Ecological Intensification of Corn-Based Cropping Systems

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Introduction

Meeting the projected global demand for food and fuel from corn systems while conserving natural resources and improving environmental quality can only be achieved by the intensification of existing corn systems (Cassman, 1999; Cassman et al., 2003). Yield analysis of the central U.S. corn-belt indicates that there is a large exploitable yield gap for corn. Since 1999 we have been experimenting with optimizing corn management systems to exploit corn yield potential. To date, our experience has shown that considerable yield increases are realized by choosing the right combination of adapted varieties, planting date and plant populations to maximize crop productivity. In addition, more intensive N management strategies that focus both on improving crop N use efficiency and residue carbon management also contribute to reducing nitrogen input over the longer-term through increases in soil organic matter and N storage that can increase the indigenous soil N supply capacity. In addition, intensification has not resulted in significant increases in the global warming potential of these cropping systems.

Yield potential

Corn yield potential represents the maximum achievable grain yield of an adapted cultivar or hybrid when grown with minimal biotic or abiotic stresses. Here the only limitations are temperature, solar radiation and genetics. How do we measure yield potential for a given region? That is best done by cultivating the crop in field experiments under optimal management without nutrient or water limitations and careful control of diseases, insect pests and weeds. An alternate and more convenient means of estimating yield potential is with well calibrated mechanistic simulation models. Figure 1 shows a timeline of National Corn Growers Association yield contest winners for the irrigated and rainfed categories with both first and second place winners in each year. Except for the 1999-2002 period, and the most recent year in 2007, the first and second place yields are very similar and the gap between irrigated and rainfed yields has narrowed owing to better adapted, more stress resistant cultivars (Duvick and Cassman, 1999). The outliers in 1999-2002 were the yields reported by Frances Childs from Manchester Iowa, which could not be verified by simulation using the actual corn hybrid and climate data at this site (Yang et al., 2004), and which were subsequently disqualified because the standard yield verification procedures used at this site did not follow contest guidelines. In fact, Mr. Childs was subsequently accused of cheating in a court case (Waterloo-Cedar Falls Courier, 2004). The 2007 yields for the irrigated category also appear to be suspicious in that they are well above the trend line of the past 18 years (excluding the disqualified yields from 1999-2002). Moreover, both the first and second place yields from 2007 come from the same farmer. Until these yields can be verified with a robust crop simulation model, we do not believe they can be relied upon as evidence that the yield plateau has been broken for winning yields in the irrigated class.

Instead, we believe that corn yield potential for the irrigated category hovers around the 300-320 bu/a range which identifies this as the probable yield ceiling, except in years with exceptional climate stress, such as the unusually high temperatures of the 1988 growing season. Figure 2 shows a similar exercise whereby yield potential is estimated with the Hybrid-maize model (Yang et al., 2004) over a wide range of sites within the U.S. corn-belt. Based upon these simulations, a ceiling-yield for corn yield potential is estimated to be in the same range as the NCGA contest winners, excluding the 1999-2002 disqualified yields and the most recent 2007 yield. The model simulation indicates that a minimum of 60 days of reproductive growth is needed to achieve this yield potential. Hence, abnormally hot years would limit corn yield potential due to rapid GDD accumulation and a shortened grainfilling period. These data also suggest that limitations in nutrient management, plant population and disease suppression have limited average Corn Belt farm yields to 60% of yield potential. At issue is whether closing this yield gap can be achieved in a sustainable fashion with minimal environmental impact and without increasing GHG emissions from agricultural land. To assess such options requires full accounting of the global warming potential (GWP) of agricultural systems including the net changes in soil organic carbon (SOC), the energy consumed in crop production and the trace gas emissions (notably N_2O) associated with N management.

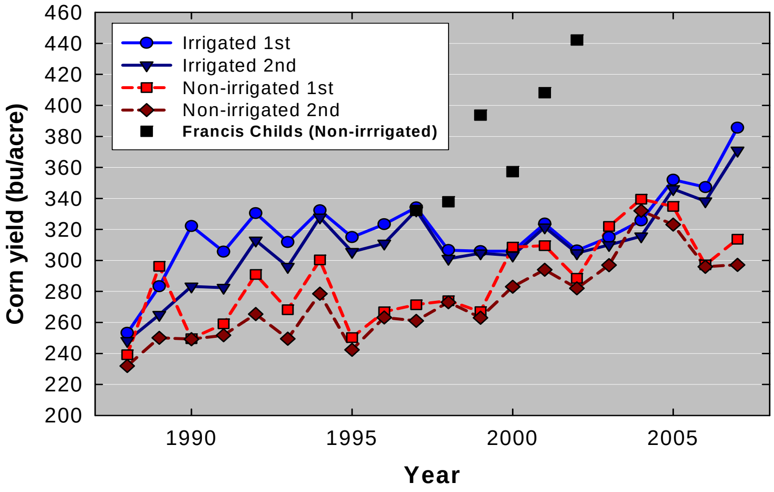

Figure 1. Yield trend for irrigated and non-irrigated corn yield contest winners of the NCGA through 2007.

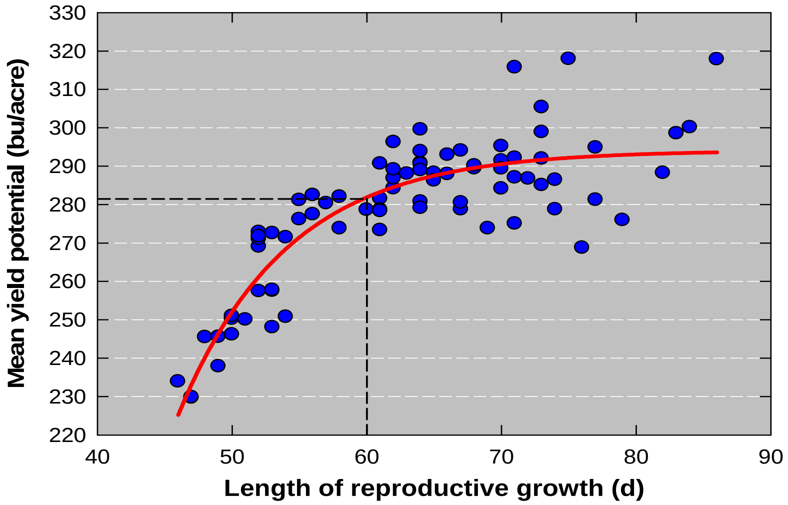

Figure 2. Hybrid-Maize simulated corn yield for 80 locations across the U.S. corn-belt within Lat 32.7-42.7 N; Long 88-102 W; Elev. 130 – 1390 m. Hybrid: 2650 GDU (110 d CRM); Planting date: May 1, 40,000 plants/acre. Management: no limitations by water or nutrients.

The Ecological Intensification Experiment

In order to address these questions, a long-term experiment was established in 1999 in Lincoln, NE. The primary objective of this experiment is to evaluate resource-efficient management concepts for achieving crop yields that approach the climatic yield potential. The soil at this site is a deep Kennebec silty clay loam with high soil fertility status (pH 6 to 6.5, 2.5 to 3% organic matter, 300 to 400 ppm K, and 60 – 80 ppm Bray P-1 P) The experiment is conducted with three crop rotations as main plots (CC- continuous corn, CS or SC – corn soybean rotation with an entry point into each crop in each year), three plant populations densities as sub-plots and two levels of nutrient management (recommended and intensive) as the final split. For this paper, four management systems are evaluated, CC-recommended management, CC-intensive management, CS-recommended and CS-intensive. Table 1 summarizes the range in nutrient management, population and yield for these treatments through 2005.

Average crop yields in this experiment were close to the yield potential of soybean and corn at this location and significantly higher than the national or state average. Corn yields were generally in the 215 to 287 bu/a range or within 84 to 97% of the simulated yield potential. Corn following soybean yielded about 5 to 11% higher than continuous corn primarily due to fewer problems with stand establishment and fewer pest and disease problems.

Table 1. Crop management practices and grain yields in continuous corn (CC) and corn/soybean rotation (CS) systems with recommended (-rec) or intensive (-int) management (2000-2005).

	CS-Rec	CS-Int	CC-Rec	CC-Int
Yield goal (% of yield potential)	80-90	90-100	80-90	90-100
Plant density, corn (1000 pl/a)	30	35-40	30	35-40
N applied to corn (lb/a)	118-127	209-227	164-218	227-281
no. of N applications to corn	2	4	2	4
N on corn residue in fall (lb/a)	0	45	0	45
N applied to soybean (lb/a)	0	70	0	70
P & K applications (lb/a)	0	40/75	0	40/75
Avg. annual N application (lb/a)	64	156	183	272
Average corn yield (bu/a)	234	249	223	239
Average soybean yield (bu/a)	72	75	-	-

Since the start of this experiment, large amounts of crop residue have been returned to the soil in all four management systems, but with significant differences among them in terms of dry matter amounts and composition. Corn returned 75 to 100% more residue than soybean, but with a much wider C/N ratio. On a whole crop rotation basis, average annual C return with above-ground residue increased in the order CS-rec < CS-int (+8%) < CC-rec (+22%) < CC-int (+39%), whereas residue N inputs followed the order CC-rec < CS-rec < CS-int < CC-int. (Fig. 3). Both residue C and N input were highest in the CC-int system, exceeding the more commonly practiced CS-rec system by 30 to 40%.

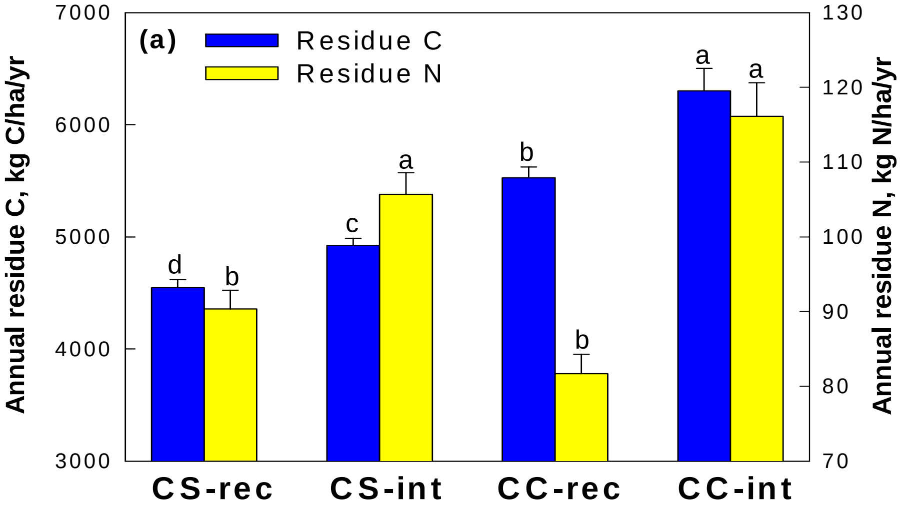

Figure 3. Average annual carbon and nitrogen input to soil in crop residues (2000 – 2006). CS = corn/soybean rotation; CC = continuous corn; rec = recommended nutrient management; int = intensive nutrient management.

Changes in Soil Organic Carbon and Nitrogen

Despite the large biomass production in our high yielding corn systems, peak growing season (about 36 to 55 lb C/a/day) soil CO_2 efflux was within typical ranges for arable crops. In a complete 2-year crop rotation with flux measurements conducted in corn and soybean, soil CO_2 efflux (respiration) in the continuous corn systems was 22% larger than in corn-soybean rotations at both levels of management intensity. Within each crop rotation, intensified fertility management did not cause a significant increase in soil CO_2 emissions as compared to the recommended practice. As a result, both SOC and total soil N (TSN) increased in the two CC systems, but decreased in the CS-rec or remained unchanged in the CS-int system. On average, SOC *declined* at an average rate of 275 lb/acre/yr in the CS-rec, whereas it *increased* at a rate of 565 lb N/acre/yr in the CC-intensive (0-12" depth). Similar trends were observed for TSN (Figure 4).

In the intensive continuous corn systems, incorporation of large amounts of residue C and N has led to a significant build-up of SOM over just a few years. Although corn yields and N use efficiency were higher for the intensive corn-soybean rotation, this excellent performance was achieved at the cost of exploiting C and N reserves. Our results here confirm those of recent eddy covariance studies at other sites, showing that significant net C losses during the soybean phase of the CS rotation prohibit gains in SOC (Verma et al., 2005; Baker and Griffiths, 2005). These observations lead us to conclude that the N-credit attributed to corn-soybean rotations appears to be due to mining of soil N reserves. Significant potential for sequestration of atmospheric C therefore exists in intensively managed continuous corn systems. In the CC-int, 14% more crop residue C was returned to the soil than in the CC-rec treatment.

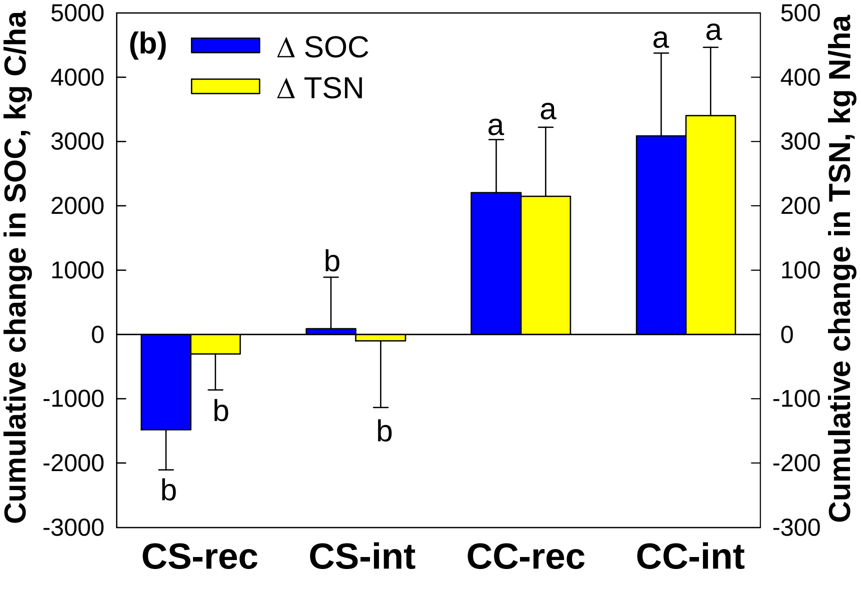

Figure 4. Cumulative change in soil carbon (SOC) and soil nitrogen (TSN) after six years of treatment. CS = corn/soybean rotation; CC = continuous corn; rec = recommended nutrient management; int = intensive nutrient management. Soil samples collected in June 2000 and 2006, 0-12"

Nitrogen use efficiency

Table 2 presents the overall N balance and N use efficiency of the four systems. Without consideration of the change in soil TSN status, most researchers would calculate N use efficiency as the total amount of N in grain / N application rate. One can see that this calculation gives an artificially high N use efficiency for the CS-rec system compared to the CS-int or CC systems. It would seem more appropriate to calculate a system-level N use efficiency given the measured loss in TSN and SOC with soybean in rotation with corn.

Table 2. System level N use efficiency in continuous corn (CC) and corn/soybean rotation (CS) systems with recommended (-rec) or intensive (-int) management (2000-2005).

	CS-Rec	**CS-Int**	**CC-Rec**	**CC-Int**
Annual fertilizer N input, lb N/a	64	156	183	272
Annual N removal with grain, lb N/a	208	216	160	176
Change in total soil N , 0-12”, lb N/a	-27	-9	195	309
Nitrogen use efficiency				
lb N in C+S grain / lb N applied	3.27	1.38	0.88	0.65
lb grain N + change in soil N / lb N applied	2.84	1.33	1.95	1.79

Note that the additional sequestration of soil N in the CC systems has resulted in system-level N use efficiencies that are more than double those determined without soil improvement as a consideration. Conversely, the system level N use efficiency for the CS-rec system represented a 13% decline (form 3.27 to 2.84) with consideration of soil N loss.

Global Warming Potential

When fossil fuel consumption, CO_2-C losses and trace gas emissions are factored into total GWP of these systems, all four cropping systems were net sources of GHG, with GWP ranging from 0.54 to 1.02 tons of CO_2-C/acre/year. Positive or negative changes in SOC, intrinsic C costs associated with crop production and soil N_2O emissions were major contributors to the net GWP. The oxidation of CH_4 (methane) by these soils gave only a small mitigation capacity (Table 3). Nitrogen fertilizer (16 to 36%), energy used for irrigation (15 to 22%), electricity for grain drying (13 to 18%), diesel (10 to 16%), and lime (9 to 13%) were the major components of the C costs associated with agricultural production. Despite higher C costs associated with agricultural production and also higher N_2O emissions, net GWP in the continuous maize systems was lower than that of the corn-soybean systems because sequestration of atmospheric CO_2 in SOC was observed only in the CC systems. Although the amount of N fertilizer N applied to corn grown in the intensive cropping systems was 40% (CC) or 64 to 92% (CS) greater than the recommended treatments, N_2O losses were not directly related to the level of N input only. Significant N_2O losses were observed during the soybean year especially after soybean harvest.

Table 1. Global warming potential (GWP) expressed as CO_2-C equivalents for continuous corn and corn-soybean rotation. Averages for corn and soybean grown during 2000-2005. GWP = Agricultural production + ΔSOC + soil N_2O + soil CH_4. A negative number indicates sequestration of C from the atmosphere.

GWP components		Continuous Corn		Corn-Soybean	
		Recomm.	Intensive	Recomm.	Intensive
		Tons CO_2-C equivalents / acre/ yr			
Agricultural Production	N fertilizer	0.22	0.33	0.08	0.18
	P,K, fertilizer	0	0.06	0	0.06
	Lime	0.06	0.09	0.06	0.09
	Seed, pesticides	0.05	0.06	0.05	0.06
	Machinery	0.02	0.03	0.02	0.03
	Diesel	0.09	0.09	0.08	0.08
	Irrigation	0.14	0.14	0.11	0.11
	Grain drying	0.11	0.12	0.09	0.10
Total		0.69	0.92	0.49	0.71
Soil C		-0.44	-0.62	0.30	-0.02
Soil N_2O		0.32	0.57	0.25	0.34
Soil CH_4		-0.03	-0.03	-0.02	-0.10
GWP		**0.54**	**0.84**	**1.02**	**1.02**

Conclusions

At a time when there is growing concern about the ability to produce adequate corn to meet demand for food, feed, and fuel (Cassman and Liska, 2007), the results from our research highlight several important points. First, while corn yield potential appears to have remained relatively stable over the past 18 years, there remains a large gap between average corn yields currently achieved by farmers and the yield potential ceiling that can be exploited through improved crop management practices. Second, intensification of cropping does not necessarily increase GHG emissions and GWP of agricultural systems provided that crops are grown with best management practices and near yield potential levels, resulting in high resource use efficiency. Therefore, high-yielding continuous corn systems have significant potential for GHG mitigation, particularly if corn grain is converted to bioethanol. Managing at high yield levels creates large sinks for C and mineral N, thereby providing the prerequisite for sequestering atmospheric CO_2 and avoiding large N_2O emissions that could result from inefficient utilization of soil or fertilizer N.

Finally, the N credit associated with corn soybean rotations appears to be the result of soil N exploitation. Net soil C loss was recorded for the conventional corn-soybean rotation. Other studies utilizing eddy covariance techniques confirm that the total gross C fixation (GPP) by corn is twice that of soybean. Ecosystem respiration of corn, however, is only 60% of corn GPP but is 85% of GPP for soybean. Thus the net C sequestration potential of corn is four times as great as soybean. The great differences in corn and soybean C sequestration potential suggest that continuous corn systems may indeed hold greater promise for mitigation of global warming than the conventional corn soybean rotation.

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