Where is Nitrogen Going in Long-Term Cropping Systems?

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Abstract

Fertilizer nitrogen use efficiency (NUE) is normally low, and has led to the idea that a large proportion of N applied as fertilizer is lost from the soil. However, N balances calculated for a long-term rotation study at Swift Current indicate that losses of fertilizer N from the soil are small, and comparison of cumulative N balances with actual soil organic matter measurements show that an overwhelming proportion of this N is cycled through the organic matter, through microbially mediated processes, enhancing the fertility of the soil

Introduction

Given the increases in the cost of fertilizers, there is an increasing preoccupation with the efficient use of fertilizer-derived nutrients by crops. This preoccupation is especially high for nitrogen (N) which is the nutrient used by crops in largest amounts, and the one that most often limits crop yield and quality.

Fertilizer N use efficiency (NUE) is a term normally used to assess the proportion of applied N used by crops. NUE can be estimated either by applying the principle of isotopic dilution in experiments using ^{15}N labeled fertilizers, or by calculating the increase in N uptake by a fertilized crop, in comparison with an unfertilized crop, per unit of applied N (difference method). NUE values reported in the literature cover a vide range, but on average they range from 20 to 50%, depending on experimental and environmental conditions.

These values have been used by groups objecting to the use of synthetic fertilizers to state that from 50 to 80% of fertilizer nitrogen is lost from the soil causing severe environmental damage, and mount well funded and active lobby against the use of fertilizers in agriculture.

Inspection of N cycling in soils reveals that there are reasons for the low observed NUE values. A fertilized crop derives its nitrogen from available soil N present at the time of seeding (soil residual N), and from N mineralized during the growing season in addition to fertilizer-derived N. Concurrently, fertilizer-derived N undergoes transformations in the soil such as immobilization into organic forms, mediated by microbial biomass, from where it could follow a path to more stable organic forms, or re-mineralization. A fraction of available N in the soil, including soil residual N, fertilizer-derived N and N mineralized during the growing season can be lost from the soil through various mechanisms, including denitrification, leaching and gaseous losses of NH_3. Further, NUE calculated by the difference method fails to account for the enhancing effect of fertilization on N mineralization resulting from increased return of plant residues to the soil in fertilized systems (Shen et al. 1989).

Most commonly NUE has been evaluated in short-duration fertilization experiments, where there is little opportunity to verify pathways of transformation and fate of N applied as fertilizer. However, not accounting for a complete N balance of the cropping system provides a biased view of the efficiency of N use by crops.

The objective of this presentation was to present a nitrogen balance of long-term cropping systems conducted in southwestern Saskatchewan, identify sources and losses of N from the system, and to discuss the fate of fertilizer-derived N within these systems.

Materials and Methods

Eight spring wheat rotations and one wheat-lentil rotation from a crop rotation study initiated in 1967 at Swift Current, SK (Campbell et al. 1984) were selected for this study. The rotations included in this study were continuous wheat fertilized with N and P (C-W (NP)), continuous wheat fertilized with P alone (C-W (P)), fallow-wheat-wheat fertilized with N alone (F-W-W (N)), fallow-wheat-wheat fertilized with N and P (F-W-W (NP)), fallow-wheat-wheat fertilized with P alone (F-W-W (P)), fallow-wheat fertilized with N and P (F-W (NP)), fallow followed by five years of wheat fertilized with N and P (F-5W (NP)), and a wheat-lentil fertilized with N and P (W-Lent (NP)). All rotations were started in 1967, except W-Lent (NP) that was initiated in 1979 by combining two continuous cropped rotations, and F-5W (NP) that was initiated in 1985 by combining two other previously continuously cropped rotations. The rotations receiving N, received fertilizer N applied at seeding at rates prescribed by soil testing, based on thenitrite-N content of the soil to a depth of 60 cm. For further details regarding management and fertilization of these rotations refer to Campbell et al. (1984).

A nitrogen balance was calculated for each rotation considering only N that moved into or out of the experimental plots across their boundaries, and thus contributed either to gains or losses. Internal transformations of N were not considered thus, for example N uptake in the vegetative portions of the crop that were eventually returned to the soil is neither a gain nor a loss.

Boundaries of the system were the lateral edges of the plots, maximum rooting depth of wheat (120 cm), and the interface of the soil-plant system with the atmosphere.

We considered the addition of fertilizer N (N_{Fert}), N contained in the seed (N_{Seed}), symbiotic N_2 fixation by the pulse crop (N_{Fix}), and wet and dry atmospheric deposition of N (N_{Dep}) as inputs to the system. As outputs we considered N exported in the grain (N_{Grain}), gaseous losses of N as NH_3 and as N_2O (N_{Gas}), and N lost through leaching (N_{Leach}).

The N balance was calculated as:

$$N_{Bal} = (N_{Fert} + N_{Seed} + N_{Fix} + N_{Dep}) – (N_{Grain} + N_{Gas} + N_{Leach})$$

Thus, positive balances indicate gain of N by the soil-plant system, and negative balances a net loss of N from the system.

Fertilizer N, N exported in the grain, and inputs of N with the seed were documented in the data of the rotation experiments. Symbiotic N_2 fixation by the legume crop was calculated assuming that 65% of the legume crop was derived from N fixation (Janzen et al. 2003), and that 12% of legume N was below ground (Biederbeck et al. 1996). Gaseous losses of NH_3 were estimated from measurements made during a 15-day period starting at seeding using a vented chamber technique, with the chambers placed over the seed and fertilizer bands (Selles, unpublished results). Gaseous losses of N_2O were calculated based on measurements for the fallow, wheat, and lentil phase of the rotation made by Lemke et al. (2000). Wet and dry deposition were calculated from determinations made by Janzen et al. (1997), and confirmed with measurements of NH_4-N in rain and snow made at Swift Current (Selles, unpublished results). Average leaching losses were estimated from nitrate profiles measured in the crop rotation to a depth of 4.5 m in 2003, using the technique described by Dyck et al (2003). Magnitude of the estimated gains and losses used in the balance calculations are presented in Table 1.

Table 1. Non-crop losses and non-fertilizer gains considered in the N balance

Item	**Lentil Phase**	**Fallow and Wheat Phases**
	kg ha^{-1} yr^{-1}	
Losses		
Nitrification and Denitrification	1.0	0.4
Ammonia Volatilization	0.1	0.1
Nitrate leaching	0.3	0.3
Uncertainty	1.0	1.0
Total losses	2.4	1.8
Gains		
Wet and Dry Deposition	10	10

Cumulative balances for each rotation were calculated for individual plots, and then averaged annually across the phases of each rotation. Total N added as fertilizer, and N uptake in the grain and in the straw are presented in Table 2.

Table 2. Fertilizer inputs and uptake of N in the grain and straw from 1967 to 2004

Rotation	**Fertilizer N**	**Grain N**	**Straw N**
		kg ha^{-1}	
C-W (NP)	1425	1606	244
C-W (P)	286	1055	192
W-Lent (NP)	927 (371)^{z}	1620 (468)	222 (65)
F-5W (NP)	1105 (523)	1446 (608)	207 (86)
F-W-W (N)	483	1170	145
F-W-W (NP)	666	1321	184
F-W-W (P)	140	1098	164
F-W (NP)	339	1158	144

^{z} Figures in parenthesis indicate amounts of N applied or taken up before establishment of W-Lent and F-5W.

Average NUE for the rotation systems was calculated as the difference in N uptake between the fertilized ($N_{\mathrm{Upt,Fert}}$) and unfertilized rotation ($N_{\mathrm{upt,Unfert}}$), divided by the amount of fertilizer N. Because our systems receiving no N fertilizer received a small amount of N from the monoammonium phosphate (MAP) fertilizer used to supply P, in the calculation we used the difference in N applied between the rotation receiving N fertilizer ($N_{\mathrm{F,Fert}}$) and the one fertilized with MAP alone ($N_{\mathrm{F,Unfert}}$). NUE was calculated as:

$$NUE = (N_{\mathrm{Upt,Fert}} - N_{\mathrm{upt,Unfert}})/(N_{\mathrm{F,Fert}} - N_{\mathrm{F,Unfert}}),$$

Results and Discussion

Because in the initial years of the rotation there were some changes in management of the rotations, we calculated cumulative balances for the period 1979-2004 for all rotations, except for F-5W (NP) that was initiated in 1985. Cumulative N balances were nearly linear, although there was some variation from year to year in response to varying growing conditions. Three rotations that had positive balances these were C-W (NP), W-Lent (NP), and F-5W (NP); all other rotations had negative balances (Table 3). It is noteworthy that within the rotations with positive balance C-W (NP) had a much larger N accumulation than F-5W (NP) that had a 1/6 fallow frequency; this no doubt was the result of the amount of N mineralized during the fallow year which affected the amount of fertilizer N added to the crop grown in the fallow phase. Within the fallow containing rotations receiving similar fertility treatments, the magnitude of the balance was inversely proportional to the frequency of fallow. Thus, the F-W (NP) rotation with a high frequency of fallow had a highly negative balance while F-5W (NP) with a low frequency of fallow had a slightly positive balance. Within the F-F-W rotations, which have the same fallow frequency, the magnitude of the balance was directly related to the amounts of N applied (Table 3).

Table 3. Average annual N balances for the selected rotations.

Rotattions	Average Annual N Balance
	($\mathrm{kg\ ha^{-1}\ yr^{-1}}$)
C-W (NP)	10.2^{a}
C-W (P)	-5.3^{d}
W-Lent (NP)	6.9^{b}
F-5W (NP)	0.39^{c}
F-W-W (N)	-6.6^{e}
F-W-W (NP)	-5.3^{d}
F-W-W (P)	-13.5^{g}
F-W (NP)	-11.1^{f}

[a…f] Means followed by different letters are significantly different ($P \leq 0.05$)

Considering that the average C/N ratio of soil organic matter is 10, converting the average annual N balances to organic C, the levels of organic C in the soil should be increasing at a rate varying from 4 to 100 kg ha^{-1} yr^{-1} for the rotations with positive balance, and should be decreasing at a rate varying between 50 and 130 kg ha^{-1} yr^{-1} for the rotations with negative balance. However, measurements of soil organic N conducted throughout the years for this rotation experiment bay Cambell et al. (2000) indicate that organic C has either remained stable in the F-W-W (P) that has received a minimum amount of fertilizer N, or have increased at a faster rate for the C-W (NP) rotation that has received the largest amount of N (Fig 1). A linear regression for the data of Campbell et al. (2000) indicate that organic C in the C-W (NP) rotation has increased at an average rate of 154 kg ha^{-1} yr^{-1}, while that for the F-W-W (P) rotation has remained nearly stable increasing by only 35 kg ha^{-1} yr^{-1}. If we were to convert these rates of C gain using a C/N ratio of 10, and compare them to the rates of gain or loss of N from these two rotations predicted by the N balance, one can verify that there is a difference in the rates of N accretion in the two systems inspected (Table 4). The C-W (NP) system according to the N balance would be accumulating 5.2 kg N ha^{-1} yr^{-1} less than direct measurements of soil organic matter. In the case of the F-W-W (P) system the N balance predicts 17 kg N ha^{-1} yr^{-1} than direct measurements. These differences suggest that there is at least one source of non-fertilizer N entering the system that is not accounted in the N balance. Because the difference is largest for the unfertilized rotation, one could speculate that the size of this unaccounted source is controlled by a source-sink relationship, and that it could point to a biologically mediated process, where the nitrogen stress imposed by the lack of fertilization has stimulated a process of N additions such as non-symbiotic N_2 fixation.

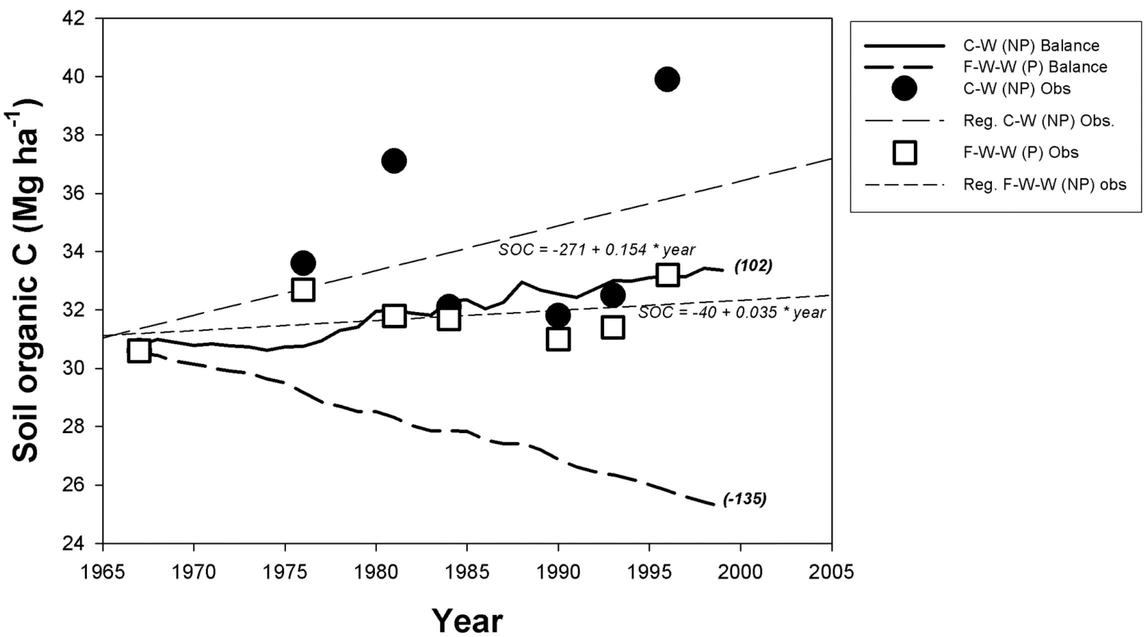

Figure 1. Evolution of soil organic C in selected rotations as determined by direct measurement (symbols and linera regression lines) and as predicted by cumulative N balances. Conversion or N to C values were computed assuming a C/N ratio =10.

Table 4. Comparison of SOC determinations and N balance predictions for Continuous-wheat fertilized with N and P (C-W (NP)), and Fallow-Wheat-Wheat fertilized woth P alone (F-W-W (P)).

Rotation	**SOC Change**		**Absolute Difference**	
	Direct Measurement	**Calculated from balance**[z]	**SOC**	**N**[z]
		($kg\ ha^{-1}\ yr^{-1}$)		
C-W (NP)	154	102	52	5.2
F-W-W (P)	35	-135	170	17.0

[z] Assumes soil organic matter C/N ratio = 10.

Further, the lower higher rates of N accumulation in the systems predicted by the direct analysis of soil organic matter suggest that in the N balance calculations for these systems, we have accounted adequately for the losses of N from the system, but we have failed to account for all the sources of N that might be entering into the system.

Calculation of NUE for the fertilizer N in for the rotations was possible only for C-W (NP), F-W-W (N), and F-W-W (NP) that had a counterpart receiving no fertilizer N. The re were no differences in NUE among the three rotations and on average 49% of the total plant N in the above ground parts was derived from fertilizer, as calculated by the difference method (Table 5).

The magnitude of N losses from the soil as proportion of soil available N in the rooting depth of the soil in spring (data not shown) is small and in the order of 2 to 3%. Assuming, then that the losses of fertilizer-derived N are equal to those of soil N, then of the 54% of fertilizer-derived N not used by the crop during the growing season, 97 to 98% would have been cycled through the soil (Table 5). This is in agreement with previous studies indicating that within the growing season up to 55% of applied ^{15}N fertilizer could be found in organic forms or fixed to clays (Stevens et al. 2005), and that 93±6% of fertilizer N was recovered in the plan and soil for wheat grown in dryland cropping in southwestern Saskatchewan (Campbell and Paul 1978). Results of similar studies in Rothamsted, UK indicate that recovery of ^{15}N fertilizer in plant parts and soil was 85% for grasslands (Jenkinson et al. 2004) and for winter wheat (Powlson et al. 1986).

Table 5. proportion of fertilizer-derived N lost from soil and retained in the soil.

Rotation	**Plant uptake**	**Loss from soil**[z]	**Cycled through soil**
		(%)	
C-W (NP)	55	3	42
F-W-W (P)	46	2	52

Conclusions

The N balance indicates that the largest loss of N from the soil-plant system is though N export in the harvested grain. Furthermore, comparison of the N balances with direct measurements of soil organic matter revealed that the balance has been able to capture adequately the losses of N from the system, and shows evidence that there are other non-fertilizer sources of N not accounted in the balance. These N gains appear to be related to the deficit of N in the balances, and the source seems to respond to a source-sink type of relationship, suggesting that this process could be biologically mediated. Contrary to the assertions of groups opposed to the use of synthetic fertilizers, in excess of 90% of the fertilizer-derived N not used by the crop remains in the soil cycling through organic forms and contributing to the overall fertility of the soil.

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