Science Societies

Soil carbon needs 4R nutrients

Why greenhouse gas mitigation depends on sound nutrient stewardship

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The application of nutrients, particularly N, is associated with greenhouse gas emissions. Thus, if we are going to apply N inputs to enhance the capacity of a system to store N in the soil, a full analysis of the greenhouse gas balance is needed. Photo courtesy of Adobe Stock/chas53.

> The use of 4R practices to manage nutrients is critical to support crop photosynthesis and make soil carbon storage an effective proposition for greenhouse gas mitigation. What is required is a delicate balancing act. Increasing primary productivity, reducing wastes, selecting climate-smart sources, and using inhibitors of N_2O emissions are all critical. The strong role of N in the multiple mechanisms of soil C storage underscores the need for integrated consideration of 4R nutrient management in programs that address both the emissions and sinks associated with cropping systems while keeping them productive.

For soils to sequester carbon (C), carbon dioxide (CO_2) must be drawn from the air. Plants normally do this. In fact, it's plant photosynthesis that limits the amount of C available to be added to soils. The use of 4R practices to manage nutrients is critical to support crop photosynthesis and make soil C storage an effective proposition for greenhouse gas mitigation.

The importance of photosynthesis to soil C storage is underscored by research in Montana in which the soil C increase over 10 years was related more strongly to cropping system intensity than to tillage and most directly to net primary productivity and total C inputs. In those studies, maintaining soil organic C levels required a net primary productivity (that is, the total amount of C taken into plant biomass) of 3 tons/ac/yr of C and 1 ton/ac of total C inputs left in and on the soil (Engel et al., 2017). Building or storing more C in the soil would require yet higher levels of productivity.

Nitrogen (N) is involved in two ways. First, since it often limits plant growth, applying it can increase photosynthetic production of organic material that can be added to soils. After all, each molecule of chlorophyll contains four atoms of N, and the enzymatic machinery of the photosynthetic process involves a lot of protein. Second, most of the forms of organic C we add to the soil contain N that is ultimately retained in soil organic matter. So building soil C requires N. This was confirmed at four long-term sites in Iowa (Poffenbarger et al., 2017) as shown in Figure 1.

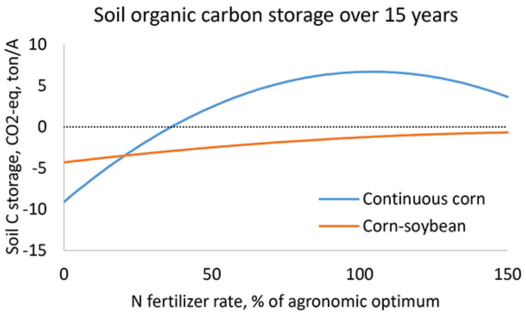

Figure 1, *Agronomic optimum N fertilization is critical to maintain or increase soil organic carbon. Adapted from Poffenbarger et al. (**2017**).*

One aspect of greenhouse gas emissions is good for photosynthesis. The enhanced concentration of CO_2 in the atmosphere stimulates faster photosynthesis. A recent analysis suggests that from 1981 to 2020, this form of "CO_2 fertilization" increased global photosynthesis by 12% (Keenan et al., 2021). But the rise in CO_2 has led to increased nutrient limitation. It has been estimated that 18% of natural land is significantly limited by N and 43% by phosphorus with the rest either co-limited by both or only weakly nutrient limited.

Do Nutrients Limit Soil Carbon in Agriculture Too?

That analysis covered mostly natural ecosystems. Do nutrients limit soil C in agriculture too?

Reviews of many long-term studies (Kätterer et al., 2012; Alvarez, 2005) have found that when N is applied at rates optimal for crop production, compared with a zero-N check, each unit of N applied increases soil C by one unit. In CO_2 equivalents, that's 3.7 tons per ton of N. A zero-N check, however, is not a real-world scenario since farmers usually don't grow crops without applying N unless the crop is a legume. That number represents what N is doing for soil C in a well-managed cropping system, but since that's business as usual, don't expect carbon credits to be sold on that basis.

Another issue is that the application of nutrients, particularly N, is also associated with greenhouse gas emissions. If we are going to apply N inputs to enhance the capacity of a system to store N in the soil, a full analysis of the greenhouse gas balance is needed. The source needs to be "climate smart." We need to account for the emissions generated in making the product (mainly CO_2) and those arising from use of the product (mainly nitrous oxide, N_2O). That might also include the CO_2 generated when the urea molecule hydrolyzes to release ammonia. How do those emissions compare to the enhancement of the soil C sink?

In the national inventory reports on greenhouse gas emissions from Canada (ECCC, 2022) and the United States (USEPA, 2022), the N_2O emissions attributed to current (2020) fertilizer use amount to 3.3 and 5.7 tons CO_2eq per ton fertilizer N, for the two countries, respectively. The differences between the two countries arise partly from the greater dominance of a semi-arid climate over Canada's cropland and from differences in methodologies. Neither country accounts for the use of 4R practices in these estimates; emissions from fertilizer are assumed proportional to the rate applied in each different production area. Thus the well-established benefit of nitrification inhibitors and controlled-release forms in reducing N_2O emissions (Thapa et al., 2016; Maaz et al., 2021) is not reflected in the inventories. For both countries, the CO_2

emission associated with urea use is assumed to be 1.6 tons CO_2eq per ton of urea-N. Selected categories of these national inventory reports relevant to nutrient application are shown in Table 1.

Table 1. Comparison of emissions (million tons of CO_2eq) attributed to selected components of agricultural cropping systems in national greenhouse gas inventory reports for Canada (ECCC, 2022) and the United States (USEPA, 2022)

	United States		Canada	
	1990	2016–2020	1990	2016–2020
Nitrous oxide emissions				
— Agricultural soil management	348	348	12	21
— Manure management	15	21	4	4
— Organic fertilizer, direct and indirect	35	35	2	2
— Synthetic fertilizer, direct and indirect	80	91	6	13
Carbon dioxide emissions				
— Urea and lime use	8	8		3
— Cropland (soil C sink if negative)	−26	−22	0	−18

Adding on the emissions associated for fertilizer manufacture, it might seem that in the current situation, applying a ton of fertilizer N generates more emissions than the 3.7 tons CO_2eq that it contributes to the soil C sink. Can this balance be changed?

The Challenge of Managing Cropping Systems as CO_2 Sinks

It's a huge challenge to manage N in a way that enables the cropping system to act as a sink rather than a source of CO_2 and its equivalents. A cropping system with net zero emissions would need to be one in which the soil is accruing C, the nutrients applied are sourced in the best way possible, and applied at the right rates and the right time and place to ensure maximum utilization by the crop. And all of this would need to be in tune with the needs to minimize soil disturbance and maintain a green cover on the soil for the greatest portion of the growing season as is practically possible.

If you are a North American farmer, you are probably already managing your N at rates close to those optimizing crop yields. Are there opportunities to go beyond that? What you'd need to look for are opportunities to extend the period during which the soil is covered by actively growing plants. Can you select longer-duration cultivars that produce higher yields? They likely also contribute more C to the soil—more biomass, more crop residues—even though they may need more N to do so (more per acre, less per unit of production). Is your soil bare in fall or spring? Can you fit cover crops into the rotation that take advantage of sunlight falling on soil that would be bare in their absence? They too may contribute more C to the soil and may require more N to do so (Grove et al., 2009). When soil is bare and sunlight falls on it, it's an opportunity wasted for generating C to store in the soil.

The consideration of N source needs to include manure, but the analysis is more complex. A large part of the greenhouse gas emissions from livestock manure occur before the material is applied to the field. Thus manure sourced from an operation with improved storage and processing may have a lower footprint. Unutilized manure still generates greenhouse gas emissions. It also contains C that could contribute to soil C. Thus utilizing manure that would otherwise be wasted provides a low-emission source of N for soil C storage. But it takes careful management to reduce emissions of N_2O and methane that accompany the storage and application of manure.

Another low-emission source of N is symbiotic fixation within legume plants. Forages like alfalfa and red clover are found on fewer acres today than in the past. Perennials like these contribute greatly to building or maintaining soil organic matter. Cover crops in their place are a small substitute, producing many benefits, but realistically, they are a smaller contribution of C to the soil store. Legumes emit negligible amounts of nitrous oxide in the process of N fixation, but careful management is needed to avoid the large potential emissions that can occur when these crops are terminated.

Global Potential to Increase Carbon Storage

Estimates of the global potential to increase C storage in croplands globally range widely. A recent analysis based on the photosynthetic limit to production of new C on cropland suggested a maximum net soil C sequestration rate of only about 0.7 billion tons of CO_2eq (Janzen et al., 2022). The authors of this analysis rightly argue for broadening the scale of analysis from soil processes to the wider ecosystem processes that start with photosynthesis. The analysis, however, is sensitive to assumptions regarding the ability to increase net primary productivity in farming systems and regarding the decay rates of C in soil. The most recent assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) estimates the mitigation potential of soil C sequestration as 3.9 billion tons of CO_2eq per year—five times as much as its estimate of the potential to mitigate by reducing emissions of both N_2O and methane combined.

Global biophysical soil C sequestration potential has been estimated at 1 to 3 billion tons CO_2eq in cropland, increasing to 5 billion tons CO_2eq when grasslands and agroforestry are included and to as much as 9 billion tons CO_2eq if “frontier technologies” like biochar, perennial cereals, and breeding crops for deeper and larger root systems are included (Paustian et al., 2019). Predicting the potential from bottom-up calculations was noted to involve “staggering complexity and commensurate uncertainty,” and thus has resulted in global estimates that range from 1.5 to 14 billion tons of CO_2 (Janzen et al., 2022).

Many express optimism that by building soil organic matter, crop nutrient requirements will diminish. But counting on soil organic matter to be the source of nutrients to replenish that removed by crops is much like hoping to have your cake and eat it too. A relevant question is: Shall we hoard it or use it? (Janzen, 2006). It makes sense to use the annual mineralization of nutrients to balance what crops need to take up over and above what is to be harvested. That effectively counters mineralization with immobilization. But aspiring to use mineralization to replenish crop nutrients removed from the soil is not consistent with the requirements for storing C in soil.

Achieving goals that have been set for soil C storage will thus require strong attention to the management of nutrients. What is required is a delicate balancing act. Increasing primary productivity, reducing wastes, selecting climate-smart sources, and using inhibitors of N_2O emissions are all critical—as they have been in 4R nutrient stewardship programs since their inception. The strong role of N in the multiple mechanisms of soil C storage underscores the need for integrated consideration of 4R nutrient management in programs that address both the emissions and sinks associated with cropping systems while keeping them productive.

nutrient stewardship

This article is part of a series from The Fertilizer Institute highlighting some of the latest 4R research.

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