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Re-thinking soil nitrogen availability to crops in the context of soil organic carbon

Keith Reid[a], **Craig F. Drury**[b], **David Burton**[c], **and Pamela Joosse**[d]

[a]Guelph, ON, Canada; [b]Science and Technology Branch, Agriculture and Agri Food Canada, Harrow, ON, Canada; [c]Department of Plant, Food, and Environmental Sciences, Agricultural Campus, Dalhousie University, Truro, NS, Canada; [d]Science and Technology Branch, Agriculture and Agri Food Canada, Guelph, ON, Canada

Corresponding author: **Keith Reid** (email: dkeithreid10@gmail.com)

Abstract

The link between carbon and nitrogen (N) in soil organic matter has long been recognized but has been largely ignored in determining the supply of N from soil for crop production. We propose that N mineralization can only be understood as a by-product of soil organic carbon (SOC) change and that progress in improving N use efficiency by crops must explicitly include consideration of SOC. This suggests some immediate avenues for improved fertilizer N management as well as future research activities. Recent advances in understanding the various fractions of soil organic matter and their role in C cycling have great potential for improving our understanding of N cycling in the soil as well, and the potential for N release that could be utilized by crops.

Key words: nitrogen mineralization, soil organic carbon, nitrogen fertilizer rates, nitrogen management

1. Introduction

Providing an adequate supply of nutrients, including nitrogen (N), is key to maintaining economic yields of grain, forage, or fiber crops. Supplemental N fertilizer is an integral component of crop production, particularly for nonleguminous crops, with estimates that the world would require up to four times the crop area to generate current production without the use of N fertilizer (Smil 2011). It is also important to note that N availability is an important regulator of how much carbon is fixed by the crop through photosynthesis and therefore an important determinant of the potential to convert carbon dioxide from the atmosphere into plant biomass, part of which will contribute to soil organic matter (SOM). The use of N fertilizer, however, comes with both economic costs and environmental risks so there is a critical need to maximize the efficiency of N use. One way to improve N efficiency is to account for the supply of mineral N from the organic N pool in the soil (N mineralization).

The apparent goal of accounting for soil organic N mineralization has been to identify the opportunity to replace supplemental N fertilizer with N being supplied from the soil. Significant effort has been expended to account for the contribution of soil organic N for corn (e.g., Melkonian et al. 2008; Zebarth et al. 2009; Nyiraneza et al. 2012; Dharmakeerthi and Kay 2013; Stoeckli et al. 2021), potatoes (e.g., Zebarth 2011; Dessureault-Rompré et al. 2012; Moulin et al. 2012), vegetables (Fink and Scharpf 2000; Chahal and Van Eerd 2020), and wheat (Chen et al. 2006), but the accuracy of prediction tools has been relatively low (Dessureault-Rompré et al. 2010). As a result, N mineralization from SOM is often not quantitatively considered in determining supplemental N fertilizer application rates, although some jurisdictions (e.g., Ontario Ministry of Agriculture Food and Rural Affairs 2017) include an empirical factor for soil texture, which is conjectured to be related to the soil organic carbon (SOC) content of the soil.

A key missing piece to this puzzle has been that these studies have been carried out without considering the inextricable link between N mineralization and SOC. A recent paper by Daly et al. (2021) begins to address this issue but the discussion is limited to cycling occurring during the time when plants are actively growing. The broader context of N and C stoichiometry over multiple years is ignored, as there is no accounting for the N removed in the harvested portion of the crop, C and N returned in the nonharvested portion of the crop or tied up in the microbial biomass and the implications of this balance on C and N cycling. The authors do suggest a possible mechanism for tighter cycling of N mineralized from SOM back into organic forms when soil mineral N concentrations are limited, with an associated reduction of nitrate leaching, but the quantities involved appear to be much less than crop removal.

If the N requirements of crops are to be met fully or partially from the soil, there are a limited number of sources. In some cases, there will be residual mineral N in the soil, as is commonly the case in prairie environments and occasionally in humid environments. The larger and more consistent source, however, is the mineralization of N from SOM, which is then taken up by crops and either recycled back to the soil with crop residues at the end of the season or removed in the harvested portion of the crop. The decomposition of SOM results in N mineralization at a rate determined by the C:N ratio of the SOM and moderated by soil temperature and moisture contents which in turn influence microbial activity.

It is important to acknowledge the seasonality of N mineralization and immobilization where in most temperate climates there is net mineralization in the early part of the growing season driven by the microbial decomposition of dynamic pools of narrow C:N ratio (<10) SOM, followed by crop uptake of the mineralized N during the summer and finally the net immobilization due the senescence and the return of the typically wide C:N ratio crop residues (roots and shoots) in the fall from nonleguminous plants. It is the wide C:N ratio (>20) of crop residues that causes net immobilization of at least some of inorganic N remaining in the soil in the fall because of N demands of microbial biosynthesis. We now understand that SOM is not a single static pool but is composed of numerous pools ranging from stabilized SOM, which constitutes the largest pool, and several more varying proportions of dynamic or labile pools that remain biologically active. Typically, net N mineralization occurring in the early growing season averages 60–130 kg N/ha for most growing regions in Canada (Cassman et al. 2002; Van Es 2023) but is influenced by soil type, climate, soil management, and cropping system. In most temperate cropping systems roughly 50% of plant N taken up during the growing season is derived from mineralized SOM (Yan et al. 2020) with the remainder provided by supplemental N sources (fertilizer, manure, legumes) and to a lesser degree from atmospheric deposition, and asymbiotic N fixation by soil microbes.

In the absence of a supplemental source of N, the removal of N from the field in grain or forage represents a net export of N. This is a nonequilibrium situation where a portion of the SON has been mineralized but is not returned to the field at the end of the growing season. This will, inevitably, be accompanied by either an outright loss of SOC, or a shift from stable mineral-associated organic matter (MAOM) or microbial necromass (Zhou et al. 2023) to less stable particulate organic matter (POM), which can have a wider and more variable C:N ratio (Lavallee et al. 2020). Previous work on N availability from soil has focused on mineral N without accounting for any changes in long-term stocks of SOC (e.g., Stoeckli et al. 2021; Arrington et al. 2024), or on changes in SOM without considering potential impacts on future N availability (e.g., Peng and Van Eerd 2024). To build or maintain SOC, it is important that sufficient root exudate and crop residue (roots + shoots) carbon is returned to the soil to offset the decomposition of SOM. Failing to do so is counter to current efforts to maintain or improve soil health, of which SOC is a key part.

The release of mineral N into the soil is a by-product from the breakdown of organic matter, so the availability of N for crop uptake from the soil can only be understood as an end product of SOM decomposition. Where N is available from the soil to support significant crop removal, this must have come through the decomposition of SOM but this N availability is a symptom of the conditions that led to this decomposition from soil including:

- Changes in capacity of soil to retain C due to tillage or residue management.
- Weather conditions conducive to SOM decomposition.
- Past accumulation of SOM through additions of organic materials (manure, compost) or deposition of eroded topsoil in the toe slope areas.

We propose that it is the decomposition of SOM that drives the supply of N from the soil, so that improved N management for crops can only be achieved in the context of SOC cycling in the soil. With N mineralization a consequence of SOM breakdown, we must endeavor to manage the N that is mineralized as efficiently as possible to maximize utilization by plants and to avoid loss to the environment and that sufficient organic residues are returned to the soil to maintain SOM. N that is held in organic compounds, either in plant tissue or SOM, is at much lower risk of environmental losses than mineral forms of reactive N (NH_4^+, NO_3^-, NO_2^-). In a way, this is parallel to the dilemma that Janzen (2006) posed for soil carbon, of determining the proper balance between storage, maintaining the stable pool, and utilization, making best use of the N flowing through dynamic pools. Dharmakeerthi and Kay (2013) did attempt to account for the SOC content of the soil, but as a static property which varied across the landscape and not in the context of SOC change.

N management (for annual crop production) will, therefore, operate at two different temporal scales. The first is seasonal, where the rate of release of N from SOM and the existing store of mineral N are considered in the context of the uptake of N by the crop, with a goal of minimized N loss. The goal in this phase is to utilize the N that is released during SOM breakdown as efficiently as possible so as to minimize the requirements for added mineral fertilizers. This will also reduce the risk of excess mineral N in the soil at the end of the growing season, and so helps to minimize the N footprint of crop production. The second phase is the management of carbon rich above and below ground crop residues such that the formation of stable SOM can occur. Within a growing season, N exports from a cropping system will be the sum of N in the harvested portion of the crop and losses from the system through volatilization, leaching, and denitrification. The N for these export pathways will come from N additions (fertilizer, manure, legumes) plus the change in soil organic N over that season, and any exceedance over what is required for crop growth will shift the balance toward N loss pathways, either during the growing season or post-harvest. This annual balance will constrain the maximum efficiency that can be achieved within the seasonal N cycles.

2. A new paradigm for N mineralization from soil

To understand the potential contribution of N mineralization to crop nutrition, it must be considered in the context of the C balance of the soil in which the crops are being grown and the partitioning of both C and N between the harvested

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portion of the crop residue (shoots and roots) left behind. The contribution of mineralized soil N to exports from the field (in harvested yield or environmental losses) can only be understood in terms of changes in SOC. This can be divided into three classes:

- Equilibrium, where the SOC and SON remain unchanged from year to year. Crop uptake of soil mineralized N matches the N returned to the soil as crop residues at the end of the growing season and/or other organic amendments and residual soil inorganic N. The corollary of this is that N from external sources (fertilizer, manure, or legumes) must produce sufficient crop residues to replace the decomposition of SOM, so the N taken up by the crop but not removed in the harvested portion is returned in primarily organic forms. In this scenario, losses through volatilization, denitrification, and leaching during the growing season will directly reduce the N available to support crop growth; some of these losses are inevitable but management to minimize them will provide tangible benefits.
- Degrading, where SOC is decreasing and the return of crop residue C is not sufficient to offset SOC decomposition. Surplus N is released from the soil that can wholly or partially offset N fertilizer requirements but can also contribute to N losses from the field. If this surplus N is not accounted for in crop nutrition programs, the result will be excess mineral N in the soil that is susceptible to losses through leaching or denitrification.
- Aggrading, where SOC is increasing because of the return of crop residues (including root exudates) and/or organic amendments more than offsetting SOM decomposition. There will be net N immobilization by the soil to match the C:N ratio of the SOM, which can vary significantly between the POM and MAOM fractions of SOM (Cotrufo et al. 2019; Daly et al. 2021; Cotrufo and Lavallee 2022). The main limitation to increasing SOC is the supply of C to the soil under most circumstances, so N immobilization is in response to the accumulation of C rather than a driver. The manner in which the crop residues are managed will also influence the extent to which stable SOM is formed.

In this paradigm, the change in SOC stock is recognized as a key driver in the supply of N from the soil to crops. Under equilibrium conditions, soil N is cycled into the crop and then back into the soil at the end of the growing season. A wide C:N ratio crop residue drives the immobilization of inorganic N remaining in the soil and thus reduces N loss. External N inputs must produce sufficient crop biomass or organic matter being returned to the soil such that the N returned to the soil and inorganic N immobilized as a result of C addition is equivalent to the N mineralized during the growing season. Further proper soil management (crop residue management and reduced soil disturbance) should be implemented to ensure SOM is formed. These external inputs may be in the form of mineral fertilizer, livestock manure, biological N fixation (symbiotic or nonsymbiotic), or atmospheric deposition, but ultimately they must result in sufficient crop residue C and N return to balance N mineralization.

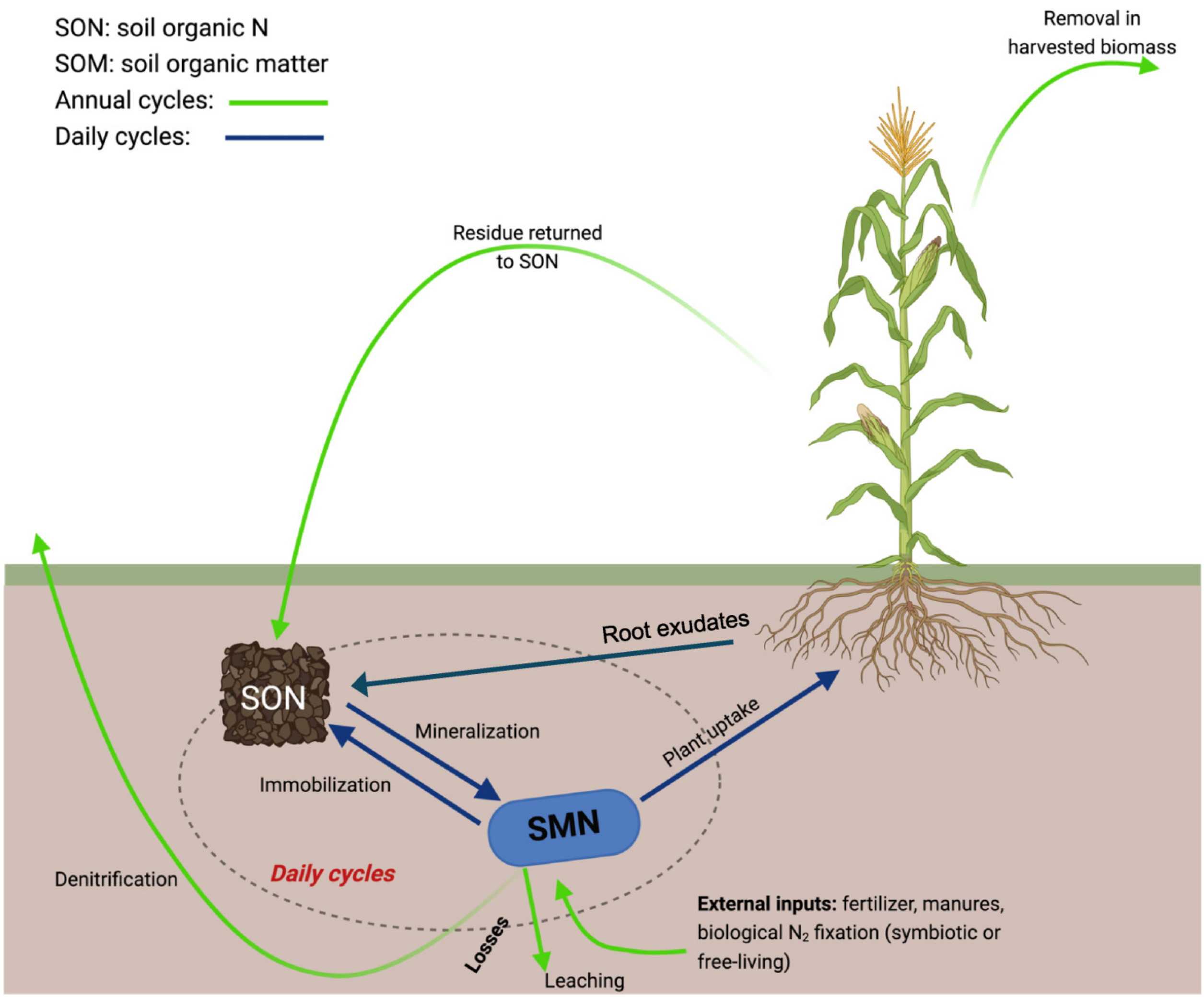
The conditions for significant N release from the soil to support N removal in crop yield will only occur where SOC is present in the soil at concentrations greater than equilibrium; the release of carbon dioxide during breakdown of organic matter will result in N mineralization. These conditions existed when the prairies were first plowed, as the equilibrium SOC content under annual crops was much less than in undisturbed grassland. As these soils approached equilibrium, the N fertilizer requirements increased to account for the subsequent decrease in mineralization. Voroney et al. (1981), for example, predicted annual N mineralization rates of a Chernozem in Saskatchewan to be 143 kg N ha^{-1} for the first 20 years following initial cultivation, declining to 7 kg N ha^{-1} after 80 years of cultivation. This reduction in N supply is exacerbated by the increased N uptake and harvest index (reducing C and N returned to the soil) of improved varieties. As more C and N are being removed in harvestable portions of the crop, less is being returned to the soil.

Fields that have been under cultivation long enough that SOC would have declined to stable levels can still exhibit temporal variation where SOC concentrations exceed equilibrium for parts of the rotation, or spatial variation where part of the landscape is above equilibrium levels. Rotating to forage crops or applying large amounts of organic materials to the soil, can temporarily maintain the soil in degrading category as a result of the amendment when the fields are returned to grain crop cultivation. Redistribution of SOM into depressional areas by soil erosion can also raise the SOC above equilibrium concentrations. Neither of these variations represent sustainable sources of N for crop production in the long term but ignoring the net N mineralization that will occur will result in over-fertilization, wasting resources, and increasing environmental losses.

The sequestration of N in SOM when it is aggrading has been largely ignored, although it should be considered when the N use efficiency of cropping systems is assessed. Although it is important to note that often this amount is small relative to the N losses that are occurring from the system and N sequestration by SOM would be difficult to measure on a short-term basis (annual), fraught as it is with the same spatial and temporal variability as SOC.

There are barriers to the practical application of this new paradigm for fertilizer recommendations. The changes in SOC that match an agronomically meaningful amount of N release are unlikely to be detectable above the normal variability in SOC concentrations and in-field variation in N loss. Determining which C balance class a field belongs to is more likely to be a matter of modelling rather than measurement, and the N supply from the soil (i.e., N mineralization potential) may be one tool that informs the modelling of SOC balance. Nonetheless, it is worthwhile to consider the implications of the link between SOC dynamics and N availability to crops at both seasonal and annual scales (see Fig. 1). It may, at least, help us to differentiate between circumstances when we may or may not expect to see significant net N mineralization from the soil, and to place boundaries on how much N mineralization we could reasonably expect to see.

Fig. 1. Nitrogen transformations occur at both short (daily or seasonal) and long (annual or multi-year) scales. These cycles require different management approaches, but they should not be treated in isolation. Figures created in BioRender. Farrell (2025) https://BioRender.com/0qbgnki. SMN, soil mineral N.



3. Contrasting goals of N management at different temporal scales

3.1. In-season N management

Within the growing season, N management should focus on identifying and utilizing the mineral N resource in the soil as efficiently as possible, followed by supplementing that resource with appropriate rates of N fertilizer at optimum times. Future improvements in this area will require a combination of implementation of existing N management practices plus research to operationalize new techniques for predicting N release from SOM, as follows:

1. Account for available soil mineral N (SMN) from soil tests. This is commonly practiced in prairie environments with fall soil samples, where nitrate remaining in the soil after the harvest of annual crops is more reliably retained until the following spring (e.g., Malhi et al. 1985) as a result of the low rainfall and low leaching or denitrification losses. It also is considered in more humid environments using a planting time or pre-sidedress nitrate test (Stoeckli et al. 2021).
2. Determine net mineralization of N from SOM, after accounting for losses between N release and crop uptake. This may be accomplished from mechanistic modelling of soil processes (e.g., Melkonian et al. 2008) or by empirical methods based on early growing season rainfall and temperature (e.g., Kay et al. 2006; Tremblay et al. 2012). There are significant challenges to these estimates, since they may depend on estimates of soil properties to a high level of precision, or the soil measurements available (e.g., SOC) may not match the parameters that are most relevant to mineralization (e.g., proportions of POM and MAOM (O'Rourke et al. 2015)). These estimates may also overlook the influence of spatial variability in soil properties, so a field-average prediction may over- or underestimate the amount of N release from different landscape positions. Further, the accuracy of the estimates may depend on predictions of weather for the period following N application.

Pedo-transfer functions have been developed to reflect the influence of soil type, landscape position, and cropping system on growing season N mineralization (Laurance et al. 2024*a*, 2024*b*). As N supply from the soil is more precisely accounted for in fertilizer programs, the estimation of in-season losses of N through volatilization, denitrification, and leaching also become more important so the crop is not left short of N.

3. Match fertilizer rate and timing to meet crop needs while minimizing the lag time between fertilizer application and crop uptake. Improved timing reduces the risk of N losses to the environment before it is utilized (Drury et al. 2024) but predicting the crop N uptake remains challenging since the growth potential of the crop is not fixed at the time of fertilizer application and can significantly impact the N requirements of the crop (Niemeyer et al. 2021).
4. Consider crop residue management to ensure (i) sufficient crop residues are being returned to the soil to immobilize residual soil N and maintain SOC levels and (ii) that the management of these crop residues is maximizing the potential for the immobilization of residual soil N and formation of SOM.

These management practices assume that the supply of N from the soil will occur independently of N fertilizer applications, so accounting for this N is sensible both economically (optimizing fertilizer investment) and environmentally (reducing residual soil N at the end of the growing season). The long-term sustainability of the soil N supply, however, can only be understood in the context of annual C and N balances and soil management.

3.2. Annual N management

It is only after the crop harvest has been completed that the overall N balance of the cropping year can be evaluated, by comparing the N removal in the harvested portion of the crop to the N fertilizer applied plus the spring SMN with the residual mineral N remaining in the soil after harvest. This evaluation may be done on a whole-field basis, or with combine yield monitor data it can be done by landscape position or management zone. Observations of crop removal equaling fertilizer N applications imply (but do not guarantee) that SOC levels in the field are stable, although the same observations could mean that net N mineralization has been balanced by N losses. There may also be situations of SOC equilibrium at crop maturity but continued mineralization after harvest. If SMN accumulates after harvest, there is significant potential for over winter loss of N via leaching and/or denitrification. Discerning these conditions may be subtle but much clearer signals will be present where there are wide discrepancies between N fertilizer and crop uptake.

1. When crop uptake and removal of N is much greater than fertilizer N application, this implies that declining SOC has led to significantly more N mineralization from the soil than has been returned in the unharvested portion of the crop. This situation requires assessment of what conditions created the release of mineral N from the soil, and the need for management changes to address potential future loss of soil carbon and soil quality:
   a. This may be a natural part of a crop rotation, where SOC is built during one phase (e.g., rotation to perennial forages) and then declines during the grain crop phase. If the long-term balance is maintained, no further action is needed.
   b. There may be significant spatial variation, where topsoil high in organic matter has been deposited at footslope positions from water or tillage erosion, leading to high levels of N mineralization in these areas. This presents opportunities for variable rate fertilizer applications to take advantage of the N availability, but also indicates that tillage management should be addressed to prevent loss of productivity in the upper and midslope positions.
   c. Consider that the crop residue management and soil disturbance practices associated with the cropping system may be causing declines in SOC, that could impact soil health and future crop productivity. Determine if this is cyclical pattern of aggradation and degradation over a crop rotation or if it is an ongoing loss of SOM that should be addressed.
2. Fertilizer N application is much great than crop removal. It is possible that some of this N may be sequestered in SOM, but this will depend on the availability of wide C:N ratio organic matter (crop residues) and will only account for a small amount of N at the rate of SOC accumulation documented under ideal conditions. Mineral N that has not been incorporated into plant tissue or SOM has a high likelihood of being lost to the environment through NH_3 volatilization, N_2O and N_2 emissions, and nitrate leaching, so assessing the potential pathways and opportunities for increasing N use efficiency should be explored. These actions will also be economically beneficial.
   a. Catastrophic crop loss from hail, frost, or severe drought or flooding will create an excess of N supply. This is not amenable to N application management but may be a situation where actions to "soak up" the SMN such as cover crops or a fall planted crop such as winter wheat or winter canola should be considered.
   b. Over-application of N fertilizer, including organic N inputs (e.g., manure, compost, biosolids), may stem from failure to account for the inherent supply of N from the soil or from organic amendments (e.g., manure), or from unrealistic yield expectations. All of these should be addressed in setting N fertilizer rates.
   c. Fertilizer or manure application methods or timing may be leading to avoidable losses of N through volatilization, leaching, or denitrification. Changes to fertilizer management could increase the proportion reaching the crop (Drury et al. 2024).

Improved N management at the seasonal or annual time scale may be beneficial under most circumstances, but there will always be exceptions. Fields that are in the equilibrium or declining classes may mineralize sufficient N over the season, but the mineralization timing may not match crop requirements due to variability in weather conditions

(Melkonian et al. 2008; Dessureault-Rompré et al. 2010). N that is applied or released before there is adequate capacity for N uptake, such as prior to planting or at planting, will be subject to losses by leaching or denitrification. Delayed N mineralization, in contrast, may result in reduced crop growth, and possibly to increased concentration of mineral N in the soil at the end of the growing season which in turn may be lost as NO_3^- through leaching or tile drainage during the late fall, winter or early spring periods (Drury et al. 2014; Woodley et al. 2018) or denitrification (Badewa et al. 2022).

4. Conclusions

As SOM breaks down during the growing season, N will be released as a byproduct and failure to account for this release will increase the potential for N losses. Accounting for the SOC balance and seasonality of N mineralization predictions will remove one source of variability, and so should help to improve estimates of N availability from the soil. Consideration of the amount, composition, and management of crop residues and/or the planting of cover crops will help to conserve residual soil N. It will also shift the mindset regarding soil N from a linear extractive perspective of soil N management to circularity by implicitly including the annual cycles of C and N from soil to vegetation and back again. Ultimately, this should improve the descriptions of N flows through agroecosystems and allow better management of N and minimization of N losses to air and water.

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Author information

Author ORCIDs

Keith Reid https://orcid.org/0000-0001-8346-3614
David Burton https://orcid.org/0000-0003-0515-2102

Author contributions

Conceptualization: KR
Writing – original draft: KR
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