NITROGEN CYCLING AND FERTILIZATION IN LEGUME INCLUSIVE CROPPING SYSTEMS

Bryan G. Hopkins and Jeffrey C. Stark
Professor and Environmental Analytical Lab Director, Brigham Young Univ., Provo, UT;
Professor and Superintendent, University of Idaho, Aberdeen, ID

ABSTRACT

Among other benefits, legumes contribute nitrogen (N) to subsequent crops. However, predicting the impact on yield and the timing of the N release is difficult. Regardless, adjustments in the N recommendation need to be made to avoid yield and crop quality problems, as well as negative environmental and social issues. Ideally, a reduction of pre-plant/early season N fertilizer is made based on field research. Two possible approaches are used, namely the Fertilizer Replacement Value (FRV) or the Difference in Maximum N rate (DMN). However, in-season assessment of soil and tissue N levels is needed to further adjust to adequately meet the N needs of the crop due to the very complex interactions impacting N status following a legume.

NITROGEN IS ESSENTIAL

Conversion of atmospheric nitrogen (N_2) gas to biologically available amine ($R\text{-}NH_2$) forms occurs through abiotic (lightning, combustion, and Haber-Bosch industrial) and biotic (microbial fixation) pathways. These life essential processes enable biosynthesis of nucleotides used in DNA and RNA and amino acids used in proteins and enzymes. Although natural levels of N_2 fixation enables plants to grow in the wild, supplemental N fertilization is generally required to facilitate the rapid plant growth required to provide adequate food, fuel, and fiber to sustain the over seven billion and increasing human population. Despite its benefits and essentiality for life, excessive N can cause yield and crop quality losses, as well as being a pollutant. Managing cropping system N is essential for environmental, economic and social issues.

LEGUMES AND NITROGEN FIXATION

Leguminous plants in the Fabaceae (formerly Leguminosae) family comprise the third largest family of land plants with ~19,000 named species (7% of flowering species). These include trees, shrubs, and annual and perennial herbaceous plants. Cultivated legumes include "pulse" grown for food grain, livestock forage and silage, and soil-enhancing green manures. In addition to their own economic value, legumes are known to provide benefits to subsequent crops, including: 1) improvement of soil physical, chemical, and biological properties; 2) reduction in pests; 3) infusion of N into soil, and, thus; 4) increases in yield and crop quality. There are potential disadvantages as well. In some cases, the economic value of the legume crop is significantly less than other species in the cropping system. Also, it is difficult to predict when the N in legume will be released to the subsequent crop and, as such, can lead to yield losses and/or environmental pollution through losses to the atmosphere or hydrosphere.

Agriculturally important legumes include: alfalfa (*Medicago sativa* L.), soybean (*Glycine max* L. Merr.), bean (*Phaseolus* spp.), pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik), chickpea (*Cicer arietinum* L.), medic (*Medicago* spp. L.), clover or trefoil (*Trifolium* spp. L.), vetch (*Vicia* spp. L.), lespedeza (*Lespedeza* spp.), peanut (*Arachis hypogaea* L.), sweet pea (*Lathyrus odoratus* L.), carob (*Ceratonia siliqua* L.), liquorice (*Glycyrrhiza glabra* L.), etc..

Most legumes work in cooperation with specific microbes to "fix" N. The microbes convert N_2 into ammonium (NH_4^+). Some are free-living in soil or water but others require a host plant. Certain plants, mostly legumes, provide carbon and other resources to N-fixing bacteria who reciprocate the symbiotic association by providing N to the plant. *Rhizobium* is the species of bacteria that infect the roots of legumes, forming large nodules.

NITROGEN CREDITS

It is well documented that inclusion of a legume into a cropping system results in lower N fertilizer need—known as a N credit. The majority of this credit is realized in the first year following the legume, but smaller amounts are also released in subsequent years (Stark and Porter, 2005). There are at least two reasons for this N credit. First is the direct contribution of N from the root and shoot biomass as decomposition of the crop residue occurs and the organically bound N is mineralized into forms available for plant uptake. All root and shoot tissues contain N, but these tissues, especially the root nodules, in legumes are especially rich in N.

The second reason for a N credit is that demand can be lessened following some legumes as compared to some species. Microbes responsible for the decomposition of crop residues require N. If the N content is low compared to carbon (C), additional N may be needed to avoid deficiency caused by immobilization. For example, corn (*Zea mays* L.) and wheat (*Triticum* spp. L.) and other small grains have relatively high carbon to nitrogen (C:N) ratio compared to alfalfa, soybean, and other common legumes. In addition, the total quantity of residue impacts the N needed. A continuous corn crop would require more N than corn following soybean because the soybean residue is minimal and has a lower C:N ratio.

Predicting the correct N credit is difficult because a myriad of interacting factors, including:

- legume species vary widely in biomass and nodulation effectiveness and N content,
- number and health of N containing nodules ,
- amount of root and, to a lesser extent, shoot biomass impacts total N supply,
- rooting depth of both the legume and the following crop and depth of nodules (e.g. shallow rooted species may not access N from nodules found deep in the soil; deep rooted species may recover more of the N, etc.),
- root morphology/architecture with deep and/or fibrous roots being better N scavengers,
- plant age and stage of growth impacting succulence, C:N, and total biomass,
- N fertilization and background levels of N in soil and irrigation water (nodulation and effectiveness of nodules is reduced if N is already present in soil),
- legume density per acre (low density equals less N credit),
- ratio of legume to non-leguminous species (e.g. grasses etc. reduce the number and quality of legume roots and nodules),
- timing of physical and/or chemical killing of the legume (decomposition is a function of time of death and amount of time in contact with soil),
- early incorporation of the legume residue in soil hastens mineralization,
- soil pH and fertility (poor soil—especially low potassium—equates to less nodulation),
- soil organic matter (OM; High OM can result in high soil N and reduced nodulation, however, high OM also provides better growing conditions for a healthy legume crop.),
- soil moisture (dry soils tend to have less N credit; high precipitation rates can result in nitrate loss from soil due to leaching and/or denitrification),

- soil temperatures and oxidation state (warmer and more oxidized soils release N quickly),
- soil texture (sandy soils get less of an N credit).

With so many interacting factors, it is apparent that a single N credit for any species is not practical. Total N contents of legume crops can be greater than 200 lb N ac^{-1} (Griffin and Hesterman, 1991). In general, scientists, agronomists, and farmers will reduce the N fertilizer applied by ~20-50 lb ac^{-1} for annual leguminous pulse crops (such as soybean) and green manures and 50-200 lb ac^{-1} for perennial forages (such as alfalfa). The USDA recommends a minimum N credit of 40 lb ac^{-1} and up to 220 lb ac^{-1} for some forages (USDA-WSARE, 2007).

SYNCHRONY

Ideally, N mineralization patterns from legume residues are matched with crop N uptake patterns. Plants need N throughout their lifespan, especially during the rapid vegetative growth stages in the middle of season. However, less N is generally needed early in the season when the plant is small and growing slowly. Similarly, end of season demands are often relatively low once a plant begins to shift from vegetative to reproductive growth stages. Root growth into new soil slows or ceases. Root biomass often decreases due to pathogens and reallocation of carbohydrates and nutrients into storage tissues. As such, water and nutrient uptake slow dramatically. Any N release into the soil at this stage is mostly wasted and has a high probability of being lost to the environment before the next season of growth unless a double or green manure crop is grown shortly after harvest.

If inadequate fertilizer N is applied and the N mineralization occurs later in the season, N deficiencies may reduce shoot and root growth, possibly impacting final yields and crop quality. Plants may overcome early season deficiency if it is not severe and the growing season is long. However, yield and crop quality losses are more likely if the bulk of the N release occurs very late in the season and N deficiency is prevalent during the rapid vegetative growth stages. This scenario is more likely if the legume is not killed until right before planting of the subsequent crop. For spring planted crops, killing the legume the fall prior and incorporating the residue into the soil begins the mineralization processes. In addition, tillage warms the soil and hastens microbial decay activities. However, killing the legume and incorporating into the soil too early may result in an early flush of N and possible later season N deficiencies. This is more likely if soil moisture is high and leaching and denitrification losses occur.

Excess N is also a problem, as this can result in a delay of the onset of reproductive growth and/or maturity. In corn and most other crops, excess N is less problematic than deficiencies. Baring soil problems, corn roots are deep and efficient at scavenging N and, as such, have a relatively higher chance of recovering any excessive mineralized N from early season release. Although excess N can cause negative impacts, some species tolerate the excess. However, other species, such as potato, tomato, sugarbeet, lettuce, etc. are very sensitive to excess N. The excess N can promote excessive vegetative growth at the expense of yield. It can also cause crop quality problems, such as with potato having poor skin set and impacts on post harvest handling. Small grains are more likely to have lodging losses when N is excessive. Furthermore, shallow rooted species such as onion, potato, carrot, lettuce, etc. have a higher probability of missing a large portion of N which may be released early season if the N is pushed past the effective root zone with precipitation. As such, synchrony is relatively more important for these crops.

Stark and Porter (2005) review the impacts of legumes with potato. They stated that potato is especially sensitive to synchrony problems, which are worse for indeterminate cultivars, especially when grown in short-season situations. Nitrogen released too early can delay tuber bulking and promote excessive vine growth, resulting in reduced yield and an increased proportion of immature tubers. Alternatively, N released too late in the growing season can reduce N use efficiency and increase the potential for nitrate leaching. They cite several studies where potato vine dry matter and N content were considerably higher following legumes, but with no impact on yield. They concluded that it was likely that the N mineralized too late in the season. In contrast, Blaser (2012) showed significant yield advantage and less N requirement for potato grown after alfalfa (Fig. 1). These varying results emphasize the difficulty of predicting the total amount and the timing of the N release from legumes grown as a previous crop.

Most of the N is released from legumes during the first year after incorporation (Fox and Piekielek, 1988). However, release rates vary widely (Stark and Porter, 2005). Griffin and Hesterman (1991) and van Cingel (1992) found that although potato plant N uptake can be increased when grown following legumes [such as alfalfa, red clover (*T. pretense* L.), bird's-foot trefoil, and hairy vetch (*V. villosa* L.)] compared to non-legumes, the N release can be too late in the season to provide adequate season long N supply for superior potato yields and tuber quality.

Legume N contributions can also be significant during the second and third year after incorporation. Neeteson (1991) found that N need reduced by 59 and 88 lb N ac^{-1} following red clover and alfalfa, respectively during the first year and by 23 and 17 lb N ac^{-1} during the third year. This proportional decrease in legume N availability to potatoes over the three year period is similar to that observed for corn following alfalfa and red clover (Fox and Piekielek, 1988).

MANAGING NITROGEN FOLLOWING LEGUMES

Despite the fact that accurately predicting N needs following a legume is impossible, N credits do need to be accounted for in cropping systems which include a legume. Because of gaps in the data and the complexity of the N release predictability, it is necessary to combine the pre-plant/early season N credit with in-season monitoring and, if needed, fertilization.

As previously mentioned, it is difficult to make the pre-season prediction, but the rate of N applied does need to reduced or eliminated. If in-season adjustments are possible, the amount of early N should be conservative, as it is possible to add more N but not vice-versa. In season fertilization is generally possible, although application via ground applicators or fertigation may not be possible if the soil is too wet. In these cases, aerial application may be the only option and, in some cases, this is not possible in some locales. Furthermore, cost of the N fertilizer and/or the application may be relatively higher than pre-plant options.

There are two basic approaches to pre-plant/early season N adjustments, namely, the Fertilizer Recovery Value (FRV) and the Difference in Maximum N (DMN) rate. Stark and Porter (2005) review these approaches and pros and cons especially as they apply for potato (Fig. 1). The FRV approach is the amount of fertilizer N required to produce a given yield following a non-legume that is identical to that produced following a legume when no N fertilizer is applied. The DMN approach is the difference between maximize crop yields following legumes and non-legumes. In general, results with the FRV method were somewhat higher than with the DMN method (about 33% on average), although the ratio of FRV/DMN was rather inconsistent, ranging from 9.4 to 0.6 (Stark and Porter, 2005).

The in-season approach to customizing the amount of N needed varies by circumstance and species. Ideally, significant research results are available to help guide growers in these decisions. For example, in barley (*Hordeum vulgare* L.) it is known that values below about 4.1% N in the flag leaf are deficient. Supplemental in-season N likely needs to be applied if the concentration is below this. However, there is concern that the N release from the legume will come after the assessment and so N rates should be conservative if conditions are conducive for this to occur. In the case of potato, there is substantial data for the Russet Burbank cultivar suggesting that petiole nitrate-N values should be in a certain range depending upon time of season (Stark et al., 2004). Growers sample petioles weekly (and often soils as well) and apply small increments of N as needed. This intensive management is ideal for accounting N from legumes. Less intensive sampling and application may lead to large errors in N management.

In a case study for commercial scale organically grown alfalfa-potato-corn and alfalfa-potato-barley research demonstration projects in Idaho, Hopkins (unpublished data) used this intensive management system to manage N. A relatively young (5 year old stand), dense alfalfa stand with few grass weeds was plowed down after the last cutting in September. A modest rate of OMRI certified manure compost was applied prior to tillage based on soil test values to supply adequate levels of phosphorus, potassium, etc. (estimated N value was about 35 lb ac^{-1}). No additional fertilizer N was applied, although there were other sources of N accounted for, including 30, 40, 30, and 18 lb N ac^{-1} from inorganic soil N, estimated N release from 2.5% soil OM, estimated N from the potato seed, and nitrate-N in irrigation water, respectively. Weekly soil and petiole samples were analyzed for N status. The petiole nitrate-N concentrations fell in the adequate zone (starting at 21,300 ppm and dropping to 8,200 ppm) throughout the growing season until mid August. However, tests showed that nitrate-N concentrations were actually increasing in the soil from continued N mineralization, becoming apparent that the soil had ample N but plants were not able to utilize it due to reducing root biomass and pathogen infection of roots and vascular tissue. Yields were within 10% of conventional fields with traditional N fertilizer and the demonstration was considered a success. If N would have needed to be applied, a suitable source would have been applied through the irrigation water. This case study shows that it is possible to effectively manage N in legume based cropping systems, but agronomists need to have a thorough understanding of the available data and the agronomic principles governing the N cycle.

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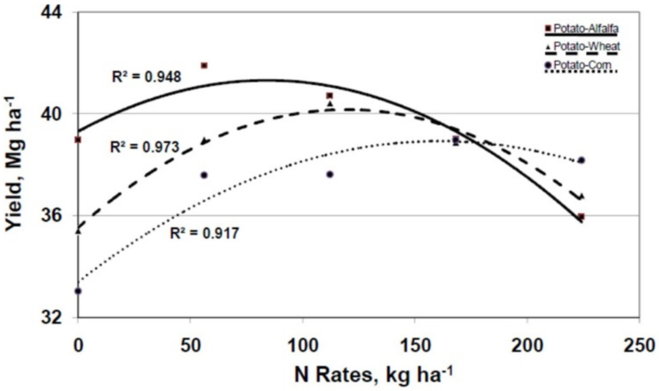

Fig. 1. Potato yield as a function of N rate for three cropping systems averaged across two years of this study (Blaser, 2012).

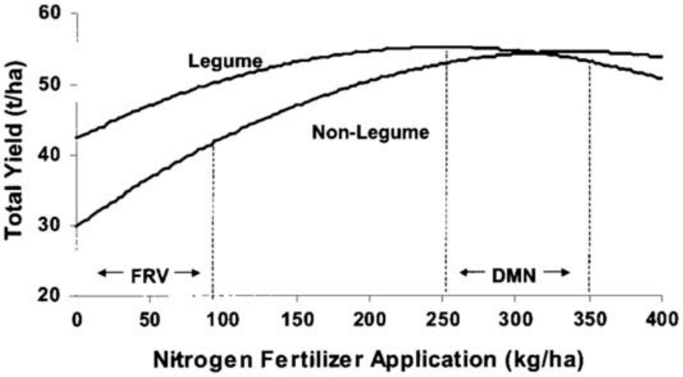

Fig. 2. Two hypothetical approaches to estimating the amount of N credit to be given for a legume (Stark and Porter, 2005). The Fertilizer Recovery Value (FRV) is determined by the difference in the amount of N needed to achieve the same yield [e.g. the Legume system with no N added has the same yield as the Non-Legume system at about 90 kg/ha (80 lb/ac)]. The Difference in Maximum N rate (DMN) is determined by subtracting the N rates from the peak of each curve [350-250 kg/ha = 100 kg/ha (88 lb/ac)].

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(208) 423-6503
David.tarkalson@ars.usda.gov

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Phyllis Pates
International Plant Nutrition Institute
2301 Research Park Way, Suite 126
Brookings, SD 57006
(605) 692-6280
ppates@ipni.net