CHANGES IN NITROGEN USE EFFICIENCY AND SOIL QUALITY AFTER FIVE YEARS OF MANAGING FOR HIGH YIELD CORN AND SOYBEAN

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Abstract

Average U.S. corn grain yields have increased linearly at a rate of 1.7 bu./acre over the past 35 years with a national yield average of 140 bu./acre. Corn yield contest winners and simulation models, however, indicate there is ~100 bu./acre in exploitable corn yield gap. Six years (1999-2004) of plant development, grain yield and nutrient uptake were compared in intensive irrigated maize systems representing (a) recommended best management practices for a yield goal of 200 bu./acre (M1), and (b) intensive management aiming at a yield goal of 300 bu./acre (M2). For each management level, three levels of plant density (30000-P1, 37000-P2 and 44000-P3 seed/acre) were compared in a continuous corn (CC) and corn-soybean (CS) rotation. Over the past six years, corn grain yields have increased an average of 10 percent as a function of management and this effect was manifest under higher plant densities. A high yield of 287 bu./acre was achieved in the CS-P3-M2 treatment in 2004. Over the past five years, nitrogen use efficiency (NUE) has steadily improved in the CC-M2 treatments due to improvements in soil quality. Intensive management and population levels significantly increased residue carbon inputs with disproportionately lower soil respiration. High NUE under the CS rotation has resulted at the expense of a loss in total soil N. Closing the yield gap requires higher plant population and improved nutrient management to maintain efficient and profitable improvement in maize production. Soil quality improvements and higher residue inputs under intensive management should make this task easier with time.

Introduction

Rainfed and irrigated systems in which corn is grown either in rotation with soybean or as continuous corn are the predominant cropping systems in the North American Corn Belt. Average U.S. corn grain yields have increased linearly at a rate of 1.7 bu./acre over the past 35 years with a national yield average of 140 bu./acre. Results of corn yield contest winners and data from well designed field experiments as well as simulation models indicate that the actual yield potential of corn in our temperate climate is > 300 bu./acre. Here we define yield potential (Ymax) as the maximum yield that can be obtained with no limitations in water or nutrient supply, and potential crop growth is limited only by genetic characteristics, solar radiation, temperature, and CO_2 concentration (van Ittersum et al., 2003). Given the apparent yield gap that exists in the U.S. Corn Belt, there are most probably significant changes in management practices that can be adopted to close this yield gap. However, there is a need to develop management systems that also preserve the integrity of the environment and are profitable in practice. Given the lack of new agricultural lands to exploit and the ever-growing need for increased productivity on existing land, intensification strategies must be developed that improve soil nutrient supply, nutrient use efficiency, and soil nutrient supply (Cassman et al., 2002, 2003).

Materials and Methods

The University of Nebraska-Lincoln research program on *Ecological intensification of irrigated maize-based cropping systems* has the following objectives: (1) improve the understanding of the yield potential of corn and soybean and how it is affected by management, (2) develop a scientific basis for evaluating yield potential at different locations, (3) develop practical technologies for managing intensive cropping systems at ≥80 percent of the yield potential, and (4) conduct an integrated assessment of productivity, profitability, input use efficiency, soil carbon sequestration, energy and carbon budgets, and trace gas emissions. Experimental details for the field experiment conducted at Lincoln, Nebraska from 1999 through 2004 are:

Soil: Kennebec silt loam (fine-silty, mixed, mesic Cumulic Hapludoll)

pH (limed to 6.0), 2.7% OM, 67 ppm Bray P1, 350 ppm extractable K.

Treatments:

3x3x2 factorial experiment conducted in a split-split plot randomized complete block design.

Main-plot: ***Irrigated crop rotations*** (**CC**-continuous maize, **CS**-maize-soybean).

Sub-plot: ***Plant population density*** (**P1**~33; **P2**~37, **P3**~44,000 pl./acre).

Maize hybrid Pioneer 33A14 (Bt) planted in 1999 and 2000; Pioneer 33P67 (Bt) planted in 2001 and 2002; Pioneer 31N28 (Bt) planted in 2003 and 2004.

Sub-sub-plot: ***Fertilizer nutrient management*** as (M1-recommended NPK rates for a yield goal of 200 bu./acre, M2-intensive NPK management for 300 bu./acre yield goal.

M1: 107-125 lbs. N/acre for corn after soybean, 161-181 lbs. N/acre for corn after corn, using UNL N recommendations; no P and K applied (high soil test values). Nitrogen split into two applications (pre-plant and V6 stages).

M2: 193-266 lbs. N/acre for corn after soybean, 223-324 lbs. N/acre for corn after corn; 92 lbs. P_2O_5/acre, 93 lbs. K_2O/acre, 10 lbs. S/acre per crop. Nitrogen split into four applications (pre-plant, V6, V10, and VT stages; only in CC-M2: N applied on crop residues in fall since 2001).

Nitrogen fertilizer application rates have been made on the basis of yield goal, spring residual soil nitrate to a depth of four feet, organic matter content, and credit for previous crop of soybean as outlined in the UNL nitrogen algorithm (Shapiro, et al., 2001). Herein we will report on corn yield, N use efficiency (NUE) and changes in both soil C and N over the course of the experiment with respect to residue C and N inputs and N balance.

Results

Table 1 shows the trend in grain yield over the period 1999-2004. Maximum grain yields were achieved in each year of the study with plant populations of 37,000 plants/acre in 2000 and 2003 and 44,000 plants/acre in 1999, 2001, 2002, and 2004 under intensive fertilizer management. When averaged over crop rotation, the M2 treatment resulted in an average yield gain of over 10 percent and this gain was manifest at higher plant populations. Although soil test values for P and K were in the very high range, current fertilizer recommendations (M1) were insufficient to supply the demand of higher biomass under the P2/3 plant populations. Yield loss at the P3 population in 2000 was due to severe heat stress and a reduced period for grain fill.

Results from this study and other high production maize experimental sites the basis for development of a new maize growth model, Hybrid-Maize (Yang et al., 2004a, 2004b). Hybrid-Maize allows for the simulation of maize development and yield potential as a result of changing management parameters such as plant population, hybrid maturity rating, and planting date using local climate data. Simulated yield potential for this site is 280-300 bu./acre, and during the first four years of this study we have achieved approximately 90 percent of this simulated yield potential. Beginning in 2003, as a result of simulations with Hybrid-Maize at our Lincoln site, we extended the planting data from late April to early-mid-May and planted a longer season hybrid (Pioneer 31N28, 119 d CRM). A combination of cool growing seasons in 2003 and 2004 and extended grain filling periods resulted in substantial and sustained increases in grain yield across all treatments.

Table 1. Corn grain yield (15.5 percent moisture) trends in the Ecological Intensification study at Lincoln, Nebraska as affected by crop rotation, fertility management, and plant population density. Yields for the M2 treatment refer to the plant density with the highest yield in the given year (see footnote).

Treatments		**Corn grain yield 1999-2003 (bu./acre)[1]**						
Density[2]	**Fertilizer**	**Average**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Continuous Corn								
P1	**M1**	**229**	-	241	223	178	255	247
P2/3	**M2**	**251**	-	229	252	242	265	266
Corn after Soybean								
P1	**M1**	**237**	219	225	230	221	268	261
P2/3	**M2**	**262**	257	248	249	243	285	287

[1] Hybrid: P33A14 (113 d) in 1999-2000; P33P67 (114 d) in 2001-02; P31N28 (119 d) in 2003-2004.
[2] M2 treatment with highest yielding plant density: P2 in 2000 and 2003; P3 in 1999, 2001, 2002 and 2004.

Nitrogen application rates are adjusted as a function of projected yield potential, previous crop and spring residual soil NO_3-N (Table 2). Application rates have remained more consistent for the corn–soybean rotation owing in part to soybean impact on reducing residual soil NO_3-N (Table 3). Beginning in 2002, we began the practice of applying 45-65 lbs. N/acre to the residue of the continuous corn M2 treatment prior to plowing in the fall. This is meant to facilitate decomposition and humification of the high amounts of residue we have experienced under this treatment with the intent of (1) decreasing the competition from decomposers for N resources during the early growing season and (2) increasing the storage of soil N (i.e., N sequestration) concomitant with soil C sequestration.

The elevated soil NO_3-N levels (most in the surface 30 cm depth) in the spring following the fall application of N to residue have resulted in a reduction in the subsequent year's fertilizer rate (see Table 2). The impact of these management changes on N fertilizer use efficiency (NUE) is given in Table 4. Average farm NUE for the U.S. is 1.03 bu./lb. N. Although average NUE for the CC-M2 treatment is below this level, we have experienced a steady increase in NUE over the course of the study. This indicates the potential that exists for increasing NUE in maize-based systems. We hypothesize that the increase in NUE we are observing is due to improvement in soil quality from greater C inputs to the soil and concomitant sequestration of N with this carbon.

Table 2. History of N fertilizer application to continuous corn and corn following soybean for the M1 (recommended) and M2 (intensive) fertilizer management treatments.

Treatments[1]	Nitrogen rate 1999-2003 (lbs. N/acre)						
	Average	1999	2000	2001	2002	2003	2004
Continuous Corn							
M1	**172**	-	181	179	161	161	179
M2	**265**	-	324	268	258[2]	223[2]	250[2]
Corn after Soybean							
M1	**117**	116	123	116	107	116	125
M2	**217**	201	266	214	193	223	205

[1] M1: pre-plant and V6; M2: Pre-plant, V6, V10, and V12-VT.

[2] CC-M2 includes fall application of 65 lbs. N/acre (2001) and 45 lbs. N/acre (2002 and 2003) applied to residue prior to fall tillage (plowing).

Table 3. Residual soil NO_3-N (spring) in the surface four feet of soil as affected by crop rotation, plant density and fertility managment.

Treatments		Average 1999-2004				NUE 1999-2004					
Density[1]	**Fertilizer**	**N rate**	**Yield**	**NUE**		**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
		lbs. N/a	**bu /a**	**bu. /lbs. N**		----------------bushels / lbs. N-------------					
Continuous Corn											
P1	**M1**	172	229	**1.30**		-	1.18	1.25	1.11	1.59	1.38
P2/3	**M2**	265	251	**0.97**		-	0.71	0.94	0.94	1.18	1.06
Corn after Soybean											
P1	**M1**	117	237	**2.03**		1.89	1.83	1.98	2.06	2.31	2.09
P2/3	**M2**	217	262	**1.22**		1.28	0.93	1.16	1.26	1.28	1.40

[1]M2 treatment with highest yielding plant density: P2 in 2000 and 2003; P3 in 1999, 2001, and 2002

[2] *CC-M2 includes fall application of 65 lbs. N/acre (2001) and 45 lbs. N/acre (2002 and 2003) on residue prior to tillage*

Table 4. Trend in N fertilizer use efficiency as influenced by crop rotation, population density, and fertility management (1999-2004).

Treatments		Average	Residual Soil NO_3-N in spring, 0-4 ft (lbs. N/acre)				
Density[1]	**Fertilizer**		**2000**	**2001**	**2002**	**2003**	**2004**
Continuous Corn							
P1	**M1**	50	-	50	56	67	26
P2/3	**M2**	149	-	105	261[2]	154[2]	75[2]
Corn-Soybean (prev. crop corn)							
P1	**M1**	45	41	38	59	62	23
P2/3	**M2**	81	45	106	94	84	76
Corn-soybean (prev. crop soybean)							
P1	**M1**	67	49	76	95	60	55
P2/3	**M2**	85	70	96	115	67	78

[1] M2 treatment with highest yielding plant density: P2 in 2000 and 2003; P3 in 1999, 2001, 2002, and 2004.

Cumulative residue C and N inputs for the four-year cropping cycle (2000-2003) are displayed in Figure 1 and reflect an equal number of corn and soybean years in the CS rotation. Percentages displayed in this figure represent the net gain or loss of soil C and N as compared to the CS-P1-M1 treatment, which is the most widespread rotation in the corn-belt. Over this four-year period, 19.5 Mg C/hectare (or metric tons C/hectare) were recycled to soil in the recommended CS-P1-M1. This amount increased to 20.5 Mg C/hectare in the intensified corn-soybean system (CS-P3-M2). Net C recycling in all of the continuous corn treatments was larger than in any of the CS treatments, reaching 21.6 Mg C/hectare in CC-P1–M1 and a maximum of 26.3 Mg C/hectare in CC-P3-M2 and represents an increase of 35 percent residue carbon inputs to soil over this four-year period. Nitrogen recycled in crop residues was highest in the corn-soybean rotation with an average four-year input of 540 kg N/hectare. In the continuous corn treatments, the recommended CC-P1-M1 treatment returned only 42-50 percent less N than measured in the CS treatments. In contrast, higher fertilizer N inputs in the M2 treatment increased total residue N inputs by 55 percent compared to the CC-P1-M1 treatment. Of the total C and N input to soil from residue in this four-year period (under the CS rotation) contribution of C was 60 percent from corn and 40 percent from soybean and residue contribution of N was 40 percent corn and 60 percent soybean.

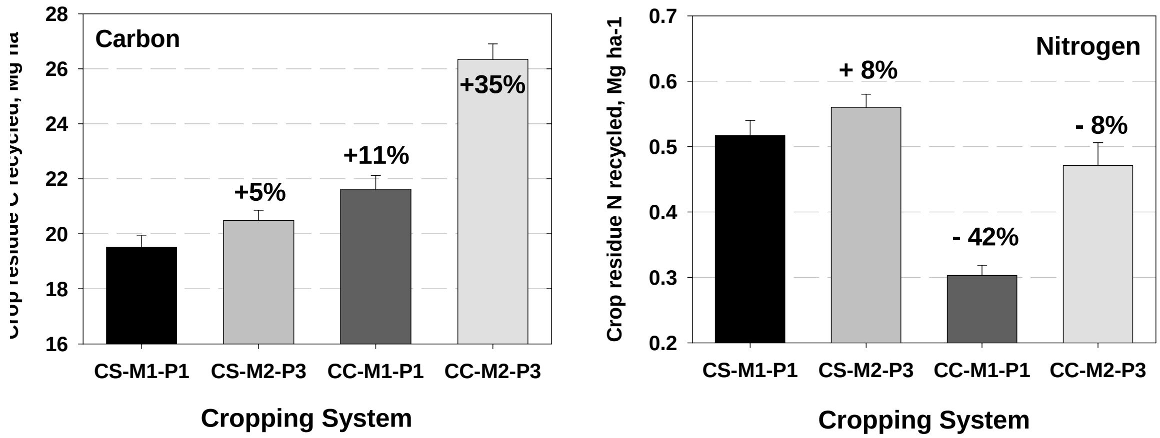

Figure 1. Cumulative C and N inputs to soil in aboveground crop residues for a four-year period (2000-2003) as affected by crop rotation, plant density, and nutrient management.

Increased C inputs to soil can only build soil organic matter if there are not elevated losses of CO_2-C from soil respiration. We have been monitoring soil CO_2-C respiration since 1999 and have noted that fertility treatments have had a minor impact on CO_2-C losses. Figure 2 shows CO_2-C losses during the 2003 growing season and are typical of what we have experienced throughout the course of this study. Although losses were higher for CC (owing to the higher residue C input) fertility management did not result in soil CO_2-C losses equivalent to C inputs. Given the higher residue N and C input in the M2 treatment, we would expect an increase in total soil C and N sequestration in the M2-CC treatment.

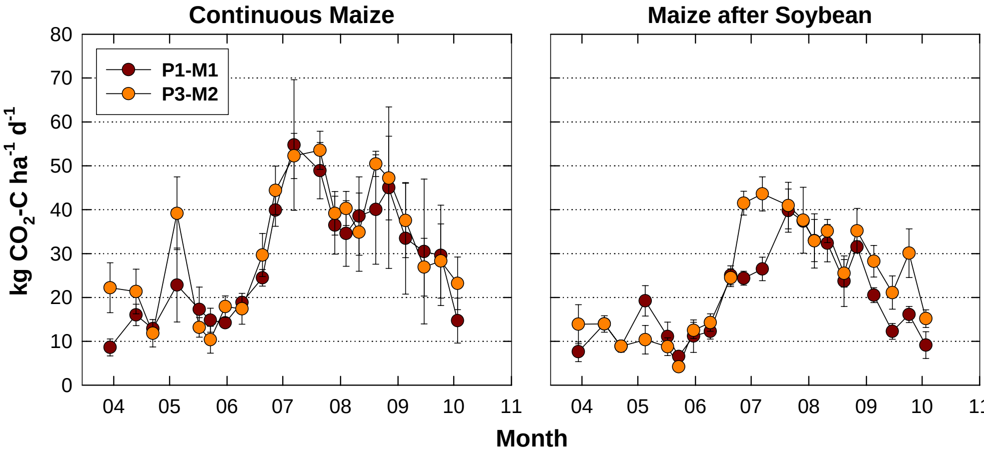

Figure 2. Soil CO2-C emissions in 2003. Cumulative emissions during the growing season:

season:	CC-P1-M1	5200 kg C/ha	CS-P1-M1	3600 kg C/ha
	CC-P3-M2	5600 kg C/ha	CS-P3-M2	4200 kg C/ha

Figure 3 shows the change in soil C and soil N for the period June 2000 to June 2004. Overall soil C stocks were calculated on a cumulative soil mass basis, following the approach described by Gifford & Roderick (2003). Unlike fixed-soil volume-based estimates of SOC, the cumulative mass approach better accounts for the variation in effective sampling depth and soil mass due to changes in soil bulk density over time. Net losses or gains of soil C and N were congruent across treatments. Soil C has remained relatively neutral under recommended (M1) fertilizer management. In contrast, the CS-P3-M2 treatment has exhibited a soil loss rate of ~1 Mg C/hectare/year. Under continuous corn, however, the CC-P3-M2 treatment exhibited a net gain in both total soil C and N. Stabilization and gain of soil N in this system has most probably resulted in increased indigenous soil N supply and better synchrony of N supply during the growing season. This has probably been a major factor in the increase in NUE we have observed over the last five years.

Studies on the nature of the changes in soil organic matter fractions and N storage and release from these fractions are under way.

Table 5 shows the cumulative four-year fertilizer N input and grain N removal as influenced by crop rotation, population density, and fertility management within the same period that soil C and N changes are tabulated in Figure 3. These data indicate the importance of N input to stabilization of C in soil. Added N input to the CC-M2 treatment, coupled with the increases realized in residue N input, have resulted in a significant gain in N sequestration. Under the CS rotation, it is interesting to note that far less N sequestration was evident in the CC-M2 treatment than the CS-M1 treatment even though net N input-output balance (Table 5) was less negative. This is probably due to added N_2–fixation by soybean under the M1-CS treatment and greater exploitation of soil N resources under the CS-M2 treatment. As a result, we might conclude that the high NUE of the CS-P3-M2 treatment has occurred, in part, as a result of changes that soybeans impart on storage of labile soil N and a resultant exploitation of soil N reserves.

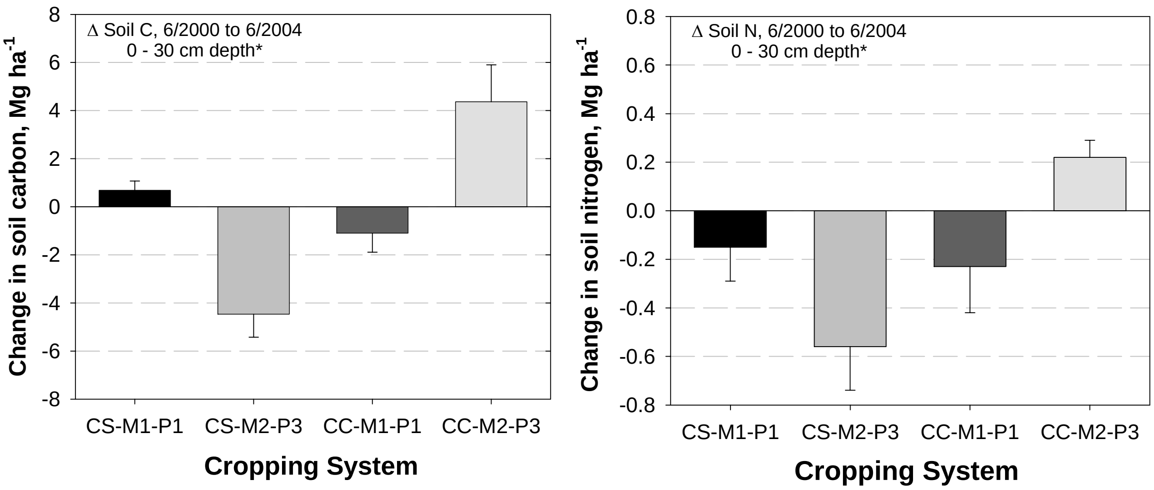

Figure 3. Change in total soil C and N in the upper 30 cm of soil from samples taken in June 2000 and June 2004 as influenced by crop rotation, plant density, and nutrient management. *Soil C and N expressed on the basis of a fixed soil mass = 400 kg/m^2 which is approximately 30 cm of soil depth (Gifford and Roderick, 2003).

Table 5. Cumulative four-year fertilizer N input and grain N removal as influenced by crop rotation, population density, and fertility management (2000-2003).

Treatments		Cumulative Fertilizer N input	Cumulative Grain N removal	Fertilizer N Input minus Grain N Removal
Density	**Fertilizer**			
<u>Continuous Corn</u>		----------------------------kg N $hectare^{-1}$-------------------------------------		
P1	M1	779	673	+106
P3	M2	1218	794	+427
<u>Corn after Soybean</u>				
P1	M1	275	964	-689
P3	M2	714	1008	-294

Conclusions

Yields approaching 90 percent of the yield potential of corn have been routinely achieved in the Ecological Intensification project at Lincoln, Nebraska. We have observed a trend toward improvement in N fertilizer use efficiency that, in part, is due to a gain in soil C and N storage as a result of intensive management in the continuous corn system. Higher NUE under the CS rotation has resulted in some exploitation (loss) of soil N reserves and the role of N_2 fixation in replacement of N removed in grain harvest must be considered with respect to the effect that fertilizer N management in the corn year has on establishment of fixation capacity on soybean. Although NUE was lowest in the CC-M2 treatment, credit should be given to the efficiency of added N in augmenting soil N sequestration of the N. Closing the yield gap requires higher plant population and improved nutrient management to maintain efficient and profitable improvement in maize production. Soil quality improvements and higher residue inputs under intensive management should make this task easier with time.

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References

Cassman, K.G., A. Dobermann and D.T. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31:132-140.

Cassman, K. G., A. Dobermann, D.T. Walters, and H. Yang. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Ann. Rev. Environ. Resour. 28: 315-58

Gifford, R.M. and M.L. Roderick. 2002. Soil carbon stocks and bulk density: spatial or cumulative mass coordinates of expression? Global Change Biology 9:1507-1514.

Shapiro, C.A., R.B. Ferguson, G.W. Hergert, A. Dobermann, and C.S. Wortmann. 2001. Fertilizer suggestions for corn. NebGuide G74-174A. University of Nebraska Coop. Ext. Serv., Lincoln, NE.

Van Ittersum, M.K., P.A. Leffelaar, H. van Keulen, M.J. Kropff, L. Bastiaans, and J. Goudriaan. 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18:201-234.

Yang, H.S., A. Dobermann, J.L. Lindquist, D.T. Walters, and K.G. Cassman. 2004a. Hybrid-Maize - A maize simulation model that two crop modeling approaches. Field Crops Res. 87:131-154.

Yang, H.S., A. Dobermann, K.G. Cassman, and D.T. Walters. 2004b. Hybrid-Maize. A simulation model for corn growth and yield. Nebraska Cooperative Extension CD 9, University of Nebraska-Lincoln, Lincoln. http://www.hybridmaize.unl.edu.