Nitrogen Management Criteria System （NMCS）

A Product of Graduate Student Cohort Challenge Managing Dairy Nitrogen

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Abstract

Nitrogen (N) helps establish the foundation of life as a macronutrient used in proteins and nucleic acids in plants and animals. Yet it can have detrimental effects when excess N escapes into the environment. Still, N limits growth in many ecosystems, particularly agricultural systems, and N applications are essential to maintaining sufficient levels of production. Therefore, N conservation is a necessary part of both economically and ecologically conscious farming. Modifying farming practices to improve N conservation can reduce the quantity of N leaded to the environment. Many methods to conserve N are costly. Initially farmers may need additional compensation for resource and income modifications to achieve improved N management.

This graduate student challenge analyzed N in dairy production systems in the United States. A team of graduate students from diverse fields of study, institutions, academic backgrounds and life experienced was assembled. Individual measures of N use efficiency were evaluated at farm level sub-components such as the dairy cow or individual field. These were considered and deemed to be ineffective or impractical even as aggregate measures due to the uncertainties in measurements of stocks and flows. Instead, a whole farm scale metric is recommended. Whole farm N balance subtracts 1) all measurable exports of N from 2) all the quantifiable inputs of N to determine the amount of N that is unaccounted for and could be lost to the environment. This metric is recommended because it can provide information that correlates to environmental impacts when considered on a per head or per acre basis and provides comparative information irrespective of farm size or region, is easy to correlate to economic value, provides useful information about conservation practices, and can be calculated easily without many additional measures beyond what is already conducted by farmers on a regular basis. An incentive program focused on N conservation requires adequate metrics to quantify existing practices and compare impacts of potential new practices.

Introduction

Nitrogen (N) is an essential macronutrient for biological growth, as it represents a primary constituent in proteins, enzymes, and nucleic acids, like DNA. Biological N limits agricultural product yields in both crop and animal agriculture. These limitations can substantially lessen the economic gain within these industries, like the dairy industry, which requires N for feed and animal production. However, modern management practices rely heavily on synthetic N, leading to anthropogenic perturbations of the terrestrial N cycle. In a natural ecosystem, microbial N fixation contributes 95% of the active N (Gomiero et al., 2011). However, due to industrial N-fixation, as much as 50% of reactive N now originates from humans (Cassman, Dobermann, & Walters, 2002; Ladha et al., 2016; Vitousek et al., 1997). The process of industrial N-fixation is energy-intensive and contributes to global greenhouse gas emissions and climate change (Galloway, 2003).

Unfortunately, surrounding ecosystems receive up to 50% of applied N, due to the leaky nature of the N-cycle, with undesirable impacts (Zhang et al., 2015). Nitrogen can leak from the system through volatilization, runoff, leaching and denitrification. Nitrogen loss in the form of ammonia, nitrate, and nitrous oxide promote climate change (Rabalais, 2002), reduced air and water quality (Hill et al., 2019; Jaynes et al., 2010), and degraded soil fertility (Gomiero et al., 2011). Financially, these losses can be estimated to be as high as 99 USD (United States dollars) per ha^{-1}, significantly reducing both the environmental and economic sustainability of agricultural systems (Burkitt,2014; Index Mundi, 2020). The severity in both economic and environmental impacts of N-loss reinforces the necessity for agricultural N monitoring and mitigation strategies, particularly within leaky production schema.

As the dairy industry begins to focus on sustainable practices and environmental stewardship, the ability to compare the performance of facilities, practices, and products becomes a crucial step to relate environmental protection to profitability, improving the industry as a whole. Minimizing losses of nutrients to environments adjacent to production facilities has long been one of the hardest environmental impacts to mitigate. Many management strategies have been developed to reduce N-losses, but the influence on N retention varies. The purpose of this project is to:

Assess and recommend metrics to evaluate dairy farm N management, with the ultimate goal of producing a framework for an incentive program to recognize high performing, innovative dairies.

An overall understanding of the N cycle in the dairy farm is required. To better understand the potential for N loss in a dairy system, a dairy system can be broken into several components. Most N enters a dairy as feed products for cattle. When consumed and processed by a cow, the cow then primarily incorporates N into milk or excretes N in manure as urine and feces. That manure is then stored and often used as fertilizer, where crops assimilate much of the N, and later the plants return as feed for the dairy herd.

The goal of this project is to identify and evaluate metrics to measure N management on dairies. Five basic principles have been identified to evaluate the effectiveness of such metrics (Eagle,2020). Measuring metrics must be:

1. Simple for farmers to perform without the significant investment of time or money as

such investment may discourage the dairy farmers (McLellan et al, 2018; Eagle 2020).

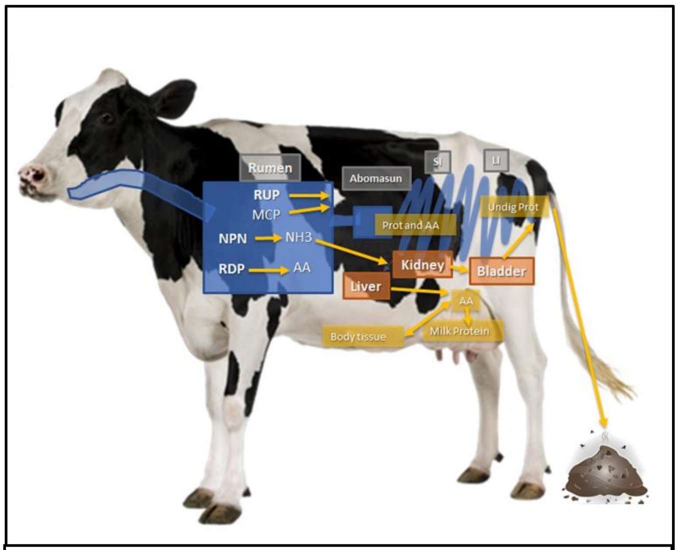
2. Robust and scalable across a variety of product types and geographical regions, while correlating with real environmental impacts (McLellan et al, 2018; Eagle 2020).

3. Credible, replicable methods that can be performed by individuals with varying backgrounds and skill levels while being providing valuable insight into nutrient losses (McLellan et al, 2018; Eagle, 2020).

4. Represent meaningful quantities, both environmentally and economically.

5. Credible to the stakeholders, policymakers, and industry officials (McLellan et al, 2018; Eagle 2020).

Nitrogen in Cattle Feed



Nitrogen content in animal feed is usually evaluated using the parameter of crude protein. Once consumed, crude protein enters the cow's rumen and can be classified into rumen. Two basic classifications exist for protein: degradable protein (RDP) and rumen undegradable protein (RUP) (Figure 1). RDP is N degraded and converted by microorganisms in the rumen into microbial protein, which can be absorbed in the intestine. It was estimated that microbial protein provides 50 – 80% of the amino acids required in the intestine by the dairy cow (Guliński, 2016). Therefore, the activity of rumen microorganisms plays a vital role in N utilization efficiency. Many factors can affect rumen microbial protein synthesis. The most important one is the balance of feedstock nutrients. It was widely reported that excess protein in the feed would reduce N conversion efficiency and increase N loss. For instance, increasing total protein from 13% to 18%, the N loss through milk urea increased from 80 to over 150 mg/ L (Guliński, 2016). Additionally, cows digest RUP post ruminally and absorb amino acids in the small intestine.

N is used by the animal to grow, produce milk (if lactating) and maintain body functions with residual N excreted in feces and urine. Nitrogen loss in cattle feed can be assessed with parameters related to N utilization efficiency. Parameters, including crude protein, metabolizable protein, milk urea N, and blood urea N, have indicated the N loss in the cattle feed. Among them, crude protein content in the feedstock is a popular one and recommended to use as it is easy to use and to obtain. For instance, the National Animal Nutrition Program (NANP) developed a free database for providing information about 121 ingredients and 129 nutrients (https://animalnutrition.org/feed-composition-database). However, to get a more precise prediction about the N utilization and loss, other parameters like the content of RUP and RDP are recommended to include if possible.

Manure Nitrogen Measures

Manure loses N in several ways (Figure 2). Urea (from urine) is quickly hydrolyzed to ammonium. Feces has predominantly organic N and only small amounts of ammonium. Losses of ammonium may result in the form of ammonia gas. As ammonium, N tends to adsorb to the manure solids or soil particles. Nitrification occur in aerobic soil conditions converting ammonium to nitrite and then nitrate. Nitrate is highly mobile in soil and tends to move with water through soil. Further N losses occur as the gaseous products of denitrification (anaerobic soil conditions) which include diatomic N gas and nitrous oxide. Conditions for each of these losses vary greatly and can be challenging to assess.

Ammonia losses are typically associated with the pH of the manure in storage (Bussink and Oenema, 1998). When the pH is high, ammonium often loses a hydrogen ion to the surrounding environment and produces ammonia gas that will be lost to volatilization. Manure pH is measured by probes or meters. Meters allow for finer precision and greater accuracy by removing the human error in comparing colorimetric methods such as pH strips. Meters and probes pose several problems when it comes to farm use. First, meters and probes are often expensive, and probes need replacing regularly. Further, they require regular maintenance and calibration to maintain the added levels of precision and accuracy. Maintenance and calibration add cost in both time and money beyond what would be expected on a farm. Although pH strips are limited in precision and accuracy, they sufficiently estimate ammonia losses while being quick and inexpensive; for these reasons, pH stirps would be the preferred method of gaging pH within manure storage.

Many trends correlate different manure storage conventions to gauge N losses from denitrification loss pathways (Rotz, 2004; Amon et al, 2001). Many methods are infeasible in certain environments, and where one method may work well in the northeast United States, the same method may not be well suited to maintaining N in the southwest US. Therefore, a survey-based tool like the NRCS's Nation Air Quality Assessment Tool (NRCS, 2020) provides more useful information for comparing a variety of different operations, over a variety of climates, and is the recommended metric for comparing manure storage practices although it does not quantify emissions.

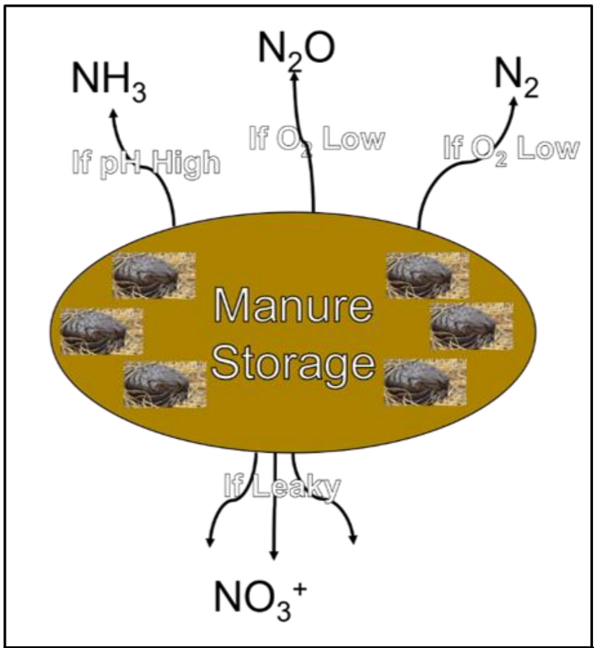


Figure 2. Map nitrogen losses and mechanisms in manure storage.

Field and Soil Nitrogen Management

Within a circular economy, dairy agriculture reuses or recycles outputs, whenever possible. Therefore, the assumption is that within the crop production component on a dairy farm, fertilizer will be supplied as manure, with supplemental N applied as synthetic fertilizer. Once applied to the soil, N is subjected to numerous microbial processes, altering the movement of N throughout the soil system. While the N-cycle is driven primarily by microorganisms, quantifying the rates of these processes is not going to be useful to farmers, as they are expensive, laborious, and dependent on regional-specific climate and soil characteristics. However, understanding their controls is essential for comprehending the influence of management strategies on N-loss, as well as which route will be the most prevalent route for loss. It is essential to understand this because every pound of N lost equates to monetary loss, reducing both environmental and economic sustainability.

Volatilization, nitrification, and denitrification (Velthof et al., 2009) are major routes for N-loss (Figure 3). The abiotic, and ultimately management, controls on these processes vary depending on the metabolic strategy that the process represents. Volatilization increases with increasing pH and temperature (Fernandez et al. 2015). In near-neutral/neutral soils, ammonium (NH_4^+) is deprotonated to NH_3, a gas, and released from the soil surface (Robertson & Vitousek, 2009). Microorganisms can also produce urease enzymes that break down urea, producing CO_2, and NH_3 (Zaman et al. 2008; Zaman et al. 2009). Numerous management practices influence volatilization, like urea/manure fertilization or soil liming (Cameron, Di, & Moir, 2013; Rotz, 2004).

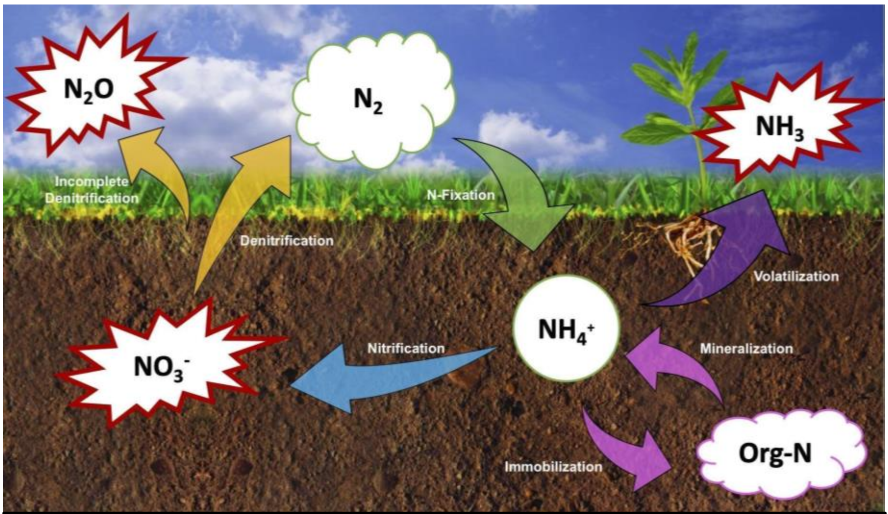


Figure 3 - The soil nitrogen cycle. Numerous microbial processes (N-fixation, Immobilization, Mineralization, Nitrification, Denitrification) influence the movement of nitrogen throughout a soil system. The products of these processes may result in deleterious environmental impacts: Ammonia (NH_3) is gaseous and contributes to reduced air quality; nitrate (NO_3^-) leads to eutrophication if subject to leaching; Nitrous oxide (N_2O) has a greenhouse gas warming potential nearly 300 times that of CO_2.

If volatilization is minimal, NH_4^+ oxidation occurs through nitrification (Wang et al., 2018). Nitrification is sensitive to low soil pH, and as it is an obligately aerobic process, it requires the presence of oxygen (Menéndez et al., 2008). Tillage influences nitrification, as mechanical aeration promotes aerobic processes, like nitrification (Liu, 2016). Additionally, synthetic fertilization which inputs NH_4^+, the substrate for nitrification, promotes increased nitrifier biomass and activity (Hayatsu et al. , 1993).

Nitrate (NO_3^-) produced during nitrification is water-soluble. Nitrate leaches into aquatic environments, causing eutrophication (Robertson & Vitousek, 2009). However, NO_3^- leaching is highly confounded by soil type, as sandy soils have higher leaching capacity than high-clay soils (Powell & Rotz, 2015). However, if NO_3^- remains in soils, as in the case of high clay content soils, denitrification will prevail (Robertson & Groffman, 2015). Denitrification is an anaerobic respiratory process, using organic matter to fuel heterotrophic respiration. NO_3^- is used in the place of O_2 as an electron acceptor (Giles et a.l 2012). Due to its anaerobic nature, and its dependence on carbon, denitrification is influenced by pH, tillage/soil compaction, fertilizer type, and water use management (Menéndez et al., 2008; Giles et al. 2012)

The soil N cycle is highly complex. Quantifying these N-cycling processes will be of limited use to farmers, as their rates are highly dependent on regional specific parameters like soil type, and climate and may vary greatly within a field. However, a survey-based system that assesses the overall N loss potential of fields, based on the types of management practices utilized, can evaluate which route of loss may be the most significant.

Combining the survey-based management assessment, with a coarse, yet scalable quantitative metric could lead to the comparison of N-loss across regions. Nitrogen-balance (N-surplus) may be a promising metric (McLellan et al., 2018). N-balance would take data that farmers may already be collecting (assuming they are keeping relatively detailed records) and transform it into a valuable assessment tool. N-balance is quantified by the inputs minus the outputs (Cela et al. 2014). In this case, the inputs would be a pre-fertilization soil NO_3^- test, manure, and fertilizer-N application rates. The outputs would be the amount of N assimilated into the whole-plant: whole-plant biomass N (Muñoz et al. 2004). Anything leftover contributes to the soil-N stock and therefore is subject to lose at the field level (volatilization, leaching or runoff). Moreover, N-balance can withstand regional specific qualities, like soil texture, temperature, or precipitation. The robustness of this metric ensures that it can be used trans-regionally, and can compare field N-loss potential across management types. It is important to note, however, that reducing N-loss at the field level may lead to increased N-losses within another dairy N cycle subcomponent (Powell & Rotz, 2015).

Whole Farm Nitrogen Balance

Nitrogen balance must overcome certain limitations for country-wide application feasibility. Nitrogen loss is confounded by region-specific parameters, like temperature, precipitation and hydrology, and soil type and texture. Region-specific management characteristics further confound N-loss, depending on animal species operation type (confinement versus pasture-grazing), animal density, feeding strategies, and others. These management characteristics may also result in greater N-loss throughout the N-cycle subcomponents, making the implication on N-sustainability challenging to determine. An additional issue in the implementation of subcomponent N-balance to assess dairy-farm N use efficiency is correlating N-balance to dairy farm performance metrics, like milk protein yield.

To combat these limitations of sub-compartment N-balance measures, the utilization of whole-farm N-Balance (WFNB) is a necessity. Whole-Farm N Balance (measured in kg N/ha) is a nutrient mass balance (NMB) quantified by summing N imported onto the farm (fertilizer, feed, forage, bedding, animals, etc.), and subtracting from N exported from the farm (milk, animals, crops, manure). Nitrogen movement within the bounds of the farm (subcompartment N-balance) is not quantified. Research at Cornell University has progressed in assessing the limitations and strengths of WFNB. By regressing WFNB with metrics for dairy efficiency (milk production - Mg/ ha; animal density - AU/ha), an optimum zone for operation can be identified (Cela et al. 2014). In a comparison of 102 New York dairies, Cela, and colleagues (2014), identified an optimum operational zone for high nutrient efficiency farms at or below 8.8. kg N/ Mg milk, or 11.8 kg N/Mg of milk (when considering N-fixation as an input). Moreover, farms were able to significantly decrease WFNB by altering management strategies, like reducing fertilization while maintaining milk yields (Cela et al., 2014). The durability of WFNB as a metric for N-loss potential within a dairy farm suggests that WFNB could be utilized at a national level to assess the N-sustainability of dairy farms. However, WFNB still requires assessment across regions and management types (Cherry et al. 2008).

Economic Evaluation for Stakeholders

It is challenging to calculate economic effect of N loss on the circular economy. A circular economy within the dairy supply chain allows for the reuse and recycling of outputs, minimizing required inputs thereby improving environmental sustainability. Considering the measurement technology, the variation between states and farms and the lack of available data, a theoretical input output (IO) model would be most useful. Many analytical methods may prove useful in development of such a model. A brief summary is provided to identify the difficulties in obtaining data needed for such an analysis.

Table 1. Analysis of the difficulties in the economic measurement of N losses. ✓ likely able to identify data and solve; ϴ data more difficult to obtain; O unable to identify data source.

Parameter	Measurement technology for individual farms	Market-oriented application value measurement for individual farms	Market-oriented application value measurement for Region or States	Present value measurement of long-term effects
Manure	✓	O	O	O
Ammonia	O	O	O	O
Water and Energy	✓	ϴ	O	O
Land	✓	ϴ	O	O
Feed	✓	✓	✓	O

The impact of N losses is most profound when considering the associated value lost in the real industry chain cycle. Such lost value can be challenging to assess, as shown in the table below. Table 1 considers measurement technology for individual farms, market-oriented application value measurements for individual farms, market-oriented application value measurement for region or states, and present value measurement of long-term effects. The amount of manure on a dairy farm is quantifiable, however the market application proportion is highly variable by region and cannot be calculated directly to a single farm. The manure’s value can only be estimated by the total value of the state or region’s manure, combined with the transportation radius. The needed assumption create substantial error in any analysis. Ammonia release may account for a considerable proportion of total N loss depending on manure handling, storage and utilization practices. However, technologies to measure emissions from individual farms is still underdeveloped, making it difficult to obtain adequate data for analysis. Water losses include both groundwater removal for facility use purposes and groundwater impairment from the production system. Facility water use can be measured and priced. However it is difficult to calculate the present value to the long-term impact on the groundwater system

Conclusion

A variety of metrics have been identified here for each of the subcomponents, and the shortcomings of each metric were discussed. The preferred metric at each level was selected for best conforming to the five principles of an effective metric. For feed, analysis of feed composition was the preferred metric identified. The preferred metrics identified for manure are pH with pH strips, and a practice-based survey to identify weather conditions for common sources of N loss are present. In the field subcomponent, a field-level N-balance was the preferred metric identified. All these metrics provide insights on conservation of N within each of their respective subcomponents that can inform farmers where N is most likely to be lost.

Although utilizing these metrics at each level provide thorough insights, the collection of all the metrics may prove rather cumbersome. Furthermore, responding in a way that conserves N at one subcomponent, could easily result in equal or greater N losses at one of the many subsequent subcomponents. Therefore, the preferred metric identified for evaluating performance was the whole farm N-balance. This metric meets all five criteria for an effective metric and provides the ability to compare the performance of multiple farms quickly and easily.

The purpose of identifying these metrics was to set up the basis of a reward-based program to incentivize environmental stewardship. The metrics identified here focused on the conservation of N, which serves a critical role in minimizing environmental impacts from a dairy. Yet, only controlling N does little to reduce damages from nutrient pollution. Controlling phosphorus is also necessary. Therefore, the whole farm N-balance can only serve as a portion of an incentivized system. To develop a fully operational system, other metrics need to be identified for comparing efforts such as phosphorus, carbon, soil, and water conservation.

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