Nitrogen Mineralization: What's Happening in Your Soil?

Fran Walley
Dept. of Soil Science, University of Saskatchewan, Saskatoon, SK, S7N 5A8
E-mail: walley@sask.usask.ca

Introduction

Most soils contain several thousand lbs/acre of nitrogen (N) in a variety of organic forms including newly added crop residues, soil micro- and macro-organisms, and as soil organic matter (SOM) in various stages of decomposition. All of these different organic materials can be decomposed by microorganisms, although different forms differ in terms of how easily they decompose. During decomposition, N tied up in organic forms is released into the soil and thus is converted from an organic form, which is unavailable for crop uptake, to an inorganic form which crops can use. In terms of planning for N fertilizer requirements, the question is, how much N is released – and when does N release occur?

In order to answer this question, we need to consider the impact of management, crop rotation, and a host of environmental factors, on decomposition and subsequent N release, remembering that decomposition is merely a reflection of the microbial activity in the soil. Afterall, N release occurs when materials decompose, and decomposition only occurs when microbes attack the organic materials. When we think in terms of microbial activity, it is easy to imagine that there are many factors that might influence the size, composition and activity of the microorganisms in the soil. For example, different microorganisms prefer different kinds of 'food', and if we view crop residues as food for microorganisms, then it seems reasonable to assume that crop rotation (and thus residue input types) will influence the microbial population. Using this kind of reasoning, it is reasonable to question if the microbial population somehow is different in pulse land compared to land that has never grown a pulse. What is the impact of zero-till versus conventional-till? Could fallow influence soil microbial populations? What happens during drought?

Although we don't have all the answers (or even all the questions), one thing is certain; if microorganisms and their activity control N release from decomposing organic materials, then there are a lot of variable factors to consider when estimating fertilizer N requirements for crop production. Ultimately, the challenge is to identify and quantify the most active or 'labile' portion of the soil organic pool (which is likely to vary depending on soil management and cropping history) and estimate the potential N contribution from this organic pool. If we can accurately estimate the size and potential N contribution from the active soil organic pool, we should be able to adjust fertilizer N recommendations accordingly, thereby matching crop N requirements with N supply from both the soil and fertilizer sources.

Currently, many soil-testing labs in Western Canada base their fertilizer N recommendations on a measure of immediately available inorganic-N, i.e., N that already has been mineralized or N that remains in the soil after a crop has been harvested. Although this inorganic N is certain to contribute to the N nutrition of subsequent crops, it may still be useful to estimate the potentially large (and variable) contribution that the soil organic matter can make to the total N availability during the growing season. Indeed, the total amount of N available for crop growth over the growing season is the sum of the inorganic N pool (i.e., the N pool typically measured by traditional soil N tests) together with the pool of organic N that can be decomposed during the growing season. Interestingly, the latter pool may well make the greatest contribution to available N during the growing season. Given the growing use of reduced tillage and the inclusion of legumes in rotations, it seems possible that N contributed from the soil organic pool during the growing season could overwhelm the contribution of inorganic N normally measured in the fall or spring. But can we really guesstimate N release from the organic N pool to improve fertilizer N recommendations? What factors need to be considered and where might we go wrong?

Soil Nitrogen Pools

Not all soil organic N is created equal. Whereas some of the soil organic N forms are easily decomposed, some remains relatively protected from microbial decomposition in the form of stable soil organic matter (SOM), and thus remains unavailable for plant uptake[21]. Thus, although most of our agricultural soils contain several thousand pounds of organic N per acre, N often is the most limiting nutrient for plant growth[2,23].

Because N exists in the soil in many different organic and inorganic N forms, all of which differ in terms of plant availability, it is useful to think of soil N as existing in different soil N 'pools'. The different pools are connected and some N may flow between the different pools. The direction of N flow, and the size of the pools, is likely to differ from field-to-field and from year-to-year. For example, on the Prairies, soil 'zones' (e.g., Brown, Dark Brown, Black, Grey) reflect different levels of soil organic matter. Because the soil organic matter is essentially a reservoir of organic N, different soil zones also differ in terms of the size of the organic N pool. For example, Agriculture and AgriFood Canada researchers[28] reported that levels of SON in the top 15 cm (6 inches) at three different sites in the Brown soil zone of Saskatchewan ranged from a low of 2958 to 4432 kg/ha (2632 to 3944 lb/acre). At sites in the Dark Brown and thin Black soil zones, estimates of soil organic N in the top 6 inches were as high as 8036 kg/ha (8036 lb/acre) and 6244 kg/ha (5557 lb/acre), respectively. Clearly, our soils hold a lot of N in organic forms – and the size of the organic N pool is very large relative to the small inorganic N pool that ultimately supplies the crop with N. How active is this enormous pool of inorganic N and how much organic N will flow to the crop?

Inorganic N can flow out of the organic pool if the conditions favor microbial decomposition of the soil organic matter – a process known as "N mineralization". It is estimated that 1 to 3% of the soil organic N mineralizes and becomes available for plant uptake each year[24] although some research has suggested that even more than 3% may be mineralized[28] (Table 1). Variations in the estimates of soil N release reflect not only the impact of different climatic and soil conditions that influence annual N release, but also the nature (i.e., quality) of the organic N pool itself.

Table 1. Estimates of organic N pool in Saskatchewan and potential release of N from the organic N pool in the 0-6 inch (0-15 cm) soil depth (assuming only 1% of the soil organic N mineralizes) (adapted from Rostad et al., 1993, Organic Matter Content of Saskatchewan Soils).

Soil Zone	**Organic N Pool (lb/acre)**	**Potentially available N (lb/acre)**
Brown	2200-2800	22-28
D. Brown	2500-5000	25-50
Black	3800-8700	38-87
Grey	2600-7700	26-77

Estimating Plant Available N

Interestingly, although, labile fractions of the soil organic matter are an important pool of potentially available N to a growing crop[22], soil testing labs in western Canada and the Great Plains region of the USA historically have based fertilizer recommendations on a single pre-plant soil nitrate test (i.e., the inorganic N pool) to account for the carryover and contribution of mineral N from previous cropping[17] and either ignore or only estimate the N contribution from the organic N pool. More recently, some of the soil testing labs have either introduced, or are in the process of adapting, measures of potentially available N for routine soil testing purposes. Ideally, a soil test for N should provide both a measure of available inorganic N pool together with a measurable estimate of the potential supply or flow of N from the organic N pool that is likely to occur during critical crop growth stages. The challenge is to identify a specific soil N pool that mineralizes rapidly and predictably, and is directly related to crop responses to fertilizer N additions[25].

Over the years, numerous soil N availability estimates, based on either biological or chemical principles[2,24], have been proposed. Because many of the methods used to estimate N availability measure, in part, the release of N from some component of the soil organic matter pool, various estimates have been found to be closely related to total soil organic matter and total soil organic N[24,54]. Stanford and Smith (1972) developed a biologically based, long-term incubation method whereby potentially mineralizable N is estimated using various mathematical models[46,30,6]. Incubation methods are time-consuming, and thus more recent research has focused on the development of more rapid chemical extraction methods for estimating potentially available N, such as the hot KCl extraction[10,45,18,4] and phosphate-borate buffer[10] methods. Anion exchange membranes also have been used to estimate soil N availability[55] and this technology has been commercially developed (e.g. PRS™-probes). Very recently, Khan (2001) described a diffusion method (commonly known as the ‘Mason Jar Method’ and the ‘Illinois N Test’) to determine different forms of N in soil, one of which (i.e., amino sugar N) was closely related both with check yield and fertilizer N response[31]. All of these methods share a common characteristic in that they measure the ‘potential’ for N release and do not provide an absolute or direct measure of N release. The latter is dependant on microbial activity that, in turn, is subject to the vagaries of weather – most importantly precipitation and temperature – and thus is expected to be highly variable. The question is, if we can estimate the size of the ‘potentially’ available N pool, can we ‘guesstimate’ N release given that we also have to account for differences in weather, to name but one important and unpredictable factor?

Factors Influencing N Release

During decomposition organic materials, including above and below-ground crop residues, are initially colonized by a variety of soil microbes and the feeding activity of the organisms serves to break up and reduce the size of these materials to the point that the original material becomes unrecognizable. Microbial activity, and consequent decomposition of organic matter and N release, is controlled largely by climatic factors such as temperature and precipitation[11,29] although soil properties such as soil moisture, total soil N, soil organic C, pH, clay content, pore size distribution and pore volume, and microbial biomass also are important[16,12,1,8]. The landscape itself also influences soil properties (particularly moisture redistribution), thereby influencing decomposition and N release[34,35,36]. Bottom line – anything that is likely to affect the survival or activity of the soil microorganisms is also likely to affect N release, one way or another.

Soil Moisture and Temperature

Ellert and Bettany (1992) suggested that soil moisture and temperature are the most influential factors affecting mineralization rates in soil. When soils dry out, microbial activity is reduced due to a reduction in the size of the microbial populations as well as reduced access to organic materials and nutrients that normally are dissolved in the water held in soil pores[33]. Conversely, in saturated soils, the microbial population can be oxygen-starved because water fills pores that normally would be filled with air[33]. The impact of these changes on soil N status is not necessarily easy to predict. For example, Carleton et al. (2004) reported that drought conditions actually increased soil N fertility and suggested that increases could be related to the fact that drought killed a large part of the soil microbial population, which in turn was decomposed to release N into the inorganic pool. While N was being released from dead microbes, the soil was too dry to support plant growth and thus the released N tended to accumulate in the soil.
To add to the complexity, the impact of soil drying can vary dramatically within a field depending on differences in soil pore sizes[5]. Large soil pores (such as those typical of lighter textured soils) tend to empty quite rapidly compared to small pores (such as those in clayey soils) and thus microorganisms in the larger pores might feel the affects of soil drying faster than those inhabiting smaller pores. Thus pore size and distribution as related to variations in soil texture would be expected to have an affect on the variability of N mineralization within a field[5] and this variability may be heightened under moisture stress conditions[5,43].

MacDonald et al. (1995) studied the effect of temperature on microbial activity and N mineralization and found that accumulation of released N increased with increasing temperature. It was suggested that because the microbial population is temperature sensitive, changes in soil temperature can affect decomposition and N release[29]. Although significant microbial decomposition can occur at temperatures as low as 0 ^{o}C, the maximum decomposition rate often has been reported to occur between 30 to 35 ^{o}C[48]. Finally, temperature must be considered together with the impact of moisture[26]. Research indicates that the effect of moisture is even greater as temperature is increased[26,37].

Soil Texture

The influence of soil texture on N mineralization is primarily related to clay content and, to some degree, the kind of clay present[1,8,42]. Soil texture influences soil pore size and soil water storage[42]. An example of the importance of soil texture on microbial activity is illustrated by the relationship between soil clay content and soil organic matter content across the Great Plains. Specifically, soils containing higher clay content typically also contain higher organic matter levels relative to lighter textured soils, assuming that all other factors are held constant[3]. It is generally agreed that coarse textured soils have a more active microbial population and organic matter is more available for mineralization than soils of finer texture[1,8,42].

Soil organic matter in coarse textured soils appears to be more easily decomposed, whereas in finer textured soils, the complex soil structure provides greater protection to the soil organic matter, thus reducing decomposition[8]. As clay content increases, the potential to 'protect' organic matter from decomposition also increases[38,51,52].

Pore Space and Soil Compaction

Soil compaction reduces the proportion of large pore spaces and increases the relative proportion of small pore spaces[1]. Given that organic material in the smaller pores is more protected from microbial attack than in larger pores, it follows that the proportion of organic matter that is protected increases (and mineralization decreases) as pore size decreases. Unfortunately, the relationship between pore size and decomposition is not entirely straightforward. Scott et al. (1996) suggested that while small pore spaces (typical of clayey soils) protect organic matter from microbial attack, really large pores will dry too quickly to facilitate N mineralization. Medium size pores allow microbes access to organic matter and retain water under dryer conditions. Thus, medium size pores are the most important to mineralization and their loss under soil compaction is the most serious. Strong et al. (1999a) agreed with this point of view but also pointed out that in some instances large pores can protect organic matter because they do not regularly fill with water. Thus, these pores cannot be easily accessed by microbes and decomposition may be severely limited. The bottom line – the tendency for pore size to promote decomposition, or alternatively to protect the organic matter from microbial attack, depends on how the pores influence soil water status.

Residue Inputs

Residue decomposition and subsequent release of N from the residue depends on the 'quality', or chemical composition, of the residue. Residues typically are comprised of three fractions: 1) easily decomposable materials; 2) slowly decomposable materials; and 3) materials that are relatively resistant to decomposition[53]. Each of these different fractions are expected to have different decomposition rates, e.g., easily decomposable materials may be decomposed and lost within a few hours to a few days whereas more resistant materials can persist for many years[33]. Differences in decomposition largely reflect the differences in the chemical composition of the materials and it is the N concentration in the plant material, or more specifically the ratio of carbon (C) to N (C:N ratio) that is most frequently recognized as the best predictor of N mineralization rates.

The C:N ratio of crop residues is dependent on the type of crop, length of growing season, soil fertility and environmental conditions, and thus is somewhat variable. Typically, however, the C:N ratio of fresh pulse residue ranges from 25:1 (i.e., 25 parts carbon to every 1 part N) to 40:1[47]. A notable exception is chickpea residue that has a reported C:N ratio of 60:1 to 70:1[9].

The C:N ratio of cereal straw ranges from 70:1 to 100:1[47]. Reported C:N ratios of canola residue are intermediate between pulse and cereal residue[56].

The relative amounts of C to N in the organic matter have a great influence on the available N status of the soil and once again we see that this is due to the activity and requirements of the soil microorganisms. The reason microorganisms attack and decompose crop residues is because the microbes are using the residues as 'food'. Just as we digest our food in order to absorb nutrients and energy, microbes decompose crop residues for energy and nutrients. The C (carbon) in the residues is used for energy and as building blocks for building new microbial structures. However, in order to use the C, the microbes also need a source of N (nitrogen); moreover, microbes require C and N in quite specific proportions. If there is not enough N in the crop residue itself to meet the specific microbial demands, the microbes will use up the inorganic N held in the soil solution, thus leading to a reduction in the amount of N available for uptake by the crop. The process whereby microbes use up N from the soil solution, thereby reducing crop available N, is called 'immobilization'. It is typically reported that a C:N ratio greater than 20:1 to 30:1 will result in rapid immobilization of N from the inorganic N pool; thus wheat residues (C:N ratio of 70:1 and greater) typically cause N to be temporarily immobilized, or tied-up, by microbes. As a consequence, fertilizer recommendations are often higher following a wheat crop as compared to a pulse crop (that have lower C:N ratios). In contrast, if sufficient N is present in the organic residues to support microbial (generally C:N ratio less than 20:1 to 30:1), release, or mineralization of the N in excess of the microbial requirements will occur.

The underlying biological principle controlling N immobilization or mineralization relates to the proportion of C and N required by soil microorganisms (Fig. 1). On average, soil microorganisms have an average C:N ratio of 7:1, suggesting that soil microorganisms must take up 7 parts of C for every one part of N. Only one-third of the C used by microorganisms is incorporated into their cells and the remaining two-thirds is used as an energy source and is respired as CO_2. Thus, microorganisms must find about 21 parts of C for every part of N assimilated. As a consequence, if the C:N ratio of the crop residues exceeds the ratio of approximately 21:1, N must be accessed from an external source (i.e., the soil inorganic N pool) and plant available N is reduced. In contrast, plant materials with a lower C:N ratio (i.e., approximately less than 21:1) will meet all the N demands of the microbial biomass and excess N will be released, or mineralized and N will flow from the organic into the inorganic N pool.

Management Practices

Typically long-term use of conservation tillage leads to a buildup of organic residues at or near the soil surface[15]. Various researchers have concluded that decomposition is hastened when crop residues are incorporated as compared to when they are maintained on the soil surface due to greater soil-residue contact, a more favorable and stable microenvironment for decomposition, and increased availability of N for decomposing microorganisms[15].

Interestingly, although the size of the organic N pool often increases with adoption of conservation tillage, this pool also tends to lock up N and, in some cases, additional fertilizer N may be needed to balance the C that also is locked up in the soil[27]. The reason C and N are both locked up in the soil together relates back to the fact that the soil microbes incorporate both C and N into their structures in fairly specific proportions and these proportions are maintained in the soil organic matter itself. Thus, conservation tillage practices that increase soil organic matter will necessarily increase the storage of soil organic N. For example, in the Brown soil zone of Saskatchewan, researchers reported that conservation tillage increased soil organic N levels, as compared to conventional tillage, by varying amounts from 16 to 28 kg/ha/year (14 to 25 lbs/acre/year)[28]. Soil N storage was even greater in the Dark Brown soil zone (31 lbs/acre/year) and was greatest in the Black soil zone (36 lbs/acre/yr).

Rasmussen et al. (1998) reported that that where tillage is used, the type of tillage equipment appears to affect N mineralization, likely due to the impact of tillage on soil disturbance and ultimately, the soil microorganisms. Sweep-tilled soil appears to mineralize the most N compared to disc and plow-tilled soils.

Conclusion

Nitrogen cycling and release is a highly dynamic process that is dependent on microbial activities. Soil microorganisms are, in turn, controlled by many different factors including climate and variable soil conditions. As a further complication, no single climatic or soil factor solely controls N-cycling – rather these factors act together and can be inter-related. Thus, even if we can measure the size of the 'potentially available' soil N pool (and current research suggests that we can do a reasonably good job), whether or not this N potential is reached remains dependent on a host of interacting factors, which can vary from year-to-year and field-to-field. Ultimately, there will always be a level of uncertainty regarding N fertilizer requirements, even if we expand our soil testing efforts to include measures of both the inorganic N pool (i.e., nitrate-N) and the organic N pool (i.e., potentially available N). However, this level of uncertainty does not negate the value of soil N testing, nor should we abandon soil testing for predicting N fertilizer requirements. Soil testing clearly measures pools of N that are, or will be, available for plant use and this information is of great value when planning fertilizer N applications. However, we need to be realistic about our expectations regarding soil N testing for predicting fertilizer N requirements and understand that any estimates of fertilizer N requirements are subject to the vagaries of weather.

The bottom line – irrespective of what pool of N we measure or estimate, fertilizer N recommendations will always have an element of 'guesstimating' involved. The guesstimates are likely to be built in to fertilizer recommendations by the soil testing labs themselves, i.e., as components of the equations that are used to generate fertilizer N recommendations, but a good agronomist can help with interpreting soil N test levels. For example, an agronomist may question whether or not conditions were average during the previous growing season, or if there were factors that may have strongly influenced decomposition processes and consequently influenced fertilizer N requirements. Thus N recommendations based on soil N tests that, at first glance, may seem 'unreasonable' may well be explainable if the history of the field is known and consideration to microbial processes is given. Applying our knowledge of potential flows between soil N pools can help us understand soil test reports and N recommendations, and help us fine-tune our 'guesstimates' of future crop N requirements.

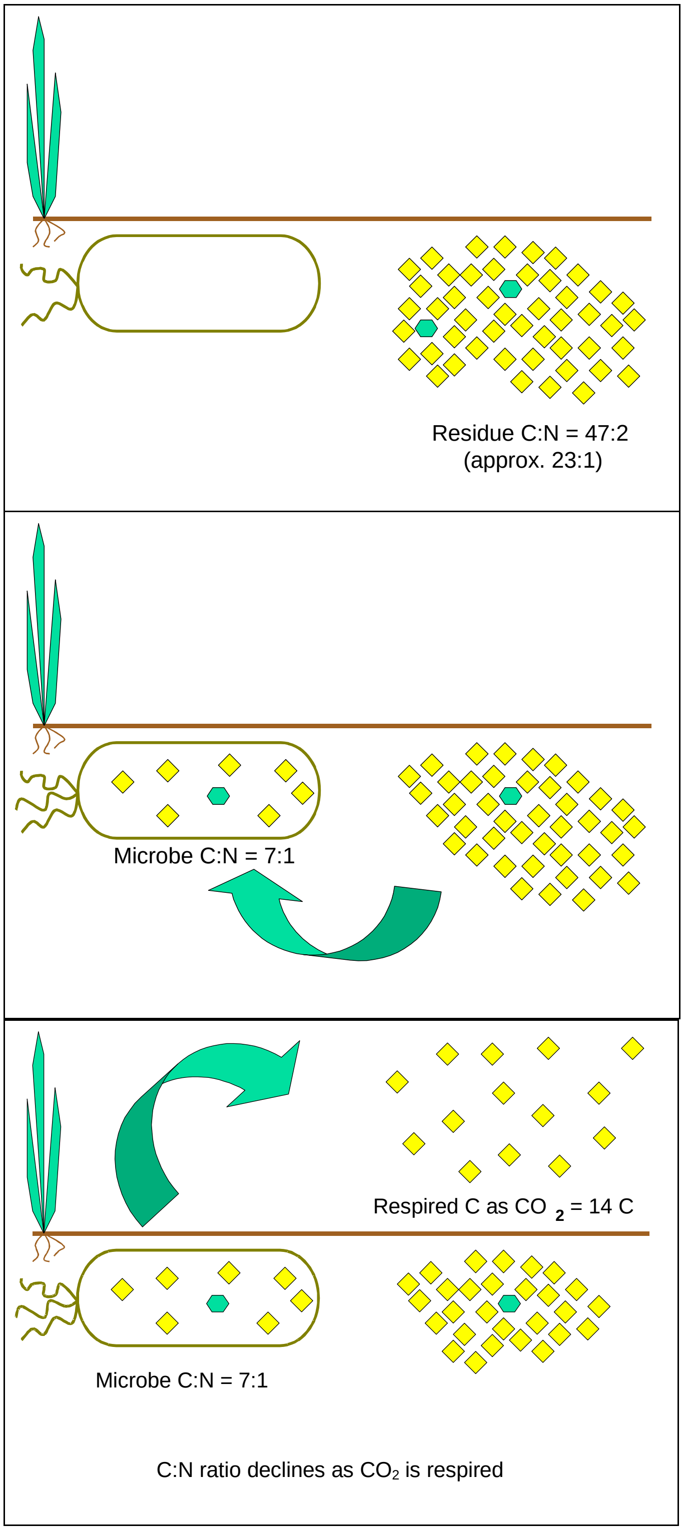

Figure 1. Residue carbon is used to 'build' soil microorganisms and as a source of energy. Some C is lost as respired CO_2, resulting in a decline in the C:N ratio of the newly added organic materials. Once the C:N ratio has declined to approximately < 21:1, N will be released or 'mineralized'.

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