Reactive Nitrogen Emissions from Agricultural Operations

A look at current approaches to mitigate nitrogen emissions from agricultural operations.

Reactive nitrogen (Nr) is essential to the growth of plants and animals and is typically the most limiting nutrient in agricultural production. Currently, 40% to 60% of the global population depends upon crops produced with synthetic nitrogen fertilizer. \(^1\) Liu et al. (2010)\(^2\) estimated that in 2000, total N input to global crop production was approximately 137 Tg N yr\(^{-1}\) with 50% coming from synthetic fertilizer, 16% from biological N fixation, 13% from manure, 11% from atmospheric deposition, 8% from recycled crop residue, and 2% from sedimentation. With a world population of 9 billion in 2050 and a global GDP that more than triples,
crop production of food and feed may need to increase by more than 50% compared with 2010. This increase must occur mainly by intensifying existing cropland and as a result Nr sources will rise from 185 to 232 Tg N yr⁻¹ over that period.

While N fertilizer has enabled the growing global population to maintain food production, the inefficient and sometimes excessive use of N fertilizers has also contributed to degradation of air, water, and soil quality. Estimates of the conversion of N used in food production to that actually consumed by humans ranges from 10% to 20% with greater than 50% of the N fertilizer applied to cropland lost to downstream and downwind habitats. The current rate of Nr loss to the environment due to agricultural production is more than 10 times the rate that occurred at the end of the 1800s. This loss is of increasing concern for its negative consequences on human, animal, and environmental health.

**Emissions in Crop Production**

Nitrogen transforms and is lost through many pathways as it cycles through agricultural operations (see Figure 1). The goal is to capture the available Nr in the protein of the crops produced, but substantial losses occur. The primary forms of Nr loss are ammonia (NH₃), nitrate (NO₃), nitrous oxide (N₂O) and N oxides (NO and NO₂ or NOₓ). The major loss in crop production is often in the form of NO₃ lost through leaching to groundwater and runoff in surface water. Ammonia emissions can also be substantial, particularly when urea fertilizer is applied to the field surface. The amount volatilized is largely dependent upon the time on the soil surface and secondarily by soil temperature and pH. Once the fertilizer is incorporated by tillage or precipitation, volatilization diminishes.

In the soil, N undergoes nitrification and denitrification processes. With nitrification, bacteria in the

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**Figure 1. Nitrogen flows and Nr losses from agricultural operations.** The width of arrows represents the relative amount of N among pathways. Adapted from Robertson et al. (2013).
soil convert NH₃ to nitrites and then NO₃. During this transformation, small amounts of N₂O and NO are produced, which can be emitted to the atmosphere. Denitrification is a microbial process where nitrate is reduced to produce molecular N (N₂). Incomplete denitrification occurs through producing N₂O and NO, which may escape to the atmosphere. The losses through these pathways are dependent upon many management and environmental conditions. A remaining source of reactive N loss is NOx emitted by combustion of fossil fuels. Operations for tillage, planting, harvesting, and handling of crops emit small amounts of NOx to the atmosphere. The amount of Nr lost from crop and pasture lands varies with N source, timing, application method, and climatic conditions (see Table 1).

Manure is stored in solid, slurry, or liquid forms. Solid manure containing large amounts of bedding material can be stored in stacks. Substantial amounts of NH₃ can be lost depending upon the depth of the stack and the length of the storage period. Nitrification and denitrification processes can also occur in this environment (see Table 1). When manure is stored as slurry in a tank, NH₃ loss can be relatively low depending upon the exposed surface area. Manure solids may form a crust on the surface that reduces NH₃ emission but promotes nitrification and denitrification processes and N₂O and NO emissions. Storing and processing liquid manure in an anaerobic lagoon increases total N loss, but denitrification processes are more complete with up to half of the N lost as nonreactive N₂. Following field application of manure, remaining ammonium N is rapidly volatilized as NH₃ until the manure is incorporated into the soil.

### Emissions in Animal Production

All forms of reactive N loss also occur in animal production (see Figure 1). Most occur from manure during animal housing, storage, and field application. The major N loss is often in the form of NH₃. Manure temperature and pH control the amount of NH₃ formed from manure N and thus the emission rate. Other factors such as the amount and type of bedding material used and the air velocity across the surface also influence the rate and amount emitted. When animals are housed on unpaved surfaces, leaching, nitrification, and denitrification processes can also emit NO₃, N₂O, and NO. Thus, the amount and type of Nr loss varies widely with the type of housing used (see Table 1).

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### Table 1. Relative amounts of annual Nr loss from U.S. agricultural operations expressed as a portion of total N input to each phase.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>AMOUNT EMITTED (% of applied N)*</th>
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<tbody>
<tr>
<td>Inorganic fertilizer applied to cropland</td>
<td>NH₃b  NO₃c  N₂Od  NOx*</td>
</tr>
<tr>
<td>Grazed pastureland</td>
<td>0–10  5–35  1–6  0–2</td>
</tr>
<tr>
<td>Open lot animal housing</td>
<td>5–20  10–40  1–8  1–6</td>
</tr>
<tr>
<td>Enclosed animal housing with daily manure removal</td>
<td>30–60  1–5  1–4  1–3</td>
</tr>
<tr>
<td>Enclosed animal housing with accumulated manure</td>
<td>5–20  0  0  0</td>
</tr>
<tr>
<td>Solid manure storage</td>
<td>10–40  0–2  0.2–1  0–1</td>
</tr>
<tr>
<td>Slurry tank manure storage</td>
<td>5–30  0  0–1  0–1</td>
</tr>
<tr>
<td>Liquid lagoon manure storage</td>
<td>20–40  0–5  0  0</td>
</tr>
<tr>
<td>Broadcast application of manure, no incorporation</td>
<td>15–30  2–25  1–4  1–4</td>
</tr>
<tr>
<td>Broadcast application of manure, rapid incorporation</td>
<td>5–15  2–25  2–6  1–5</td>
</tr>
<tr>
<td>Subsurface injection of manure</td>
<td>2–10  5–25  2–9  2–7</td>
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**Notes:**

a General values drawn from literature review (Rotz, 2004) and modeling experience with the Integrated Farm System Model (Rotz et al., 2014) and Manure–DNDC (Li et al., 2012).

b NH₃ emissions are primarily influenced by exposure time, temperature and ambient air speed.

c NO₃ leaching to ground water and runoff to surface water vary widely as influenced by the amount and distribution of precipitation and the timing of N application.

d N₂O and NO formation and emissions are influenced by moisture, temperature, and anaerobic conditions that control nitrification and denitrification processes in soil and manure.
Other minor emissions of reactive N can occur from feed and animals. When crops are ensiled for storage, NO₂ is produced and emitted during the first few weeks of ensiling. The relative amount of N emitted is small, but it is a toxic and dangerous gas for those working with silage. Minor amounts of reactive N may also be emitted from the open surface of silos. Losses of crude protein (total N) are known to occur and this loss is probably in the form of NH₃. With poor ensiling conditions and spoilage, nitrification and denitrification processes might also occur. Ruminant animals may emit minor amounts of enteric N₂O and equipment operations for feeding and manure handling emit NOₓ through fuel combustion.

Combining crop and animal production in an integrated system can improve N use and reduce Nr losses through more efficient recycling of manure nutrients in feed production. By applying manure to cropland at the right time and at the right amount for crop uptake, leaching and denitrification processes are minimized. When manure N is applied in excess of crop needs, nearly all of the excess is lost to the environment, mostly in a reactive form. When animals are grazed, closer integration of nutrient cycling occurs where fecal and urine excretions are deposited directly on the pasture. These excretions apply very concentrated applications of N on small areas, which can enhance leaching and denitrification processes. Use of rotational grazing strategies and avoiding the congregation of animals under shade or around watering and feeding areas helps reduce these emission pathways and improve nutrient use efficiency.

**Mitigation of Emissions**

Gains in N use efficiency are required to reduce Nr emission to the environment. This can be achieved by either better utilizing the N input to increase production or reducing the N input while maintaining production. Galloway et al. (2008) estimated that increasing N use efficiency of crops and using improved animal management could
In dairy free-stall barns, NH$_3$ emissions have been reduced by up to 50% by sloping floors to drain urine away from fecal material.

Mitigation of reactive N loss from animal producing operations must begin with feeding. Generally, 20% to 30% of the protein N consumed by animals is retained in the animal products produced and the remainder is excreted.\textsuperscript{7} Feeding the right amount and quality of protein improves animal utilization and often improves production. This reduces the N excreted by the animal and often reduces the portion of that N excreted in a form that is readily lost as Nr. Feeding animals in groups with similar nutrient requirements is one method to more accurately meet protein requirements. Feeding specific amino acids (protein building blocks) can also tailor diets to more accurately meet nutritional requirements. In ruminant animals, obtaining the right degradation of protein in the rumen and having an appropriate bypass of protein to the intestinal tract is important. Feeding the right amounts and types of carbohydrates can also improve N utilization. Feed additives, such as enzymes, antibiotics, probiotics, organic acids, and growth hormones, may also reduce N excretion. Feeding well balanced diets to maximize performance and N utilization is often the most cost-effective way to reduce N excretion and thus mitigate Nr emissions from all manure handling processes.

After N is excreted by the animal, steps can be taken to mitigate emissions during manure handling.\textsuperscript{7} This can begin on the barn floor. By separating urine from feces, hydrolysis can be reduced and the N remains in a less volatile organic form. In dairy free-stall barns, NH$_3$ emissions have been reduced by up to 50% by sloping floors to drain urine away from fecal material. When long-term manure storage is used, NH$_3$ emissions can be reduced by up to 80% and N$_2$O emissions can be eliminated using a storage cover. Bottom loading of a slurry tank allows a natural crust to form on the surface. This is a cost-effective way to reduce NH$_3$ emissions from storage by up to 70%, but nitrification and denitrification processes are enhanced causing N$_2$O and NO emissions. Microbial and acid additives have been evaluated to reduce manure emissions, but safe and cost-effective mitigation materials have not been found. When manure is applied to cropland, N losses are greatly reduced through rapid incorporation into the soil. Use of direct, subsurface injection of manure reduces NH$_3$ emissions following application by 70% to 95%, compared to broadcast application without incorporation, but the higher concentration of N in the soil may enhance leaching, nitrification, and denitrification processes (see Table 1).

Management to reduce N losses requires a whole-farm approach. Changes can be made to reduce N losses in each step of manure management between animal excretion and crop uptake. However, the benefit of reducing the loss in any one component is low if steps are not taken to reduce losses from subsequent components. For example, reducing NH$_3$ emission in the housing facility has little benefit if that retained N is not maintained through improved management during manure storage and field application. Reducing NH$_3$ emissions also may not provide overall benefit if that additional manure N leads to greater losses through denitrification and leaching. Only by providing similar levels of mitigation to animal feeding, housing, manure storage, and field application can production systems be developed with reduced or optimal environmental impact.

**Conclusion**

Reactive N is a critical input to agricultural systems and a major contributor to the substantial improvement in food production made in the 20th century.
Nr losses cannot be eliminated, but strategies and technologies are available for reducing these losses and other alternatives can be developed. Mitigation of Nr emissions often increase the cost of production so more economical methods are needed or strategies must be implemented to help cover the increased costs to maintain sustainable food production systems.

References