue. In some cases they are seeking and incorporating non-improved varieties both as cover crops and cash crops. Incidentally, one farmer achieved better yields with non-improved corn varieties than their high-tech counterparts under a cover crop system. Such results were anecdotally attributed to mycorrhizal associations and greater root mass being better able to access organic nitrogen pools.

MAXIMIZING ECONOMIC RETURN

Interviewees' discussions of yield showed that cost is generally a factor in any attempt to increase yield. A subtle change from maximizing yield is maximizing economic return: recognizing the point where paying for more fertilizer does not improve yield enough to justify the cost. One formalized initiative for prioritizing economic return over maximizing yield, called Maximum Return to Nitrogen (MRTN), was developed in the Midwestern United States. Rate recommendations are tied to a model and database, considering yields from nitrogen trials under different treatments and in different geographic areas, and current input and commodity prices (Sawyer

2012). It is an interesting question how closely the point of diminishing economic return coincides with the inflection point between loss of NUE and loss of yield discussed by Roberts (2007).

USING WHAT'S ALREADY THERE: RECOGNIZING ALTERNATIVE NITROGEN SOURCES

There are two ways in which already-present nitrogen may be commonly overlooked. All nitrate may be assumed to have leached over the winter, and nitrogen present in organic matter may never be considered. These assumptions are not just opinion but are based on experience where these pools were not large or apparent. Two geographic regions were described as leaching all nitrates, and another in which any ammonia applied is immediately nitrified. Still, there was some recognition by interviewees describing hopelessly leaching soils that the nitrogen dynamics could change slightly if soil organic matter was increased. The no-till with cover crop approach to prevent leaching is scavenging leftover mineralized nitrogen at the end of the season with grasses and broadleaf plants, which protect it from leaching overwinter and re-mineralize it when they are killed in the Spring.

Hope was expressed that improving soil test technology will better reveal organic nitrogen pools in soil. One interviewee said that in the past, it was mainly organic farmers who were interested mineralizing organic nitrogen, but it is now increasingly considered in conventional systems. Many interviewees who happened to discuss more detailed or "biological" soil tests were farmers or advisors in the no-till with cover crops group. Seemingly, better testing and modeling technology will be the key for farms to include organic nitrogen pools in fertilization planning.

BETTER NUE, SUBJECT TO YIELD GOALS, THROUGH THE 4R'S

When introducing the 4R's, Roberts (2007) discussed the tension between public distrust and regulation of fertilizers and the economic realities of production. The 4R's strive to improve NUE within the constraints of a realistic yield, aiming for the inflection point on the curve between dramatic drops in NUE on one hand, and dramatic losses of yield on the other (Roberts 2007). This section will review discussions of practices which strive towards synchronizing nitrogen availability to crop needs in accordance with the 4R's framework.

Timing

Ideally, from a synthetic nitrogen standpoint, mineralized nitrogen availability would be fully synchronized to crop uptake so that very little was lost. Fertilizer takes labor to apply, however, and mineralizes nitrogen very quickly. As a most basic solution, a few discussed that farmers are applying more of their nitrogen for Summer crops in the Spring as opposed to the Fall, despite fertilizer being much cheaper in the Fall due to lower demand. More exact timing of nitrogen was said to be enabled by improved sensing and modeling, fertigation, and high-clearance tractors.

Timing of operations in the no-till with cover crops method is about utilizing every growing degree day to maximize biomass and reach a C:N ratio suitable for mineralization once killed. In organic, timing is about applying organic inputs – whether providing mineralized nitrogen more quickly or slowly, or tilling to mineralize nitrogen, in time to match crop uptake. In both methods, weed control interacts with planning for nitrogen timing – perhaps moreso in organic, which cannot use herbicides. Several said no-till with cover crop systems could be designed to control weeds by controlling what is growing throughout the year, and killing them before they could go to seed so the following cover crop mix could be controlled. In organic, nitrogen applications are timed so as not to fertilize weeds, and in many cases, tillage is used to ensure weed control.

Inhibitor products exist to slow both nitrification and ammonification, and interviewees reported using them for two slightly different purposes: loss prevention, and to time nitrogen release to a slightly later date closer to plant uptake. The latter was expressed as an inadequate solution, saying that ideally nitrogen release could be delayed even longer. There exist polymer-coated slow release (SRF) or controlled release (CRF) fertilizers which do release nitrogen even more slowly. However, these were said not to be widely considered or used in the United States, perhaps because of the high cost.

Amount

Practices which better synchronize applied nitrogen to plant uptake can reduce uncertainty and risk, and reduce the total amount of nitrogen applied. Beyond synchronicity, inclusion of biological nitrogen phenomena can also help determine appropriate amounts of nitrogen to apply. The precision approach of course varies the amount of nitrogen applied per area, whether applied by tractor or fertigation. Irrigation systems were discussed which are equipped for precision application, varying the amount of nitrogen-containing water per "pie slice" of a center-pivot system, or in more elaborate equipment, per nozzle as it passes over a field.

From those relying mainly on organic inputs such as compost and manure, there was an expressed need for better nutrient calculators for these materials, because their nutrient ratios are less consistent. A few noted that some nitrogen added in a given year goes into the biological system and is uptaken by crops in subsequent years; these interviewees were associated with methods utilizing biological nitrogen pools – whether organic or no-till with cover crops. One advisor to organic farmers often tells them not to be too conservative applying nitrogen for this reason.

Interviewees discussed efforts in research and extension to provide better calculators for required nitrogen input amounts. These efforts are often aimed towards a large-scale precision approach, and may also strive to include biological nitrogen dynamics present in those systems. Specific advancements to nitrogen measurement and modeling will be covered in more depth in the section on Infrastructural Support.

A way of transcending the question of how much nitrogen to supply to a crop is asking what crop will use the nitrogen that is easily made available. One researcher spoke of choosing crops more logical to grow in an area. Another researcher illustrated the challenges of growing the tropical plant corn in temperate regions of the United States: nitrogen mineralizes from soil pools early in the Spring, but corn does not aggressively take up nitrogen until later in Spring and Summer. In the interim, the risk of nitrogen loss, and thus the amount of supplemental nitrogen needed, is dependent on early Spring weather. In this case, the focus was on estimating these losses and replenishing with a more correct amount of synthetic nitrogen, rather than the full rate. It is an interesting question whether cover crop or rotation systems could change this dynamic and allow better nitrogen synchronicity when growing crops adapted to different climates. Depending on when cover crops are killed and the main crop planted, would their gradual residue mineralization lower leaching risk, or contribute to excess mineralized nitrogen that could be lost?

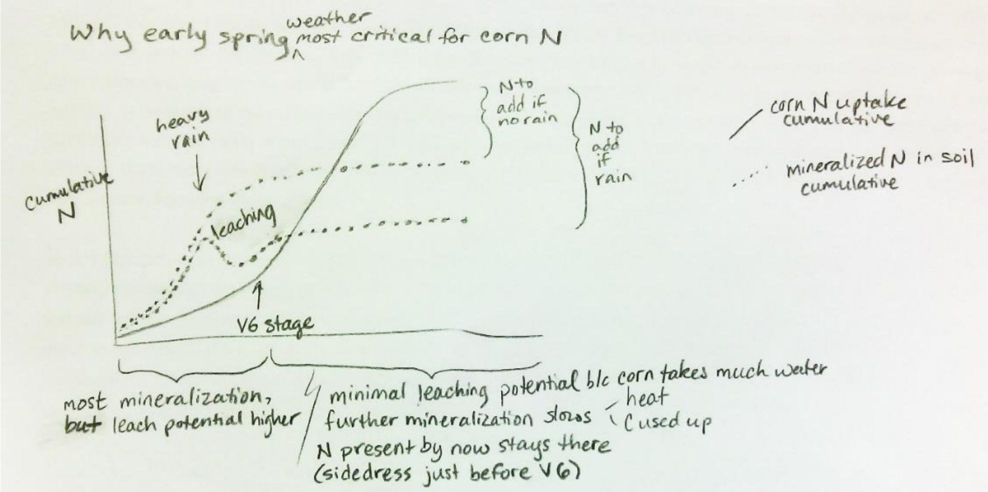

Figure 1: Sketch based on interview discussion about effect of early Spring weather on mineralized nitrogen

Placement

There was an expressed assumption that nutrients applied anywhere besides right at the crop roots are not utilized, but wasted on weeds or lost from the system. Conventional fertilizer application – whether with a precision approach or not – often uses methods to place nitrogen and other nutrients as close to the crop as possible. Several described applying fertilizer a few inches under or to the side of a seed at planting, and applying again later as a thin sidedress next to the crop once it is growing. One mentioned that these practices were proven effective as long ago as the 1930's and 40's.

In no-till with cover crop systems visited, cover crops were planted in a uniform blanket over a field, although the following main crops would typically be planted in rows. From a precision standpoint, this is an oversight. However, there were some mentions of planting cover crop radishes in the exact spot where corn seeds would later go, because the radishes are said to scavenge and consolidate nitrogen, releasing it later on. There was also more discussion within no-till with cover crops that nutrients stay in the system multiple years, and that mycorrhizal fungi and other synergistic relationships between cover crop species can make nutrients available from organic pools and over larger areas. These perceptions point to the questions: is the physical location of mineralized nitrogen less critical if it is tied up in growing biomass, decomposing residue mulches, and eventually soil organic matter? Do losses from these systems still occur in places where nitrogen is mineralized but not uptaken by crops?

Form

Recommendations about form in the 4R's have to do with choosing a fertilizer product appropriate to the crop and soil dynamics. This includes the chemical form of nitrogen and when it will become available in ammonium or nitrate form, as well as balance with other nutrients which affect its utilization (Roberts 2007). Synthetic nitrogen forms also have different potential pathways for loss, with varying tendencies to volatilize as ammonia to the air or rapidly convert to nitrate. These properties were discussed by many in the context of nitrogen loss prevention: which products were chosen and recommended for different situations, along with techniques used to counteract loss from specific products.

It was observed that the 4R's were also taught in presentations geared towards soil health, no-till, and cover crops. The no-till with cover crops system does use synthetic nitrogen when there is a deficit, but it is interesting to consider how best practices for "right form" might evolve under a system where nitrogen comes from legume residues.

TOWARDS PERFECT NUE AND MINIMIZING LOSS

Most interviewed brought up nitrogen loss and its consequences early in the conversation: most often nitrate leaching, followed by ammonia loss, particularly by those having experience with ammonia fertilizers or manure. Few brought up nitrous oxide; when asked, some were familiar with it and others not. Many were quick to follow with environmental consequences according to the form being discussed – for example, eutrophication and drinking water quality issues from nitrates, and global warming from those very familiar with nitrous oxide. Fewer environmental hazards were discussed with ammonia, but one researcher noted that a significant portion of nitrogen in the Gulf of Mexico originally came from ammonia volatilization.

Several said it is a common and good practice to use urease and nitrification inhibitors, also called stabilizers, when using urea and ammonia fertilizers. Urease inhibitors were described as buying time until the next rain could soak in urea fertilizer. Nitrification inhibitors were seen as essential to include with ammonia fertilizers, with one noting that preventing leaching and nitrous oxide are a major argument for using them. A researcher pointed out that the effects of nitrification inhibitors on soil should be questioned, along with what might happen as ammonia oxidizing bacteria become resistant to inhibitor products.

Some said excess mineralized nitrogen is tolerated in organic because of the high uncertainty of having enough. This was seen as less of an environmental problem in systems with high SOM and slower nitrogen release than systems using synthetic, quickly-mineralized nitrogen. In no-till with cover crops, there was an attitude that more cover crop biomass is always better, with none expressing concerns of excess mineralized nitrogen. One farmer using this system, when asked if there was such a thing as too much cover crop biomass, said simply, “No.” Recall that some species in the cover crop mix are chosen to capture and hold nitrogen, which may protect it from leaching, but the flux of nitrogen remains high. Similar to organic, yield in cover cropping systems is achieved through biological nitrogen cycling rather than primarily with synthetic nitrogen.

BEYOND TAMING NITROGEN: SYSTEM REDESIGN BEYOND DIRECT NITROGEN MANAGEMENT

Research questions:

- Which problems do different nitrogen management practices* address, and with which solutions?
- What norms and values influence nitrogen management practices?

(* - Discussions in this section go beyond direct nitrogen management)

It is possible that the 4Rs’ focus on the details of nitrogen use but not on system design limits thinking on the nitrogen problem. Highlighting this, a chapter by Delgado (2015) states the 4R’s alone do not encompass soil quality, carbon sequestration, or sustained productivity, and then proposes 7 R’s which intertwine fertilization with conservation. In the case study interviews, many ideas about best nitrogen management were also inextricably linked to conservation farming practices. Some felt a strict focus on nitrogen loss was the wrong approach, and went hand-in-hand with a hyperfocus on nitrogen fertilization. A few went even farther with big-picture ideas about food and farm system redesign.

NITROGEN IN THE GLOBAL FOOD SYSTEM – WHERE FOOD IS PRODUCED

Some researchers brought up the point that nitrous oxide emissions are not always linear in response to added fertilizer. In low-input systems incremental nitrous oxide emissions are very slight, while in overfertilized systems they may be exponential. In light of this, there was some discussion of inputting more nitrogen to systems which have a low state of productivity as in parts of Africa, raising the productivity to a new equilibrium state. In this there is significant debate over whether aid should be organic or include synthetic nitrogen. Synthetic nitrogen was said to achieve this transition most rapidly as a first stage, after which the strategy could be reevaluated. Similarly, there was discussion of extensifying nitrogen use and food production in dense agrononomic regions of Europe with nitrogen pollution issues, and intensifying in other regions of Eastern Europe. These were discussed mainly by nitrogen scientists, and not with great detail of what logistic or social implications these approaches might have. In contrast, some farmers expressed that food should not be grown to be shipped around the world.

NITROGEN IN DIET – WHAT WE EAT

From a dietary standpoint, it was mentioned that most people in the United States and many other developed countries consume much more nitrogen than they need. Consumption of meat was discussed by several people, both because it is a nitrogen-dense food, and the production of grain feed also uses a lot of nitrogen. Nitrogen experts in collaboration with sociologists are working to educate consumers on their personal nitrogen footprint, and trying initiatives at universities such as food labeling to change consumption.

The nutrient value of food crops was also said to be in decline, so that people are eating more calories, and more empty calories, leading to health problems. Several cited that a soil health approach addresses this by balancing nutrition – again the mantra "health soil for healthy food." One warned not to overfertilize vegetables in the winter because nitrates accumulate in the food which are unhealthy, and another said that natural agriculture produce, which contains less nitrogen, tastes better.

NITROGEN IN FARM SYSTEMS DESIGN

Debates over how to do the things we already do

There is a strong debate of the nitrogen and greenhouse gas impact of producing meat indoors versus outdoors, and grazed versus grain-fed. Many of the no-till with cover crop farmers spoke of reintegrating grazers into their systems as an additional way to cycle nutrients, pointing out that good soils were created with grazing animals, and one saying reintegration will restore soil more quickly. On the other hand, livestock production is perceived as a greenhouse gas risk, and others discussed technology to prevent ammonia loss from manure storage, and containing animals indoors to capture methane. A researcher discussed a recent proposal by the United States as part of climate change discussions to reduce methane emissions by moving most dairy cows indoors, but this raised the question of the climate impact of additional grain needed.

Also discussed by a few was breeding for high yield under low-input conditions – for example, they may have more root mass or better association with mycorrhizal fungi. A farmer using no-till with cover crops has tried high-tech varieties alongside open-pollinated organic varieties, and found the open-pollinated ones do better under the system, and the seeds are less expensive. This is in contrast to breeding for high yield under controlled environment of specific inputs, which can give extremely high yield in perfect conditions, as in the account of a farmer doubling a field's average wheat yield through dense planting and precision application of nutrients, herbicide, pesticide, and growth inhibitors to prevent lodging. Low-input breeding may be the purview of farmers: it was noted by one that participatory breeding programs managed by universities and government programs but carried out by many farmers in a region have produced more varieties for less cost than a seed company might spend developing one variety. These varieties were also adapted to broader conditions, and readily adopted by farmers in the area.

Finally, a few discussed manipulating soil microbes to solve nitrogen cycle issues. Genetic biotechnology, one said, we think of as being for plants; but it may increasingly be used for microbiology. The more grassroots practice of using compost tea to add microorganisms to soil has a similar goal: improve microbiology for nutrient cycling. Both approaches were met with the same skepticism – like "a teaspoon of salt in the ocean", it is unclear whether they can affect the soil microbial population long-term. However, inoculants and other biological products were said by several to be gaining popularity, with many companies now developing them.

Rotations, diversity, and cover crops

There is a perceived potential to close the nitrogen cycle through rotations and cover crops, and the no-till with cover crops movement as well as the NRCS and some extension offices were said to be studying and promoting this. At a workshop, an extension agent said they encourage the very basic shift of adding wheat to a corn and soy rotation for nutrient efficiency and soil health; that even though the wheat may be less profitable, the yields of corn and soy are both increased and the overall economics are improved. Even longer and more complex rotations are now being studied, particularly in organic and no-till with cover crop systems, seeking even more synergistic benefits.

Farmers relying heavily on rotations or cover crop mixes often listed these as one of their first points in interviews, farm visits, and conference presentations. Some were extremely nuanced, considering performance and interactions between warm and cool season plants, C3 and C4 plants, whether species benefited from frequent grazing or periods of rest, and differences in management of species which were native, perennial, or formed mycorrhizal associations. In all cases, rotations and mixes aimed to maximize biomass with the correct nutrient balance for grazing or future crop goals.

Figure 2: Attempting to re-establish a native grass which was suspected to form better mycorrhizal associations and have 2-3 times more root mass than introduced species.

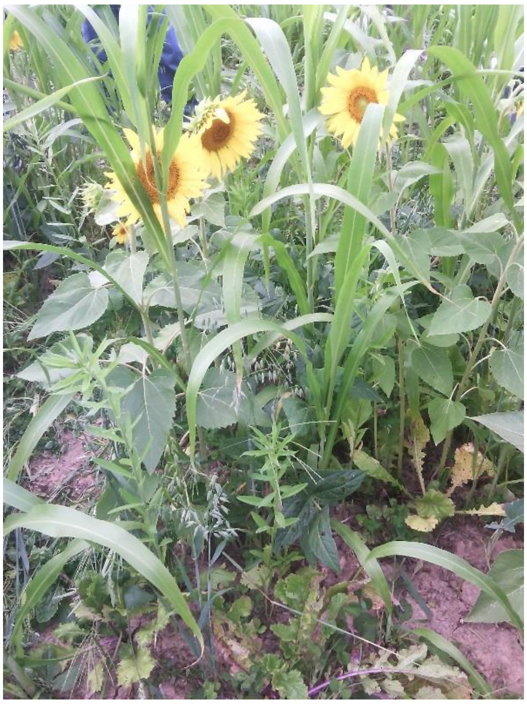

Figure 3: A cover crop mix including sunflower, sorghum sudan grass, oats, radish, sunn hemp, and mung bean.

Paradigm shifts? Undisrupted and mid-succession agricultural systems

Some schools of natural agriculture do not rotate crops at all, citing disruption of the plant-soil symbiosis. Natural agriculture systems may still be biodiverse, allowing certain weeds, some of which fix nitrogen. There was a trust that all necessary nitrogen would be made available to plants by the soil system, less would be lost, and that low nitrogen inputs resulted in a healthier nutrient balance. Only one interviewee spoke about agroforestry, and two farmers discussed native perennial grass species in grazing. Perennials and mid-succession agricultural systems may better synchronize nitrogen to crop needs and produce less reactive nitrogen than annual and early-succession systems (Crews 2016).

Although the interviews asked very straightforward questions about nitrogen management, visions arose which went far beyond current agricultural practice – from what we eat and where we grow it, to how it is grown. Although these visions were not driven by a desire to control N2O, they suggest a desire to redefine agriculture to better fit into some perceived natural or social order.

REINFORCING AND CHALLENGING NITROGEN PRACTICES

Research question:

- What norms and values influence nitrogen management practices?

YIELD AND CONSERVATION FOR SURVIVAL: TENSIONS ABOUT THE ABILITY TO CONTINUE PRODUCING FOOD, AND CHANGING ENVIRONMENTAL FACTORS

Discussing the balance between yield and conservation tapped into strong issues for many: from the ability to stay in business and keep farmland, to concern for future generations and a growing population, changing biogeochemical and climate systems, and survival as a species. These concerns often came up early in conversations. The laddering technique and questions about nitrogen loss elicited these themes for some, while others jumped straight to them on their own from basic questions about how to best manage nitrogen. Similar worries were shared across schools of thought and institutions.

MOVING BEYOND DIRECT NITROGEN MANAGEMENT

Norms in aesthetics and language may play some role in reinforcing current practice. Some discussed the preference or pride for neat, tilled fields free of debris or weeds, or gave the contrasting imperative to "farm ugly" – showing how accepting methods which look different may involve overcoming a visual aversion to them. It was observed that the no-till with cover crops method was promoted very carefully so as not seem too alternative. A field day panel discussion at a field day speculated on a better and more appropriate name for the farming concept. They noted its emphasis on soil health and cutting back on fertilizer and chemicals, but distanced themselves from the term organic. For one thing, they said, the organic method uses tillage to control weeds, while vilifying the responsible use of chemicals. An interviewee also discussed some farmers' aversion to concepts like farming naturally – that it implies haphazard methods and disregard for science. In contrast, new products developed in a scientific setting were said to be perceived as more reliable, and capable of drastically improving agriculture.

Nitrogen management is evolving through conversations within agriculture, but some talked about how these themes reach the wider society. One interviewee discussed the growing popularity of small market gardens – sometimes organic, sometimes not. They were said to emulate practices used by large-scale farmers, but perhaps with less control of application rates. This interviewee worked to educate small-scale market gardeners on soil health and cover crop principles, and said this was a huge shift in thinking for them in the same way it is for large-scale farmers. Another interviewee who is both a farmer and advisor devotes time to teaching soil health principles to urban populations. The hope was to educate consumers about choosing food that was grown with responsible nutrient management, building on already-existing preferences for organic or local food. Several thought it essential for the public and policymakers to better understand responsible nutrient management, both to ease distrust of farming and to create a push for change.

INFRASTRUCTURAL SUPPORT OF NITROGEN MANAGEMENT

Shove (2010) argues that relying on individual choices may stop us from considering what infrastructural or systematic factors shape those choices. There were many themes about how institutions and technologies shape nitrogen management practice.

Research questions:

- What infrastructure and practical considerations influence nitrogen management practices?
- What norms and values influence nitrogen management practices?

PROCESSES (NOT?) REFLECTED IN MEASURING, MODELING, AND CALCULATING NITROGEN

Standard NPK soil tests measure mineralized nitrogen at a point in time, but nitrogen is very dynamic. Interviewees talked about new soil tests and the phenomena they measure, and the direction new models and calculators are being developed. They discussed details of nitrogen cycling, some of which have been known for a long time, which are getting more attention from people who want to measure them in farming:

- There are some nitrogen stores already present in soil organic matter, residues, and living biomass.
- Nitrogen is mineralized over time from these stores, not all at once.
- Nitrogen may be mineralized most quickly at a time of year other than when the chosen crop needs it, so it becomes vulnerable to loss depending on weather.
- Some portion of added nitrogen, including synthetic, enters a these stores and is not uptaken immediately by crops. Some is uptaken in subsequent years.
- Nitrogen may be fixed, scavenged, or released by main crops or cover crops in rotation.
- Nitrogen dynamics may be changed by emergent properties of mixed plant families and mycorrhizal fungi.
- N2O emissions depend on many variables which vary in space and over time, thus there is a spatiotemporal variation of N2O emissions.

Mengel (1991) discussed how past soil test technology has been unable to reliably measure not-yet-mineralized nitrogen, contributing to organic nitrogen not being considered in fertilizer plans. New methods are being developed which better reveal nitrogen mineralization from soil. One prominent fertilizer calculator estimates available nitrogen from soil organic matter percentage rather than currently mineralized nitrogen at a point in time. Another route to estimate nitrogen mineralization potential was measuring CO2 respired from soil microbiota. Another suite of tests includes a CO2 respiration field test plus additional nutrient extractions from organic pools, and using organic solvents rather than strong acids to better represent field conditions. Further developments were discussed to better measure crop-usable nitrogen from organic pools, as well as factor organic matter quality – C:N ratio and lability – into these estimations.

Both nitrogen mineralization and loss are affected by weather, and weather is increasingly being incorporated into models. Some reported that benefits of this were knowing how much supplemental nitrogen is needed after Spring losses, and whether there would be a yield boost from adding late-season nitrogen. An interesting application of these models could be to compare the excess mineralized nitrogen of crops which are native to the climate in which they are grown, as well as how rotations and cover crop systems change the dynamics.

Two mentioned research that found that only some applied nitrogen is uptaken by crops in the year applied, while a portion goes into the soil biological system. An organic farmer using cover crops observed the same fertilizer effect from applying manure to a cover crop before the main crop, as when the manure was applied directly to the main crop. The next point raised was that added nitrogen should be protected or retained in the system using biological processes. This could imply a subtly different standard for managing nitrogen – if some fertility can be assumed to come from the soil system, then it may be a matter of calculating what nitrogen is needed to replenish that system, and when synthetic nitrogen or high-nitrogen organic inputs are needed at critical stages for yield. The no-till with cover crops method is attempting to quantify the replenishment of the soil nitrogen system, and so it pushing the edge of researching nitrogen in farming.

Also pushing the edge of nitrogen research are emergent properties of the plant and soil systems, from a diverse mix of plant species, to how plants receive nutrients through associations with microorganisms such as mycorrhizal fungus and free-living nitrogen-fixing bacteria. CO2 respiration is sometimes used to approximate the flux of nutrient cycling in the soil, and new methods are being developed to extract and studying organisms not previously been able to be cultured in the lab, but this is still a long way off from being a part of soil test kits or real-time monitoring.

Finally, although not discussed in any interviews, it was noted at meetings of a nitrogen research group that N2O emissions vary in time and space, making research into the phenomenon very difficult with tools which measure the gas at a point in time. New measurement tools such as a mobile robot taking measurements over space and time are expected to deepen the understanding of N2O emissions under different farming systems.

SETTING SOIL TEST STANDARDS

The rigid institution of soil testing was seen by many as a barrier to disseminating biologically-based soil nitrogen management. Soil test methods used, and the recommendations they offer along with test results, were blamed by several for contributing to the problem of overfertilizing. Soil testing labs themselves rely on an infrastructure of land-grant universities, government programs, and regulations which described in the interviews. The NRCS is tasked with conserving farming resources, as a branch of the USDA, which is tasked with ensuring the success of agriculture. The NRCS was said to be reviving its programs over the past 10-15 years. It cannot do its own research or set soil nutrient standards, however – that responsibility falls to the land-grand universities in each state or region. Where universities once employed five or six soil nutrient specialists, there is now perhaps one per institution. New farming paradigms and practices such as no-till, and new plant varieties bred for very different farm ecosystems, likely alter the nutrients needed since they were made in prior decades. Still, updating nutrient recommendations is low on the funding priority list. Soil testing labs are regulated for test accuracy, but not regarding the recommendation amounts. One noted that the same application rate appears on test results regardless of physical qualities of the soil. A manufacturer of some new biological soil tests spends much time and effort encouraging soil testing labs to consider new methods, and also contributes peer-reviewed scientific papers to the nutrient management conversation.

DEVELOPMENT OF PRECISION AGRICULTURE AND BIG DATA

The sheer amount of data emerging from precision agriculture is sometimes overwhelming to those seeking practical applications of it, attractive to an IT sector eager for the next big opportunity, and represents a new frontier in agriculture for many. There was a feeling that translating data into decisions is not fully developed, and that much data generated is not able to be put to use yet. A kind of crowd-sourced information pool is being formed by compiling precision agriculture data from farmers across the country – some through direct commercial backing by inputs companies, others by IT giants. A farmer described using these systems to check how crop varieties perform in different climates, soil types, and management systems. Farmers, inputs and service providers, and advisory organizations like extension and the NRCS find a synergy in using precision agriculture data to document what was done on-farm for conservation payments and regulatory purposes – some regulations being anticipated for the future.

Sensor technology is improving: beyond pre-season soil tests, progress towards yield can be monitored through infrared sensing, and perhaps soon by energy absorption and fluorescence by the plant – described by one as sensing 2.0. Many expressed a wish for just-in-time detection of nutrient deficiencies in the soil, a kind of “magic wand” to guard against threats to yield before they become apparent in the plant. This in turn is driving development and use of equipment that can apply inputs later in the season.

There is a subtle difference between modeling and planning based on pre-season conditions and ongoing weather information, versus adaptive, real-time management aided by measuring farm variables as crops grow. These complementary approaches seem to merge in the visions expressed for precision agriculture’s future. This vision may in fact be co-created by people in agricultural practice, agricultural research, and the fast-paced IT sector. Challenges expressed regarding this fusion were that the IT sector expects a quick and large return on investment, yet people in agriculture “don’t behave like that,” and scientists, particularly agricultural scientists, require a slower process in which results are replicated over time and space. Still, there was a strong sense of optimism and hope that precision agriculture will continue to develop into something more useful, sustainable, inexpensive, and perhaps more engaging - “more fascinating to the farmer.” While new sensors and fertilizer calculators may increase consideration of organic nitrogen mineralization in precision agriculture, there was reflection among some scientists that these technologies should go even farther in incorporating biological processes.

Figure 4: Precision equipment applying variable-rate fertilizer.

RESEARCH AND SUPPORT OF COVER CROPS

Some extension and university researchers said the no-till with cover crop farmers were far ahead of them in innovation, and their research may never catch up. Research had shown benefits of diversity up to a certain point, but not necessarily of 10-20 species mixes being practiced by farmers. But as one farmer noted, the experiment designs do not capture emergent properties of the system. Several farmers also mentioned that government subsidy and crop insurance programs are not set up to work well with cover crop farming systems. One said most extension agents “don’t get it,” but that a few are very good. There may be a feeling among farmers in this movement that although their roots are in conventional farming, they are finding themselves a bit outside the current system. The farmers, researchers, and advisors who are enthusiastic about the no-till with cover crops practice are collaborating to prove and promote it within mainstream channels.

As demand for cover crop seed grows, private cover crop seed companies were said to be on the rise. Some of these have developed calculators for cover crop seed mixes which can be used to achieve the desired nutrient levels and C:N ratio so that nitrogen is mineralized at the correct time. These, along with biological soil tests, were said by farmers to take the guesswork out, make cover cropping a lot easier than it used to be, and may help more people adopt the method.

INFRASTRUCTURAL SUPPORT OF ORGANIC NITROGEN MANAGEMENT

Rotations appropriate to organic systems were described as being under development for decades. An organic farmer described getting organic transition and crop rotation help from a university, and later adapting these rotations because they included too many legumes, leading to fungal problems in the organic system and a slowing of biological nitrogen fixation. The rotation was redesigned in part to grow nitrogen fixers and nitrogen feeders at appropriate times for most efficient nitrogen cycling. This system also used manure and compost inputs, and it was noted that little information existed for application rates in organic systems. Some collaborative on-farm research followed, which turned out to match information from the 1950’s.

A prominent organic research institute is now promoting organic no-till with cover crops, facilitated by a roller-crimper attachment invented at the institute, which was designed to kill cover crops without herbicide. The language used in promoting this practice was observed to signal that it was a new best practice standard for organic farming, and the institute was observed to be in close cooperation with many farmers and advisors in the no-till with cover crops movement.

Figure 5: A roller-crimper, photographed on a conventional farm using no-till with cover crops.

PROMOTING PRACTICES AND PROVIDING SERVICES

Because Extension and the NRCS are not regulatory – they only serve an advisory role – some said they must focus on practices that help farmers' business alongside any environmental goals, called "win-win" solutions by several. There are reportedly fewer agents than there used to be, and so more farmers get advice from commercial service providers and private crop advisors. Extension and the NRCS often work with these private groups to assure everyone has the best and latest information about soil management, and also to help with planning and documentation for government conservation payments. These collaborations also sometimes took the form of research projects.

Agricultural inputs and service providers have the capacity to offer specific planning and advice as part of their business with farmers. Some farms want a service provider to do precision agriculture planning and applications for them – citing that it is a useful technology but they do not have capacity to do it on their own. Others do it on their own, but may work with a service provider for some tasks, especially if it involves equipment they do not own. Private crop advisors often take certified crop advisor training, along with internal training from their companies. Precision agriculture and the timely "spoon-feeding" of nitrogen have reportedly been important topics in these trainings in recent years.

Role of firsthand experience and collaborations

Direct experience of a new farming practice is very important to gain familiarity and trust. Changing farming practice involves a large cost and effort, and may even jeopardize crop insurance payments; so it is vital to have proof that the risk is worth it. Proof of concept on one's own farm is best, followed by neighboring farms ("almost as good"), and demonstrations in the same region. Many advisors and farmers spoke of encouragement to "just try it" in a low-risk setting – such as designating small test strips or areas of a field to try something new, and compare with the old way. This was said to not risk the whole business model by changing everything at once. Test areas were relevant for cover crops, organic, and precision agriculture alike.

One case also depicted the important role common resources can play, and incidentally may have been an important step in creating the no-till with cover crops movement in the Midwest. Squeezed by high input prices, a farmer worked with a local NRCS office to incorporate intensive cover crops methods which had been presented at a recent regional no-till conference. The NRCS office happened to have some available land for experiments, and purchased special equipment which was shared by participating farmers early on. Once the concept was proven, it moved onto individual farms and they could justify investing in their own equipment.

TO CHANGE QUICKLY

Many were confident that technology exists to manage nitrogen more sustainably, we just need to disseminate it better. Several expressed that change needs to happen as quickly as possible, which would be difficult because agriculture is often seen as changing slowly. There was a basic trust in the science – that there is much we already know about nitrogen timing and dynamics. This points to the importance of understanding how decision makers and groups interact with the problems and solutions that already are out there. Several mentioned a new initiative which was launched in December 2015 to intensify research and dissemination of soil health into farming practice. One of its main strategies will be coordinating efforts between the different stakeholders – farmers, academia, government, industry, and also consumers (Soil Health Institute 2015). Again, the rationale described for the initiative's efforts was to create change as quickly as possible.

3.2 COMPLICATIONS SPECIFIC TO NITROUS OXIDE MANAGEMENT

There was significant confusion about what nitrous oxide is, and some were unfamiliar with it. Those somewhat familiar felt that nitrous oxide was not a problem that could be solved easily or directly in farming, and moreover that it is not widely considered. Others who were more familiar thought it critical to link agricultural nitrogen management to climate and global nutrient systems, and to raise awareness of nitrous oxide as part of that link. In the context of agricultural practice and policy, N2O was overshadowed by more pressing nitrogen issues, and in the context of climate change it was overshadowed by a dominant focus on carbon.

Research questions regarding N2O specifically:
- In which decision situations is N2O loss considered a relevant problem, and by whom?
- In decision situations where N2O loss is not considered a relevant problem, but perhaps could be, why isn't it? What other factors override its importance?

A WEAK SENSE OF IMPORTANCE

There were many reasons cited why nitrous oxide was not considered important. An extension outreach on nitrogen which does not include N2O, the intangible and indirect consequences of emissions, and beliefs about climate change and environmental quality issues all affect its prioritization.

There seemed to be a basic belief among many stakeholders that for farmers, it is all about the bottom line – practices are ultimately judged by how they affect the farm business. From the perspective of a farm, a very small percentage of applied nitrogen is lost as nitrous oxide, so it does not represent a large economic loss or decrease in fertilizer efficiency as do ammonia and nitrate, which are lost in greater quantities. Perhaps stemming from this, extension and conference presentations for farming audiences do not typically give details about the nitrogen cycle. Nitrous oxide was said to be rarely if ever discussed at these events.

Nitrous oxide was seen as difficult to conceptualize. Some noted that you cannot see or smell it. One said the link between denitrification, nitrous oxide and its greenhouse gas effect is amorphous, and another that it is difficult to understand how the gas nitrous oxide can result from nitrates, which are seen as leachable in water. Emissions were said to be difficult to measure, and would not easily fit polluters-pay regulations. In contrast, the eutrophication and drinking water hazards of nitrate are visible and getting attention. Several mentioned news stories from the past year about emergency levels of nitrates in drinking water in large Midwestern cities.

Nitrate pollution is increasingly regulated, and in some areas anhydrous ammonia use is also regulated – raising concern for farmers who feel increasing hardship despite their efforts to manage nitrogen in the best way.

Groups who were said to consider nitrous oxide included bioenergy researchers analyzing the lifecycle greenhouse effects of different fuel alternatives, or air and water quality specialists. Specific facts about nitrous oxide were given by these interviewees. One researcher noted that nitrogen deposition from the air and transported in runoff are significant sources of nitrous oxide emissions. Also mentioned were nitrous oxide's long atmospheric residence time, and that its warming potential is nearly 300 times that of CO2. Some suggestions emerged here for nitrous oxide mitigation. There are existing cap and trade schemes for air and water quality. Many of these are for carbon, but some are for nitrogen, mainly nitrates, such as in the Chesapeake Bay watershed. One scheme actually paid farmers from a carbon credit fund to apply less nitrogen, so they would emit less nitrous oxide.

CONFUSION - N2O, OTHER CYCLES LINKED IN PEOPLE'S MINDS

The species of reactive nitrogen were unclear or confused by many interviewees, both in terms of the different forms nitrogen can be lost as, and what types of loss different fertilizers tend to cause. The various synthetic fertilizers come with different risks of loss and application methods to prevent loss. Several discussed these, with a few seemingly mixing up the details, for example between urea and ammonia. Nitrous oxide emission and ammonia volatilization were also sometimes not distinguished apart from one another. Others treated ammonia loss separately from loss of nitrate and nitrous oxide, because ammonia loss was a specific risk of using anhydrous ammonia fertilizer, whereas the other two arise from a general excess of nitrates in soil. Finally, there was some confusion between nitrous oxide and NOx, which was associated with factories. Blurred lines in the nitrogen cycle were seen among farmers and scientists alike, and across the different groups. It should be noted that this research was neither quantitative nor using a statistically representative sample.

Though there were no interview questions about phosphorus, it came up in conversation about managing nitrogen. Nitrogen and phosphorus were linked together as pollutants, as regulated inputs, and as limited or critical resources to farming. Some also discussed the nitrogen and carbon cycles together in the context of building soil organic matter, and in some cases carbon sequestration and climate.

CLIMATE – A CARBON OR NITROGEN FOCUS?

There were differing viewpoints on whether it was better to focus on carbon or nitrogen when approaching agriculture's role in global systems change. The global climate conversation was said to focus on industrial CO2 first. The secondary focus was on methane, the next largest warming gas, from animal production. Methane was said to be the primary reason agriculture is talked about in climate change now. Efforts are being made by agricultural stakeholders to bring agriculture more into the climate change discussion, primarily by emphasizing the soil's ability to sequester carbon, or drawing attention to agricultural practices which release carbon and inhibit soil's ability to sequester carbon in the future. Still, one researcher said that agricultural nitrogen and nitrous oxide should be discussed more in the climate conversation. It is harder to understand, but expands the conversation from animal farming to how grains are produced to supply animals, people, and industry.

It was said that many farmers in the United States do not believe in climate change, or that they can affect it, though this was said to be slowly changing. It was observed at some field days and farming conferences that when climate change was discussed in a presentation, the language used was careful, resigned, or apologetic, such as "we have to face this, guys," or "I know we don't want to talk about this, but…" This was followed by how better practices could sequester carbon or prevent nitrogen overfertilization.

SHIFTING FROM A CLIMATE TO BIOGEOCHEMICAL AWARENESS

It seems that a focus on agricultural N2O may only come about from what is now the climate discussion. Even though it is currently focused on carbon and industry, agriculture may be entering the conversation. One researcher said as more people are becoming aware of the link between agriculture, soil and climate, they are starting to treat them jointly. Marrying this awareness of soil carbon to the separate awareness of nitrate pollution may require a better public understanding of how these elements interact and cycle through the globe. Calling it a nitrate problem or an N2O problem or a carbon problem or a climate problem may all be too narrow – combined they are a complex biogeochemical problem. Still, to recognize N2O in agriculture at least would mean understanding a more complete picture of the nitrogen cycle. N2O offers a critical link between the two disparate worlds of agriculture and the climate discussions among the general public and policymakers.

3.3 TOWARDS A FUTURE OF NITROGEN AND N2O MANAGEMENT

THINKING IN TERMS OF NITROGEN ENTROPY

As discussed in the introduction, N2O can be managed somewhat certainly by reducing nitrogen flux, or very uncertainly by reducing the entropy of conversions within the nitrogen cycle. Managing nitrogen flux via improved NUE has been getting better in recent decades, largely to reduce nitrate leaching. Thus along the spectrum from conservation to yield, an axis of nitrogen flux can be thought of in close alignment. An axis of nitrogen entropy can also be superimposed on the practice spectrum. It may not be as closely aligned with conservation and yield, since many of the system redesign suggestions which went beyond direct nitrogen management and addressed how to feed ourselves with less nitrogen-intensive systems. An intuitive sense for entropy can perhaps serve as a compass to explore practices showing promise in this regard, and guide the development of research and technology to confirm these intuitions. Of course, this intuitive sense relies on people having a better understanding of the many nuances in nitrogen cycling.

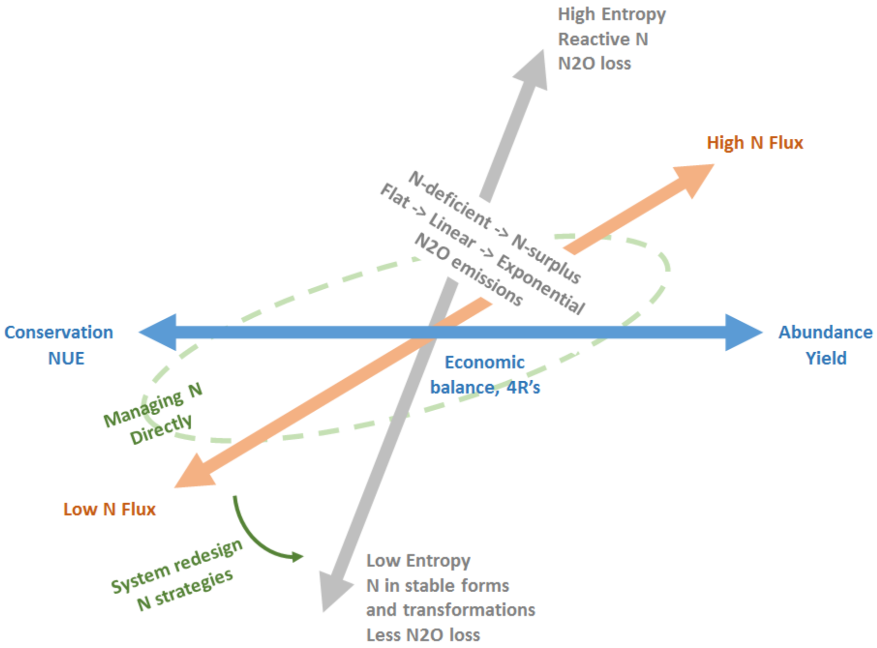

Figure 6: Direct soil nitrogen management strategies fell along a balance between NUE and yield, and by impacting the amount of fertilizer used, nitrogen flux. Other ways to reduce flux and entropy fell outside direct nitrogen management.

CONVERGENCE OF NITROGEN MANAGEMENT PRACTICES

How specifically might current practices change and converge to better mitigate nitrous oxide? Following the decision-making model from Cohen (1972), solutions to similar problems were compared between approaches to nitrogen management. Those which illustrate contrasting ways of controlling nitrogen, and possible decision oversights or flights, are listed in the following table.

Table 3: Problems and solutions matched in different ways by different approaches to nitrogen management, organized based on concepts from Cohen's model (1972).

Problems	**Solutions**	**Oversights / Flights**
Synchronicity of available N to crop needs		
Soil nitrogen may naturally be mineralized earlier or later than crop uptake needs.	Make up the gap at the last minute with readily mineralized nitrogen	Is it appropriate to grow a crop in a region where N does not mineralize when needed? Can different rotations or cover crops alter when N mineralizes?
	Use extra mineral fertilizer or organic inputs ahead of time to be safe	
Weather creates uncertainty for mineralization and losses, and yield potential	Track weather to estimate N losses occurring when crop is not uptaking all that is mineralized	Can soil structure, SOM content, and continuous cover crops change the risks of weather?
	Apply late-season N only if conditions are good enough for high yield	
Mineralized N may be left over after season, especially if yield was low	"Scavenge" leftover N at the end of the season with cover crops	Does scavenging N, or assuming it goes into SOM, justify using extra fertilizer, cover crop biomass, or organic inputs?
	Increase SOM content to lessen overwinter leaching	
Contrasting slowly-mineralizable vs. readily-mineralizable N sources from an N2O perspective		
N in readily-mineralizable fertilizers converts rapidly between forms, often too quickly or early for crop uptake	Inject, incorporate, apply closer to time of uptake, use nitrification and urease inhibitors, slow and controlled-release fertilizers.	Can cover crops uptake N at a better time, releasing it later? (Example: same effect of applying manure to previous cover crop as when applied directly to main crop, and causing fewer weeds). Would considering biological N sources lessen this problem?
Nitrogen mineralized from residues, organic inputs, and SOM difficult to quantify and control. They may have equally high N2O effects as synthetic.	Improved measurement and modeling tools	Systems using intensive cover crops or organic inputs for nitrogen may justify using excessive inputs because it is seen as harmless or less harmful than synthetic fertilizer.

Table 3 (continued from previous page): Problems and solutions matched in different ways by different approaches to nitrogen management, organized based on concepts from Cohen's model (1972).

Problems	**Solutions**	**Oversights / Flights**
<u>Heterogeneous soil conditions</u>		
Available N is not uniform throughout a field	Measure N needs per smaller areas of a field and apply only what is needed to each area	Any non-precision system does not account for N varying in space.
Assumed that N not physically near crops is not used by them (instead grows weeds or risks being lost)	Apply N only directly near crop roots	Is this assumption always true? Can cover crop mixes fix or uptake N, then relocate it in residues? Can microbial associations relocate nutrients closer to plant roots?
	Grow N in uniform cover crop mix, then "consolidate" it e.g. with radishes in planting rows	
<u>Determining the ideal amount of N flux</u>		
Curved inverse relationships were discussed between: (1) yield and NUE, (2) cost of added N and economic return in yield, and (3) added N and N2O emissions depending on how N-deficient or -oversupplied a system is. If not balanced, consequences increase on either end.	Approaches to calculating the right amount of nitrogen can be tweaked for different outcomes: NUE, economic return, or N2O emissions. Global efforts to intensify / extensify production to balance nitrogen use in each area.	These relationships are mainly considered by scientists and those developing tools for efficient fertilizer application. In practice, they may be overridden by economic factors, or not considered in detail. Land-grant university and soil test recommendations set a flat standard which is followed by most.
Plants can be bred for lower or higher levels of mineralized N, and did not always work as well in systems with different levels of N.	Varieties were sometimes chosen based on ability to yield with lower input N, or conversely to utilize extra N if weather conditions were ideal.	Varieties bred under certain levels of mineralized N may reinforce that those levels are ideal.
Natural agriculture: Added nitrogen in any form disrupts the symbiosis between plants and soil microorganisms which gives ideal nutrient balance*.	Natural agriculture does not treat nitrogen as a limiting factor or high yield as a goal, but relies on whatever N replenishment occurs naturally.	Natural agriculture: N replenishment relies on continuous cover, but not necessarily planned species mix. Could yield be improved by using some cover crop mix rules, while staying true to the method?
*See above: Natural agriculture said added nitrogen disrupts nutrient balance of human food. Others said too much nitrogen produces unhealthy nitrates in food, or produces empty calories.	Soil health or organic methods are thought to improve nutrient balance.	If research showed health claims to be true, is the appropriate amount of N flux lower than that which balances NUE, economics, or N2O emissions?

Synchronicity of available nitrogen to plant needs is a key challenge for all of the different cropping systems, and the approach to controlling synchronicity depends on the nitrogen sources used. Improved modeling and measurement gives an opportunity to verify nitrogen mineralized from biological pools, taken up by plants or immobilized in soil, and/or lost in weather events. This improved understanding could be used to decrease nitrogen inputs (flux), and also keep nitrogen within stable forms and transformations to prevent loss (entropy).

From a practical standpoint, **slowly-mineralizing (generally biological) versus quickly-mineralizing (generally synthetic) nitrogen sources** were both managed to control where and when mineralization happens, just on a different time scale and level of certainty. The ongoing debate over which should be used was weighed in on by the need to feed a world population, and their effects on reactive nitrogen – as always, yield and conservation. If our ability to measure N2O improves, this debate may benefit from new insights into when each approach is appropriate (entropy).

Heterogeneous conditions in soil were addressed primarily by precision agriculture. There may be an opportunity for more utilization of biological nitrogen pathways in the precision approach, and an opportunity for more precise applications of organic inputs or cover crop seeds to account for varying field conditions. This is especially relevant for N2O, because emissions vary highly in space and time, along with soil conditions. A fusion of precision and cover crop technologies would require not only innovations in sensing and modeling of nitrogen dynamics, but also a bridging between schools of thought which are not quite connected.

The ideal amount of nitrogen flux in agriculture was most commonly identified to balance NUE, economic return, or nitrogen losses (for a few, N2O specifically). There is no objectively correct answer to this question because each supports different important goals. A few people discussed breeding for high or low nitrogen inputs, and a few others discussed the nutrient balance in human food resulting from different levels of nitrogen. Though beyond the scope of this research, these probably have a strong normative effect on nitrogen levels – plant varieties by reinforcing the cropping systems they are bred for, and what nutritional values are deemed acceptable.

All of the convergences above deal with transforming our current cropping systems as they are in widespread use today. Some of the system redesign ideas may be even more relevant to reducing nitrogen entropy. Though beyond the scope of this research, they call into question its premise that we should look to nitrogen management practice to solve N2O emissions. Instead, they encourage us to redesign food and farming systems to have less of an inherent tendency to create reactive nitrogen in the first place.

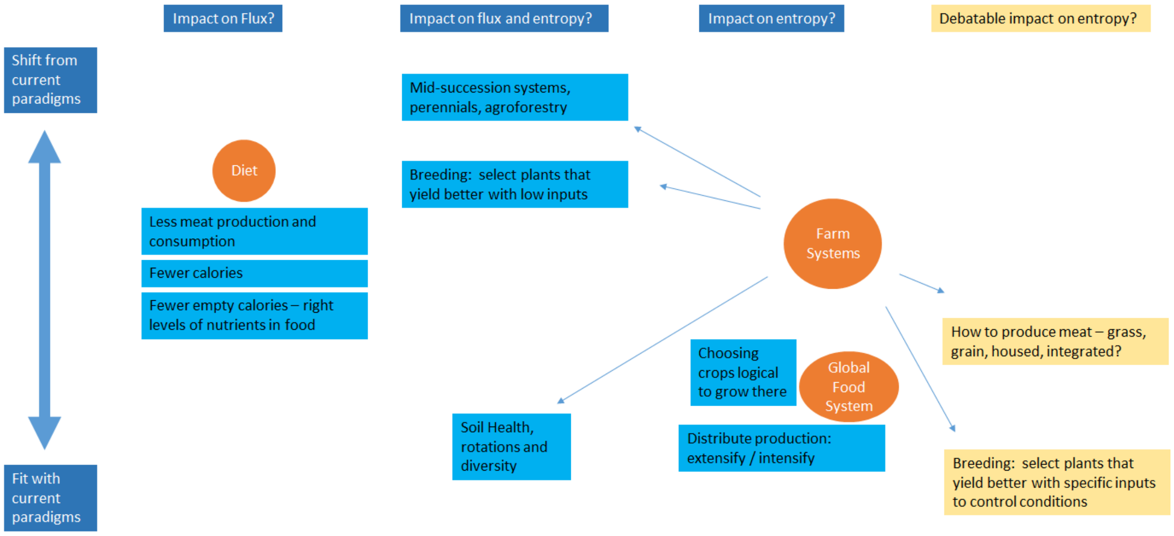

Figure 7: Suggestions from the interviews which deal with the nitrogen problem indirectly through re-design of diet, food and farm systems, arranged fit with current paradigms and impacts on nitrogen flux and entropy.

CONVERGENCE OF MOVEMENTS AND INSTITUTIONS

While it is impossible to predict the future from current practices and their context (Bland 2007), Seppänen (2002) discusses identifying the zone of proximal development in changing agricultural practices, which is the path between current practice and a future state which resolves some problem. If the problem to be solved is N2O emissions from agriculture, then the path begins with convergences between soil health and dynamic nitrogen management which are already in motion.

The renewed soil health focus, possibly having evolved from early organic thought, may now be giving new energy to changing agricultural norms and practices. Organic and conventional farming alike are looking beyond direct nitrogen management to dynamic nitrogen management as it interrelates with soil and cropping systems. Along with this have come enthusiasm and funding for collaborations between universities, extension, and government programs – comprising an official support network which guides best practices, and a vibrant grassroots effort as each school of thought innovates practices and promotes new ideas through conferences and publications. Supportive organizations also partner with and influence service providers who work directly with farmers to make fertilization plans and carry out operations. A relatively new fusion between the IT sector and precision agriculture could help capture and make sense of the large amounts of data already being generated in the field, especially if the multidisciplinary world of agricultural research engages with it. This could potentially facilitate real-time spatial data on results from biological nitrogen management, as well as N2O emissions, should research tools continue to be developed towards these ends. Even for those not using precision agriculture or farming at a large scale, new insights may loop back into the practices which feed into it, as they have with organic and cover crops. Unpredictable new innovations may as easily come from the field as from industry.

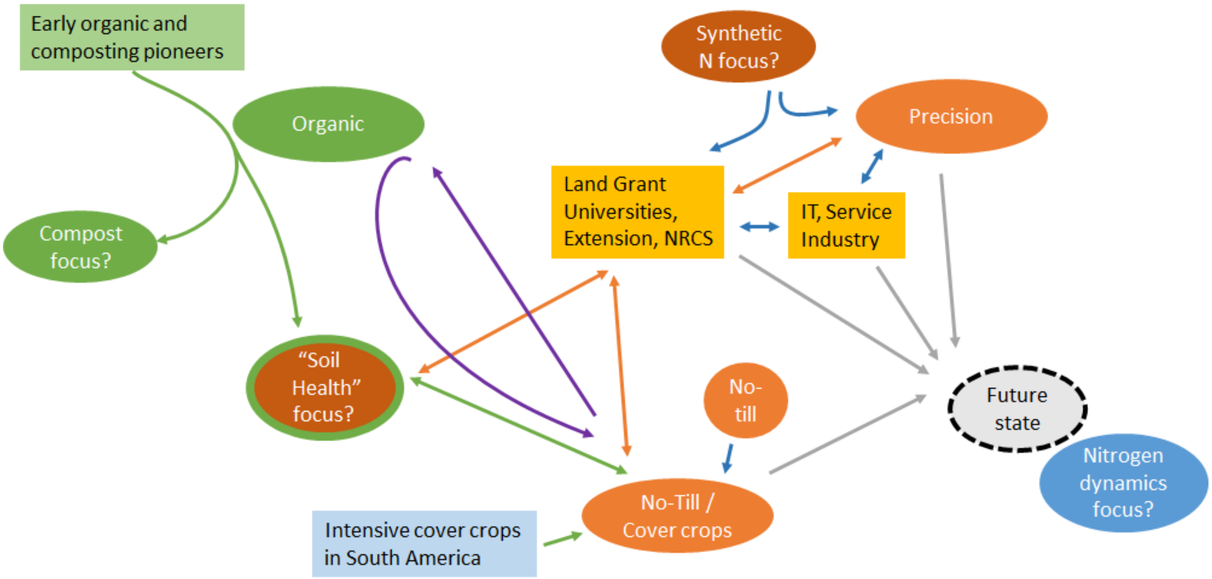

Figure 8: Historic, current, and possible future interactions between schools of thought, infrastructural institutions, and focuses in agriculture management.

To continue bringing soil health and dynamic nitrogen management into farming practice, there will be a delicate balance between a holistic systems view and the practical and scientifically valid. The distancing between soil health and nitrogen management and the trust that soil health will prevent nitrogen losses may be helpful for breaking out of the "hyperfocus" on nitrogen. However, this mindset also risks not actually solving the nitrogen problem, and not being relatable to the majority of conventional or large-scale agriculture.

The norm of pushing the limits which perhaps led to a hyperfocus on nitrogen and yield may shift to support a new focus dynamic nitrogen management. This can be seen in the enthusiasm of the soil health movement to increase soil quality and biological activity, with the no-till with cover crops movements for pushing the constraints of how much nitrogen can be fixed and recycled, and in precision agriculture for understanding the minutia of nutrient availability in space and time.

Why not include all of the details about the nitrogen cycle in extension outreach, and combine soil health and nitrogen tracks at conferences? Although N2O has no direct effects on farm operations, if certain practices are found to better control nitrogen flux and entropy, and to reduce N2O, enthusiasm for using them could only follow from understanding. As illustrated in the case study, only after understanding the paradigm shifts underlying cover crops, and likewise precision agriculture, did newcomers begin to adopt and innovate within them.

To link agriculture with climate change is to add nitrogen to the climate change discussion, fostering a basic sense of the biogeochemistry of our planet and how agriculture affects it. Just as an increased societal awareness of nitrates has led farming practice to become better at mitigating it, recognizing nitrous oxide in fertilization practice is a step towards a less greenhouse gas intensive agriculture.

4. CLOSING

This research was an exploratory inquiry into how nitrous oxide might fit into nitrogen management. Using a case study with experts representing different angles of farming and the nitrogen problem helped identify what is relevant to whom. It also gave important context of norms and social patterns. Analyzing decision-making patterns – problems, solutions, and possible oversights – in a scaleless framework which could equally accommodate individuals, ideals, and institutions revealed some emergent themes which suggest strategies for change. Perhaps the narrative presented here could have been synthesized only from literature. However, if agricultural nitrous oxide is seen as both a scientific and social problem, information vital to finding the way forward lives in the people working for a better agriculture every day.

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APPENDIX 1. INTERVIEW QUESTIONS

Questions from the interview guide are listed below. Research questions they were designed to answer are shown in italics. Please note the wording of the research questions may have changed slightly since the interview guide was written.

Interview questions: Farmers/Advisors	**Interview questions: Science/Industry**
Today I want to listen about what, in your view, is the best way to manage soil, soil fertility and nutrients. Also about the advice your organization, and you through your role, give to farmers. I also want to hear about what is being practiced in the field by the people you advise or work with. As we go, I'll keep track of the things you tell me are important, writing them on cards. Later, I'd like to come back to these for you to rank these in importance. Then last we'll talk about the people you meet in agriculture who you share your knowledge with, or get information from.	Today I want to listen to you talk about soil nutrients in agriculture, particularly nitrogen. Both the applied side –best practices and technologies for managing fertility; and the research and development side – the kinds of things we're monitoring, discovering and creating for the future. I want to hear about your own experience, and then also what you've come across that other people are working on. As we go, I'll keep track of the things you tell me are important. Later, I'd like to come back to these for you to rank them in importance.
RQ's: Context and information about the system: problems, solutions, issues, norms and values, priorities.	
(Grand Tour) I want to hear your describe your role in promoting certain soil management practices, especially having to do with nitrogen management, throughout the year. I may ask obvious questions, because I want to hear what's true for you in your own words. So assuming I know nothing, please walk me through what you do in your role in the Spring, [then through growing season, harvest, and into the Winter].	(Grand Tour) I want to hear your describe your career experience that relates to soil nutrients / nitrogen / fertility / technology, starting with how you first got involved in this area. I may ask obvious questions, because I want to hear what's true for you in your own words. So assuming I know nothing, please walk me through your first involvement with nitrogen research [then Currently/Recently, Immediate future, Long term future / what hope others will do]
RQ's: How do personal norms and values affect nitrogen management in general, and N2O consideration specifically?	
In your view, what is the most important thing to consider when managing soil?	In your view, what is the most important thing to consider about agricultural soil nutrients?
(Laddering) What are the main reasons you [do this / promote this to farmers?] Tell me some of the reasons it's important for [you/farms] to do things this way? And what does it mean to you to [do/promote] [method] and to have [important thing]? / What if you didn't have that? Are there other important things you recommend? [Repeat laddering, Refer to grand tour].	(Laddering) Tell me some of the reasons it's important for [farmers/researchers/developers/your organization] to do/consider that? And what does it mean to you to have [that important thing]? / What if we didn't have that? Are there other important things you recommend? [Repeat laddering, Refer to grand tour].
RQ's: How is N2O prioritized alongside other problems and issues? In which decision situations is N2O considered a relevant problem, and by whom? In decision situations where N2O is not considered a relevant problem, but perhaps could be, why isn't it? What other factors override its importance?	
I want to talk about the different ways nitrogen is lost from fields. In what ways is nitrogen lost from [your farm / the farm systems you come across?] (Follow up) In what ways, if any, can we keep nitrogen from leaving the system this way?	I want to talk about the different ways nitrogen is lost from fields. In what ways is nitrogen lost from farm systems? (Follow up) In what ways, if any, can we keep nitrogen from leaving the system this way?

<table>
<tr><th>Interview questions: Farmers/Advisors</th><th>Interview questions: Science/Industry</th></tr>
<tr><td>If not mentioned already:
Can you talk about losing nitrates in the water?
Can you talk about losing nitrogen as a gas, as ammonia?
Can you talk about losing nitrogen as a gas, as nitrous oxide?
[How do you / In your experience, how, if at all, do farmers] think about N2O / denitrification?
Relative to leaching or ammonification?

[Advisors:] In the message you give to people through your role, from your organization’s point of view, please tell me about how managing for nitrogen losses, especially as N2O gas/denitrification, fits in to all the other priorities you balance in your advice and outreach.</td><td>If not mentioned already:
Can you talk about losing nitrates in the water?
Can you talk about losing nitrogen as a gas, as ammonia?
Can you talk about losing nitrogen as a gas, as nitrous oxide?
In your experience, how, if at all, do farmers think about N2O / denitrification?
Relative to leaching or ammonification?

From your organization’s point of view, please tell me about how managing for nitrogen losses, especially as N2O gas/denitrification, fits in to all the other priorities you balance in your recommendations / research.</td></tr>
<tr><td colspan="2"><i>RQ’s: How is N2O prioritized alongside other problems and issues? In which decision situations is N2O considered a relevant problem, and by whom? In decision situations where N2O is not considered a relevant problem, but perhaps could be, why isn’t it? What other factors override its importance?</i></td></tr>
<tr><td colspan="2"><i>(The rank prioritization section was only completed if time allowed)</i></td></tr>
<tr><td colspan="2">(Rank Prioritization) Let’s look back at what you’ve told me so far is important. I want you to show me how you/your organization ranks these different factors. Here are some things that I heard, in no particular order… does this belong on the list?

Prompts, as needed:
First, choose the top three, by the priority they have to you.
We don’t have to use everything discussed. But are there some others that belong in the list?
[If some issue mentioned earlier that hasn’t been written down:] Earlier you mentioned (issue). Does that belong in this list, in your view? Where does it fit in?
What about some factors that are very important but difficult to solve? Whether it’s something already on the list, or something else?
If N2O or Nitrogen card not already placed: Where, if at all, does N2O gas loss / denitrification fit in?
Can N2O be managed as part of any of these [cards in list]? / What role, if any, does [card] play in managing nitrogen/N2O? (If N2O not discussed in detail, leave out.)</td></tr>
<tr><td colspan="2"><i>Research questions: How do norms and values promoted by different institutions, and different schools of thought, affect nitrogen management in general, and N2O consideration specifically?</i></td></tr>
<tr><td colspan="2">When you look for information about soil management, or nutrient management, where do you look? (Prompt for: magazines, newsletters, websites, conferences.)

What does [source] say about nitrogen or soil management? What about [other important issues discussed so far]?
Would you say you have low trust (confidence, belief), or high trust of that source? (If mentioned several, are there some of those sources you especially trust or don’t trust?) What is it about them that makes you trust / not trust them?
(For conferences, meetings, etc.) Describe your role. Do you speak at any of them? How did you get involved?
Do any of these sources talk about N2O? What do they say? To you in your role, is that important or not important?</td></tr>
<tr><td colspan="2"><i>Research questions: Identifying strategies to increase consideration of N2O in soil management practice. These may be technological or social.</i></td></tr>
<tr><td colspan="2">Projective questions:
What would your vision be to manage N2O in farming, if there were no barriers?
Comparing your approach to [other group if mentioned, or, “to other researchers/scientists/professionals”], who may have a different approach to yours, what do you want to tell them about the methods you promote?</td></tr>
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