THE ENVIRONMENTAL IMPACTS OF N_2 FIXATION BY ALFALFA

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ABSTRACT

Symbiotic N_2 fixation by alfalfa provides substantial amounts of nitrogen (N) to livestock operations, subsequent crops, and soil organic matter. Fixed N can be a pollutant if alfalfa is not managed well. Symbiotic N_2 fixation is an adaptive process that declines as other N supplies increase. Well-managed stands of alfalfa effectively absorb mineralized N from manure and remove residual nitrate from the subsoil, irrigation water, and shallow ground water, and fix less N from the air. Although N losses can occur both during and after alfalfa production, it is possible to use this adaptive N_2 fixation process to reduce excess N supplies on farms.

Key Words: alfalfa, nitrogen fixation, crop rotation, pond water, leaching, runoff

INTRODUCTION

Plants have evolved to absorb inorganic N (mainly ammonium and nitrate). Nitrogen is the main limiting nutrient for crop growth in most of the world. Agricultural productivity increased dramatically as N fertilizers became widely available. However, excessive or inefficient N use can cause contamination of ground and surface waters and the atmosphere. Thirty years ago, Brown (1975) concluded that soil organic N was the main source of nitrate in drainage water in the San Joaquin Valley. Although he predicted that fertilizer N rates would not exceed about 50 lb/acre due to economic and environmental pressures, he suggested that 'A program of source control should be initiated to ensure that nitrogen fertilizers do not become a problem in the future' (p.537). Fertilizer N rates have doubled (Krauter et al., 2002) and controls of all N sources (e.g., fertilizers, manures, and composts) are not being widely applied. This is where N_2-fixing legumes, like alfalfa, may help. Legumes are one of the few types of plants that have developed symbiotic partnerships with microorganisms that convert atmospheric N_2 gas into plant-available forms. Here I discuss how alfalfa contributes to excessive N supply through symbiotic N_2 fixation, but also how they can help protect and improve the environment.

WHAT IS N_2 FIXATION?

Specific soil bacteria, called rhizobia, can infect the roots of legumes, like alfalfa. Unlike the response to pathogenic bacteria, legumes produce specialized root structures called nodules, into which the rhizobia grow. There they are fed and protected by the plant, they multiply, and they capture N_2 gas from the air and convert it to amino acids that the plant uses for growth. Although the millions of alfalfa nodules in an acre weigh only a few pounds, they each may contain a billion rhizobia that can manufacture hundreds of pounds of N per acre each year. We recently

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estimated that N_2 fixation by alfalfa ranges from about 40 to 420 lb N/acre annually in the Mississippi River Basin (Russelle and Birr, 2004), similar to the range of N_2 fixation rates reported from individual field experiments (Russelle, 2005). Why does N_2 fixation vary?

N_2 fixation and inorganic N. Nitrogen supply from other sources is one of the most important factors affecting N_2 fixation. Legumes absorb N from the soil, fertilizer, manure, and irrigation water. Symbiotic N_2 fixation is an adaptive process, and declines with N uptake from these other sources. The legume will fix the ***additional*** N it needs for growth.

During establishment of alfalfa on some soils, nodule number and activity may be too low to supply the N needed for maximum yield of the first cut (Trimble et al., 1987). Afterward, N supply from the soil, stored reserves, and symbiotic N_2 fixation may remain inadequate, and yield responses to low rates of fertilizer N may be seen (Bélanger and Richards, 2000). Like other perennials, alfalfa relies on stored N for shoot growth after harvest (Graber et al., 1927). One-third to one-half of the stored N in the roots and crown is used during shoot regrowth of established alfalfa (Russelle et al., 1994), because both symbiotic N_2 fixation (Vance et al., 1979) and inorganic N uptake (Kim et al., 1993) are limited for one to two weeks after harvest. In established stands, therefore, yield response to fertilizer N is rarely seen, although herbage N concentration (Walgenbach and Marten, 1981) and stored N levels in roots (Barber et al., 1996) may increase. Still, added N may increase alfalfa yield when soil N supply is very low (Hannaway and Shuler, 1993) and when N_2 fixation declines in autumn (Raun et al., 1999). The general lack of yield response has led to the perception that the crop does not utilize applied N. This is not true, because the plant merely substitutes inorganic N for N_2 fixation (Allos and Bartholemew, 1959), and this is a major way alfalfa helps prevent environmental pollution.

REDUCED N LOSSES

Alfalfa has high N removal potential (large yields of high protein herbage), a deep effective root zone of as much as several meters below the soil surface, and high water use – all three characteristics are important to environmental protection. In addition, loss of N in surface runoff from alfalfa fields is generally low (Miller et al., 1984).

Reduced leaching losses. Soil inorganic N concentrations typically are small throughout the root zone during alfalfa production (Rasse et al., 1999) and nitrate losses below the root zone or in subsurface tiles are lower than with annual crops (Randall et al., 1997). Ground water was cleaner than the public drinking water limit (10 mg N/L) under alfalfa, but not under annual crops or a dairy in New Mexico (Taylor and Bigbee, 1975). In a subhumid region, the most effective way to reduce nitrate leaching was to follow four years of alfalfa with two years of wheat (Entz et al., 2001), although stand decline caused higher soil nitrate under older stands. If the next crops do not capture the N released after alfalfa termination, N may be lost by leaching or other means, mainly between the time of stand termination and rapid growth of the next crop (Tan et al., 2002). Under irrigation, nitrate losses were substantial when alfalfa was followed by dry beans or corn (Robbins and Carter, 1980).

Uptake of irrigation water nitrate. Alfalfa also removes N from irrigation water. We compared nitrate uptake from irrigation water by alfalfa with forage grasses and soybean on a sandy soil by measuring nitrate concentration of water leaving the root zone (Russelle et al., 2004). Except during autumn when forage growth was slow, soil water was cleaner than the public drinking water limit under all perennials, even when 50 mg N/L was applied. Differences among forage species increase at high water application rates. Although alfalfa and orchardgrass are equally efficient at absorbing nitrate at low water flow rates, we found that the grass is more effective at high water flow rates through the root zone (Bellrichard, Russelle, and Ochsner, 2004, unpublished data). This may be due to greater fine root length density in grasses.

Estimated ***minimum*** ground water loading rate from flood- or furrow-irrigated fields on dairy farms in the northeastern San Joaquin Valley is 250 lb N/acre per year (Harter et al., 2002). This is likely due to rapid nitrification of applied pond water N after it is applied to the soil, then leaching with the next irrigation, which is applied at rates of 3 to 9 inches on many farms using border flood irrigation (Campbell-Mathews and Harter, 2004). Given 1) the rapid mineralization of organic N in pond water (Pettygrove et al., 2003), 2) fast nitrification of applied ammonium-N in pond water, 3) the excessive quantities of N that are applied (Harter et al., 2001), and 4) limits on the effectiveness of alfalfa to capture nitrate when water moves very quickly through the soil, alfalfa may not be able to prevent ground water contamination under these conditions.

Fluctuations in shallow water table depths may increase nitrate concentrations under alfalfa, which requires well aerated soil conditions for root persistence. In Nebraska, ground water nitrate concentrations increased after the water table rose about 6 feet (Spalding et al., 2001). These authors suggested that root death and decomposition after inundation lead to nitrate release in this 3-year-old alfalfa stand.

One potential way to reduce nitrate contamination of shallow aquifers and drainage water is to recirculate it through alfalfa. This phytofiltration approach may be an effective way to reduce ground and drainage water nitrate concentrations, although salt levels must be low enough so that soil salinization is prevented. Not only would water quality improve, but overall N excess in the region will be reduced, because N_2 fixation would decline.

N CONTRIBUTIONS

Alfalfa provides fixed N to farming systems as feed, soil organic matter, and plant residues.

Harvested protein. The amount of protein harvested in alfalfa on a large scale is difficult to know with precision, because protein concentration is affected by leaf retention, stage of maturity, rain during field curing, etc. Using a protein concentration of 22%, the nearly 12 million tons of alfalfa hay harvested in California, Nevada, Arizona, and New Mexico contain about 840 million pounds of N. Most of this enters local farms. Although that is not possible to say with certainty, it is likely that between 50% and 75% is fixed N.

Soil organic N buildup. Legumes release fixed N and build up soil organic matter during growth (Russelle et al., 1994). The increase in soil organic carbon reached a new plateau after only three years on a clay soil (Angers, 1992), and one would expect similar increases in soil organic N. There are two reports that estimate an annual accumulation of 45 to 50 lb N/acre in alfalfa fields (Keeney, 1979; Andrén et al., 1990), but this certainly will vary in stands that fix more or less N.

For soil N buildup to occur, alfalfa must add more than enough newly fixed N to replace soil N removed from the field by forage harvest. The main pathways for N to return to the soil are through above- and below-ground residues (Andrén et al., 1990; Goins and Russelle, 1996).

Nitrogen benefits in rotations. Effectively nodulated legumes generally provide an actual N benefit to the subsequent crop, but the net addition of this N and its availability depend on how much fixed N remains in non-harvested residues, the fixed N contributed to decomposable soil organic matter, and crop management (tillage, timing of stand termination, etc.). Estimates can be made in various ways, but the most common is to use the fertilizer replacement value, which is the amount by which fertilizer N can be reduced in the rotation compared to monoculture.

Based on the amount of N present in roots, crowns, and regrowth, Kelner et al. (1997) estimated that 75 lb N/acre was added to the soil after a one-year alfalfa stand and about 130 lb N/acre was added after two- or three-year-old stands. Fixation rates were estimated at 155 and 450 lb N/acre, respectively. Estimates of fertilizer N replacement value range from 0 to 100 lb N/acre after a one-year stand to 120 to 170 lb N/acre after two or more years (Hesterman et al., 1986; Fox and Piekielek, 1988; Oberle and Keeney, 1990). Corn in Iowa rarely responded to fertilizer N after alfalfa (El-Hout and Blackmer, 1990). On irrigated sandy soils, however, N credits for legumes typically are smaller because of higher leaching losses. Some states recommend that fertilizer N additions be reduced an average of 30 lb/acre during the second year after alfalfa termination, and in drier regions, where N losses are low, N benefits may last several years (Forster, 1998).

Tillage plays a role in determining the N benefit after alfalfa. In some situations, seeding cereals or corn directly into alfalfa stands killed by herbicide the previous fall provides adequate N (Carter et al., 1991). In any case, it is important to manage both stand termination and the following crop to maximize N uptake and reduce N losses (Meek et al., 1994).

CONCLUSIONS

In general, we can conclude that alfalfa makes significant N contributions to cropping systems – additions in many situations, and reductions in others. The flexibility of symbiotic N_2 fixation is a key element in this benefit. With good management, alfalfa reduces nitrate leaching and runoff, improves soil organic matter, and lowers the need for fertilizer N on succeeding crops. Alfalfa may also be used to reduce excess N that is cycling on farms, and help remediate contaminated soil and water.

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