SOIL ACIDIFICATION PROCESSES IN AGROECOSYSTEMS AT WISCONSIN INTEGRATED CROPPING SYSTEM TRIALS

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ABSTRACT

Soil acidification associated with nitrogen inputs, both as acid-forming fertilizers and biological nitrogen fixation, has been noted in a variety of agroecosystems. Previously reported acidification rates range from 1.1 to 11.4 kmol ha^{-1} yr^{-1}, largely associated with crop productivity and nitrate leaching losses. The objective of this research was to determine acidification rates at the Arlington site of the Wisconsin Integrated Cropping System Trials (WICST) for several cropping systems that represent major agroecosystems of the Upper MidWest: continuous corn (CS1), corn/soybean rotation (CS2), and corn/alfalfa/alfalfa/alfalfa rotation (CS4). Average annual acidification rates for these rotations at WICST were 0.8, 1.3, and 6.5 kmol ha^{-1}, respectively. The legume phases of CS2 and CS4 were particularly associated with strongly acidifying processes. At WICST, however, 'best management practices' reduced annual acidification rates in continuous corn by the use of pre-plant nitrate tests (PPNT) to judiciously apply nitrogen fertilizer by as much as 5.2 kmol ha^{-1} and by stover return by 3.7 kmol ha^{-1}. The use of manure, which also returns plant alkalinity to soil, in CS4 reduced soil acidification rates by as much as 6.0 kmol ha^{-1} yr^{-1}.

INTRODUCTION

It has long been known, since the pioneering work of W.H. Pierre in the 1930s, that use of ammoniacal N fertilizers in excess of crop uptake and removal induces acidification in agricultural soils. This knowledge has been broadened to include legume-derived nitrogen as well. In recent years, estimates of soil acidification rates have been established for various agricultural systems. Legume-based pastures in New Zealand showed acidity inputs of 1.1 to 11.4 kmol ha^{-1} yr^{-1} that were correlated to the rate of biological N_2 fixation (BNF; Bolan et al., 1991). Wheat and barley in Canada, fertilized with 90 and 180 kg N ha^{-1} yr^{-1}, showed acidity inputs of 1.3 and 5.6 kmol ha^{-1} yr^{-1} (Bouman et al., 1995). In Wisconsin, continuous corn receiving 56, 112 and 168 kg N ha^{-1} yr^{-1} as ammonium nitrate or urea showed net acidity inputs of 1.5, 4.2 and 8.9 kmol ha^{-1} yr^{-1} (Barak et al., 1997). Soil acidification associated with nitrogen inputs has been shown to trigger loss of base cations (Ca and Mg; Bolan et al., 1991; Barak et al., 1997) and manganese toxicities in crops. With acidification, there is also loss of cation exchange capacity and evidence of accelerated soil weathering (Barak et al., 1997).

The Wisconsin Integrated Cropping Systems Trial (WICST), a long-term study with measured nutrient fluxes and archived soil samples, provides an attractive test site for measuring acidity fluxes in Midwestern agroecosystems because of its well-managed, highly productive fields. Of the six cropping systems at the WICST, continuous corn (CS1), corn-soybeans (CS2), and alfalfa-alfalfa-alfalfa-corn (CS4) were studied in this project because of their predominant roles in Wisconsin agriculture and their representation of extremes of cultural practices, ranging

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from monoculture relying on N fertilizer (CS1) to legume-based rotations that rely heavily on biological N_2 fixation (BNF; CS2 and CS4). (The WICST nomenclature, i.e., CS1, CS2 and CS4, is used here to facilitate use of our data in the context of current and future research efforts at the WICST.) Furthermore, some of the current practices at WICST have reasonable alternatives, such as harvesting corn stover for biomass instead of returning residue to soil surface for conservation tillage to reduce erosion (as in CS1, CS2, and CS4) or forgoing the use of dairy manure in the corn/alfalfa rotation (CS4); careful analysis of the fluxes of acidity will allow evaluation of these practices in terms of soil acidification without separate long-term experiments.

MATERIALS AND METHODS

The WICST fields at Arlington (WI) Agricultural Research Station are on a Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudoll), with adequate drainage. Denitrification potential of similar plots in the area is limited (Brye et al., 2001). The experimental design of WICST has four replicates in the field combined with cropping sequences that allow for each phase of the rotation to be grown each year in each block of the trial. Thus, continuous corn has one sequence, corn-soybean has two, and corn-alfalfa-alfalfa-alfalfa has four. Full acidity budgets were prepared for each of the rotations selected and for 1997 through 2002.

Plant tissue sampling and analysis:

Corn, soybean, and alfalfa tissue samples were taken from the field and dried at 60EC; harvest indices were estimated for the corn and soybean crops in the rotations to supplement the grain and bean harvest data collected by the WICST team. After drying, plant materials were ground and sent to the Soil and Plant Analysis Laboratory (SPAL; Madison, WI) for total elemental analysis. Total macronutrients (Ca, Mg, K, Na, total-N, total-S, and P) were determined for grain, stover and cobs (corn), beans and straw (soybean), and whole tissue (alfalfa hay). Soluble SO_4^{2-}, NH_4^+, and NO_3^- were measured in some tissue samples in order to estimate accumulation of N and S as inorganic anions that can affect the cation/anion balance calculations. Organic N and S were estimated as the difference between total tissue content and soluble forms. Grain and stover/straw yields were estimated based on the harvest index; nutrient concentrations of all tissues sampled were determined at the University of Wisconsin Soil and Plant Analysis Laboratory (SPAL).

Acidity/alkalinity inputs:

The inputs of acidity in agricultural systems are primarily due to chemically-reduced N (Helyar, 1976; Johnston et al., 1986; Bolan et al., 1991; Barak et al., 1997). The acidity budget therefore relies heavily on the knowledge of the reduced-N inputs as a source of potential acidity upon nitrification and permanent acidification upon nitrate leaching. The main sources of acidity associated with N inputs in the cropping systems of the WICST are: fertilizers in CS1 and CS2, dairy cattle manure in CS4, atmospheric NO_x deposition, Fall $NO_3^!$-N measured by the WICST in CS2 and CS4 (assumed to be the result of BNF and subsequent nitrification), soybean credits to corn in CS2, alfalfa plowdown N credits to corn in CS4 (also from BNF), and crop residues (corn stover additions in CS1, CS2, and CS4, as well as soybean stover additions in CS2). In our computations, the N inputs from all sources are converted from lb N per acre or kg N ha^{-1} to kmol ha^{-1} (kilomoles of charge) and summed. This sum is the potential acidity of the reduced-N

inputs, assuming that one mole of reduced-N from any of these sources generates one mole of H^+ during nitrification.

In addition to acidity inputs from reduced N in these sources, alkalinity inputs from manure and H+/alkalinity excretion by the crops were considered. Crop excretion of H+/alkalinity was calculated following the procedure of van Beusichem et al. (1988), which assumes that in the corn crop, all N, S, and P were taken up as nitrate, sulfate, and $H_2PO_4^-$, respectively (see Avila-Segura [2004] for details). Manure alkalinity per unit N was calculated based on ASAE (2003).

Crop potential Acidity:

Organic alkalinity in plant tissue was based on plant tissue analysis of the various aboveground plant parts, following the procedure of van Beusichem et al. (1988). The potential acidity was calculated based on the total N and S composition of the plant material, after considering small corrections for nitrate and sulfate.

Net H+/OH input of the cropping system:

The net effect was calculated by summing the acidity/alkalinity inputs and crop potential acidity components, both for standard harvest and several additional scenarios. When comparing the effect of different crop rotations of different durations on the soil or nutrient fluxes, it is necessary to calculate the "average" annual effect of a particular rotation. Obviously this "average" does not have a statistical meaning for an individual block because the dry matter production or the nutrient fluxes due to harvest of two or more different crops belong to different statistical populations; however, the 'average' annual effect is necessary to compare a system with a one year rotation (continuous corn, CS1) to a two-year rotation (corn-soy, CS2) or a four yr rotation (corn-alfalfa-alfalfa-alfalfa, CS4). More details found in Avila-Segura, 2004. All quantities were tabulated for all replicates of each treatment, where indicated, and analyses of variance were performed using the Statistical Analysis System software with the General Linear Model and the Student-Newman-Kuels test for differences among treatment means.

RESULTS AND DISCUSSION

The calculation of the acid/base balance of a crop or rotation of crops is not a trivial exercise since not only the fluxes of N must be known but also their origin, nature, and chemical formulation (whether nitrate or reduced). In order to calculate the acid/base balance of the rotation it is necessary to estimate and then sum the cation/anion uptake balance of the crops (acidity/alkalinity excretion), total acidity inputs from reduced-N sources, and the alkalinity inputs from manure and crop residues returned to the field at the end of the season. First, the cation uptake is calculated. Second, the total plant N and the uptake of P and S are calculated. The amount of N present in the tissues can have different origin depending upon the crop and the availability of NO_3^- in the soil during the season. Thus, in the case of corn crops, all plant N is considered as NO_3^- uptake. In the case of soybean and alfalfa, of the total N present in the plant only an amount equal to the N inputs to the crop (other than BNF) is considered as taken up in the form of NO_3^-; if the total plant N is greater than the N inputs then the difference is considered to be the result of biological N_2 fixation by soybean or alfalfa. Thus, if the soybean or alfalfa crops extract less N than the NO_3^- available we assume that little or no BNF has taken

place throughout the season and that the crop fulfilled its N needs exclusively through $NO_3^!$ uptake.

Once the NO_3^- uptake is calculated (total plant N in corn; total plant N minus soil available $NO_3^!$-N in soy and alfalfa) then the total anion uptake can be calculated as ($H_2PO_4^-$ + 2 SO_4^{2-} + NO_3^-). Once the cation uptake and the anion uptake are calculated, OH^-/H^+ excretion is calculated as $\Sigma_{cations}$ - Σ_{anions}. If the total aboveground biomass is harvested, this is the contribution of the crop to the acid/base balance of the cropping system. However, if the corn stover or the soybean straw are returned to the field, the contribution of the stover/straw to the general acid/base balance (normally alkaline) has to be ascertained and explicitly included in the acid/base balance. Furthermore, the alkalinity from manures must be also added to the balance.

Finally, the acid/base balance of the cropping system is calculated by summing the acidity inputs (from reduced-N) plus the OH^-/H^+ excretion, manure alkalinity and the stover/straw alkalinity. This value can also be expressed as the calcium carbonate equivalent (in kg ha^{-1} yr^{-1}) necessary for neutralizing the acidity added the cropping system, based on 50 kg $CaCO_3$ per kmol H^+.

Acidity and alkalinity inputs in CS1, CS2, and CS4 of the WICST

Results of these acidity/alkalinity calculations for WICST at Arlington are shown in Table 1. Examination shows that the total nitrogen fluxes—the sum of BNF and all other N inputs—in the continuous corn (CS1) and corn/soy rotation (CS2) are almost identical, 18.2 and 19.1 kmol N ha^{-1} yr^{-1}, while the corn/alfalfa/alfalfa/alfalfa rotation (CS4) cycles 30.5 kmol N ha^{-1} yr^{-1}, on average. Interestingly, BNF in the direct seeded alfalfa (DSA) phase of CS4 appears to be almost completely suppressed by the addition of manure-N and its mineralization.

Annual acidity inputs to CS1, CS2, and CS4 average 13.0, 10.7, and 17.5 kmol H^+ ha^{-1}, respectively (Table 1) and the means are statistically different in the order CS2 < CS1 < CS4. In CS4, acidity inputs come mainly from the manure applications to corn and DSA and from BNF during the two hay production years of the alfalfa rotation. For CS2, acidity inputs come from N fertilizers applied to the corn phase of the rotation and BNF by the soybean crop. In CS1, the acidity originates mainly from N fertilizers.

On the basis of total acidity inputs, it seems reasonable for CS4 to have greater net acidity input to the soil; however, the effects of manure alkalinity and crop anion excretion must be considered. Manure alkalinity inputs to CS4 average 6.0 kmol $OH^!$ ha^{-1} yr^{-1}, and to a varying degree affect each phase of the rotation. Crop alkalinity excretion averages 3.9, 6.0, and 8.5 kmol OH^- ha^{-1} (negative values denote alkalinity; Table 1) in CS4, CS2, and CS1 and show that continuous corn at the WICST has much greater potential for neutralizing acidity inputs than either corn-soybean or corn-alfalfa (statistically significant in the order CS1 < CS2 < CS4, following sign convention). This is further confirmed by the distribution of the alkalinity excretion among the individual crops of CS2 and CS4 (Table 1). Alkalinity excretion by the corn crops of CS2 and CS4 average 8.6 and 10.0 kmol OH^- ha^{-1}, respectively, and represent the bulk of the alkalinity excretion in both rotations. In CS2, soy alkalinity excretion accounts for only about a third of the anion excretion of the 2-yr rotation. In CS4, anion excretion is lower in the legume phases, particularly A1 and A2, where NO_3^- uptake is replaced by BNF. The 1-yr corn phase in CS4 excretes more than 60% of the alkalinity excreted in the 4-yr rotation, and DSA excretes most of the rest, with the production phases contributing only minor amounts of alkalinity (A1) or acidity (A2) as the result of cation/anion uptake balance.

Potential acidity in the crop:

The harvested portions of these agroecosystems, whether corn, beans, or alfalfa hay, are major sources of potential acidity (Table 1), primarily by virtue of the reduced N as protein, stored in the harvest and the generally low quantities of organic alkalinity in the harvest. By contrast, corn stover and soy straw contain considerable organic alkalinity in the leaves, which offsets the potential acidity associated with the residual protein and gives a net alkaline value for these materials.

Net H+/OH input of the cropping systems:

The standard harvest of continuous corn (CS1) at WICST consists of a grain-only harvest (9.0 kmol H^+ ha^{-1}), returning -3.7 kmol H^+ ha^{-1} as stover alkalinity to the soil, thereby offsetting a significant portion of the total acid input, 13.0 kmol H^+ h^{-1}. The net acidification rate for this crop and management practice is 0.8 kmol H^+ ha^{-1} (±0.58), which is virtually zero and considerable lower than that cited by other authors (Bolan, 1991; Bouman et al., 1995; Barak et al., 1997) for other crops and management practices. The cause of this near-zero acidification rate in continuous corn at WICST is related to the both the residue and nitrogen management techniques. The return of corn stover to the soil returns both organic nitrogen, which is potentially acidic, and organic alkalinity. The mineralization of the residue and nitrification to nitrate generates acidity, but the acidity is counterbalanced by the greater amount of stover alkalinity that is added simultaneously. Furthermore, the WICST fertilization strategy is to employ pre-plant nitrate tests (PPNT) to assess residual nitrate in the soil profile and to subtract the amount of preplant nitrate from the total nitrogen added, thereby reducing the amount of acid-forming ammoniacal nitrogen added. This practice has led to application of 90 to 140 kg N ha^{-1} (80 to 120 lb N per acre) at WICST instead of the full recommendation of 180 kg ha^{-1} (160 lb N per acre) as fertilizer N, which is common in Midwestern corn agriculture. The use of PPNT at WICST is therefore likely to have reduced the net acidification of continuous corn by 5.2 kmol H^+ ha^{-1}.

The results for CS1 at WICST can be used to estimate the effect of total removal of corn grain and stover on soil acidification rates, assuming that the nitrogen in the corn stover would be replaced on a one-for-one basis with fertilizer to maintain identical nitrogen supply. Such a practice might be put in place if corn were harvested for silage or stover or biofuel. In such a case, harvest of total aboveground biomass would lead to an annual acidification rate of 4.5 kmol H^+ ha^{-1}, which is significantly higher than that of the current practice that removes grain only and is quite in line with rates reported by Barak et al. (1997) for continuous corn in Wisconsin.

The average annual acidification rate of corn/soybean rotation at WICST (CS2; Table 1) average 1.3 kmol H^+ ha^{-1}. The acidification process is here related entirely to BNF in the soybean phase, but averages out over the two phases to be not significantly different than those of continuous corn. If, on the other hand, crop residues were also removed, e.g., stover for silage or biofuel and soybean straw for animal bedding, then the annual acidification rate would be 4.7 kmol H^+ ha^{-1}, almost identical to that of continuous corn with complete removal of aboveground plant material.

The corn/alfalfa/alfalfa/alfalfa rotation (CS4) as practiced at WICST produced an average annual acidification rate of 6.5 kmol H^+ ha^{-1}, significantly greater than CS1 and CS2 (Table 1). The major acidifying phase of this rotation is A1 and A2, the period of great productivity and active BNF. The potential removal of corn stover would only modestly increase the annual acidification rate of CS4 to 7.6 kmol H^+ ha^{-1}. However, one of the interesting practices at

WICST associated with this cropping system is the use of dairy manure before and after the corn phase. Withholding the manure applications and its associated inputs of alkalinity in favor of enhanced BNF or added ammoniacal fertilizer (for non-legumes), both potentially acid-forming, would add an average of 6.0 kmol H^+ ha^{-1} yr^{-1}, leading to projected total annual acidification rate of 12.5 kmol H^+ ha^{-1}. Such a value is slightly higher than the value reported by Bolan et al. (1991), 11.34 kmol H^+ ha^{-1} yr^{-1}, for a highly productive (16.5 t dry matter ha^{-1} yr^{-1}) rye grass/white clover pasture in a temperature climate with 1600 mm annual rainfall in Waikato, New Zealand; intensive dairy pastures in New Zealand require application of ~2.5 tons of lime per ha every 6 years and Bolan et al. predicted an annual requirement of 550 kg $CaCO_3$ ha^{-1} yr^{-1}. At the WICST trials, the use of manure to return back to the alfalfa fields some of the alkalinity generated by the leafy tissue that was harvested from those fields serves as means to cycle alkalinity in a manner that had been previously considered only for nutrients; in the process, the manure serves as a liming agent and reduces the total lime requirement. Since 50 g $CaCO_3$ neutralizes 1 mole H+, the current CS4 rotation is predicted to generate a requirement for 380 kg $CaCO_3$ ha^{-1} yr^{-1}or 1520 kg over a 4-yr rotation; in local units, the anticipated lime requirement would be 0.68 'English' tons aglime per acre, or 0.80 tons 80-89 aglime per acre, per 4-yr rotation. In the absence of manuring, the anticipated lime requirements per 4-yr rotation would be proportionately higher—2500 kg $CaCO_3$ ha^{-1}, or 1.31 tons 80-89 aglime per acre.

CONCLUSIONS

Of the three cropping systems examined and compared, the total and net acidity inputs ranked CS1<CS2<CS4. When standard harvest practices are implemented, continuous corn (CS1) has net acidity inputs to the soil that average 0.8 kmol H^+ ha^{-1}. In comparison, corn-soybean (CS2) and corn-alfalfa (CS4) average 1.3 and 6.5 kmol H^+ ha^{-1}. Throughout, the legume phases of these systems were more strongly acidifying than the corn phase, even though continuous corn was fertilized by acid-forming ammoniacal fertilizers. This was largely due to lower anion excretion under BNF and nitrification of unutilized chemically-reduced N at the end of the season.

These acidification rates reported here are somewhat smaller than those reported in the literature for other sites and other agricultural systems (Barak et al., 1997, Bouman et al., 1995; Bolan et al., 1991). Examples of higher acidification rates documented (Barak et al., 1997) are associated with N fertilization rates normally greater (160 kg N ha^{-1} or more) than those of the WICST in combination with total removal of aboveground biomass and no manuring practices. At the WICST fields, 'best management practices' included preplant nitrate tests that substantially reduced the rate of application of acid-forming ammoniacal fertilizers. The use of manure in the corn/alfalfa rotation also cut the potential acidification rate of that rotation in half.

A final observation worthy of mention is that the net acidity inputs in CS1 and CS2 are similar in size to those associated with acid rain in the Upper Midwest, which are ~0.5 kmol H^+ ha^{-1} based on atmospheric N deposition data. However, the total acidity inputs in these three cropping systems—13.0, 10.7, and 17.5 kmol H^+ ha^{-1} in CS1, CS2, and CS4, respectively—are 20 to 35 times greater than those from atmospheric inputs. Therefore, concerns about acidity inputs from acid rain to agricultural soils in the Midwestern United States are irrelevant in comparison to acidity inputs from sources related to agricultural activities.

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Table 1: Acid/base balance of CS1, CS2, and CS4 at the WICST

	CS1	CS2			CS4					
	corn	**corn**	**soy**	**rotation**	**corn**	**DSA**	**A1**	**A2**	**rotation**	**LSD***
	---------- kmol ha^{-1} ----------									
Nitrogen Inputs										
N input (other than BNF)	**18.2**	16.9	4.5	**10.8**	26.4	20.6	13.3	11.0	**16.1**	
Biological N_2 fixation (BNF)	**- -**	- -	16.2	**8.3**	- -	1.1	21.4	27.5	**14.4**	
General Acidity and alkalinity inputs†										
Total H^+ input	**13.0b§**	11.3	9.9	**10.7c**	17.9	17.9	15.2	18.1	**17.5a**	1.7
Manure OH^-	**0.0**	0.0	0.0	**0.0**	-6.4	-8.6	-5.4	-3.5	**-6.0**	
Crop H^+/OH^- excretion	**–8.5c**	–8.6	–3.6	**–6.0b**	–10.0	–5.8	–0.6	0.8	**–3.9a**	0.5
Crop potential acidity‡										
grain, beans and hay	**9.0**	9.2	11.8	**10.4**	10.3	5.8	15.0	14.2	**11.5**	
stover stover/straw	**–0.6**	–0.6	–1.3	**–1.0**	–0.3	0	0	0	**–0.1**	
Aboveground	**8.5**	8.6	10.5	**9.5**	10.0	5.8	15.0	14.2	**11.4**	
Net $H^+/OH^!$ input of the cropping system										
Aboveground harvest	**4.5b**	2.7	6.3	**4.7b**	1.5	3.5	9.2	15.4	**7.6a**	0.5
stover/straw H^+/OH^- return to soil	**–3.7b**	–3.8	–3.0	**–3.4b**	–4.3	0	0	0	**–1.0a**	0.2
Standard harvest	**0.8b**	–1.1	3.3	**1.3b**	–2.8	3.5	9.2	15.4	**6.5a**	0.58

* LSD = "Least Significant Difference" of a Duncan test for separation of experimental means, or the first "critical range" in the "Student-Newman-Keuls" multiple range test.

† Total H+ input although dependent on N inputs, is not identical in magnitude to N inputs due to internal recycling of N in the soil-plant system and decoupling between proton production and N uptake by the crop.

§ Means accompanied by different letters in the same row are statistically different at the 0.05 level.

¶ negative signs denote alkalinity and are used for convenience in this table but are not used in the discussion.

‡ The "net potential acidity" of corn aboveground material is identical to the "crop $OH^!/H^+$ excretion". In soy and alfalfa, however, BNF produces differences between these two quantities.