Global Warming Potential of High-Yielding Continuous Corn and Corn-Soybean Systems

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The global warming potential (GWP) of recommended (average) and intensive (high-yield) levels of management for both continuous corn (CC) and corn-soybean (CS) rotations was determined in this Nebraska study. Measurements included net changes in soil organic carbon (SOC), intrinsic C costs associated with crop production, and net emissions of greenhouse gases (GHG) such as N_2O and CH_4. Results indicate that intensification of cropping does not necessarily increase GHG emissions and GWP of agricultural systems provided that crops are grown with best management practices (BMPs) and near yield potential levels. In fact, high-yielding CC systems have significant potential for GHG mitigation, particularly when corn is converted to ethanol.

Meeting the future global demand for corn (maize) and soybean, including the rapidly rising feedstock demand for biofuel production, will largely have to be achieved through yield increases (Cassman et al., 2003). Average crop yields may have to approach 80% of the yield potential or more, particularly in areas with favorable rainfall or irrigation. At issue is whether such high crop yields can be achieved without increasing GHG emissions from agricultural land. A central hypothesis for such an ecological intensification of agriculture is that an optimal balance of high productivity, sustainability, and minimal environmental impact can be achieved by fine-tuning of management towards better exploitation of crop yield potential. To assess such options requires full accounting of the GWP of agricultural systems, including net changes in SOC, intrinsic C costs associated with crop production, and net emissions of GHG such as N_2O and CH_4. Such information is scarce for cropping systems that are designed to explore the upper limits of agriculture.

The Ecological Intensification Experiment

A long-term experiment on Ecological Intensification of Irrigated Maize-Based Cropping Systems was established in 1999 in Lincoln, Nebraska, USA. The primary objective of this study is to evaluate resource-efficient management concepts for achieving crop yields that approach the climatic yield potential. In this article, we summarize the net GWP of four high-yielding cropping systems. The soil at the study site is a deep Kennebec silty clay loam with relatively high soil fertility status (pH 6 to 6.5, 2.5 to 3% organic matter, 300 to 400 ppm K, and 60 to 80 ppm Bray-1 P). The field experiment was conducted with three crop rotations as main plots (CC – continuous corn, CS – corn-soybean with corn in even years, SC – corn-soybean with corn in odd years), three plant population densities as sub-plots and two levels of nutrient management as sub-subplots. Four management systems were selected for this analysis: 1) CC-rec: continuous corn with recommended management, 2) CC-int: continuous corn with intensified management, 3) CS-rec: corn-soybean rotation with recommended management, and 4) CS-int: corn-soybean rotation with intensified management.

Management practices are summarized in **Table 1**. The CC-rec and CS-rec systems represent recommended plant populations and nutrient and water management practices for growing irrigated corn and soybean in eastern Nebraska, aiming at corn yields of about 14 Mg/ha (223 bu/A). In the CC-int and CS-int systems, management aimed at corn yields of about 18 Mg/ha (287 bu/A), which is equivalent to the climatic yield potential at this site in favorable years. Key additional measures included increased plant populations, increased fertilizer rates, and more frequent N applications to achieve high N use efficiency at high input levels. In all systems, annual amounts of fertilizer-N were adjusted using an algorithm which includes yield goal, SOM content, residual NO_3-N in spring, and credits given to legumes as previous crops, manure, or N applied with irrigation water (Shapiro et al., 2003). In CC-rec and CS-rec, N fertilizer was applied pre-plant (50 to 60%) and at 6-leaf stage of corn. In CC-int and CS-int, N application to corn was done in four split applications (pre-plant, V6, V10, shortly before tasseling). Since 2001 (CC-int) or 2004 (CS-int), N management in the two intensive systems included an additional N application of 50 kg/ha (45 lb/A) on the corn residue before plowing in fall to facilitate better decomposition and humification of corn residue. Nitrogen rates of the succeeding crop were adjusted accordingly. Under soybean, N fertilizer was applied only in the CS-int system at R3.5 stage. Due to high soil test levels, no P and K fertilizer was applied in CC-rec and CS-rec, but corn and soybean grown in CC-int and CS-int received annual applications of P and K to replenish crop removal.

Soil surface fluxes of CO_2, N_2O, and CH_4 and associated environmental variables were measured weekly to bi-weekly during the 2003 to 2005 growing seasons using a portable photoacoustic spectrometer. Changes in SOC and total soil N (TSN) in the top 0.3 m (1 ft.) were measured by collecting soil samples in June of 2000 and 2005. Total SOC and TSN stocks were calculated for a dry soil mass of about 0.3 m depth as described by Gifford and Roderick (2003). Grain yields of corn (15.5% moisture) and soybean (13% moisture) as well as crop N and C uptake in different plant parts were determined annually. Calculation of net GWP followed Robertson and Grace (2004) and included intrinsic C costs associated with all production inputs and field operations, measured changes in SOC, and measured fluxes of N_2O and CH_4.

Crop Yields and Crop Residues

Abbreviations and notes for this article: C = carbon; CO_2 = carbon dioxide; ppm = parts per million; N = nitrogen; N_2O = nitrous oxide; CH_4 = methane; SOM = soil organic matter; NO_3^- = nitrate.

Table 1. Crop management practices, grain yields, and crop residue input in continuous maize (CC) and maize-soybean (CS) systems with recommended (-rec) or intensive management (-int).

	CC-rec	CC-int	CS-rec[1]	CS-int[1]
Plant population, plants/m^2	7-9	9-11	7-9 (C);25-28 (S)	9-11 (C); 28-35 (S)
Row spacing, m	0.76	0.76	0.76	0.76 (C); 0.38 or 0.76 (S)
Annual N application, kg N/ha	180-240	250-310	130-140 (C); 0 (S)	230-250 (C); 80-130 (S)
N applications during growing season	2	4	2 (C); 0 (S)	4 (C); 1 (S)
N application on maize residue in fall	None	since 2001	None	since 2004
Annual P application, kg P/ha	0	45	0	45
Annual K application, kg K/ha	0	85	0	85
Long-term averages, 2000-2005:				
Annual fertilizer N input, kg N/ha	201	299	70	172
Annual total crop N uptake, kg N/ha	260	317	324	346
Annual N removal with grain, kg N/ha	176	194	229	238
Grain yield of corn, Mg/ha	13.95	14.95	14.71	15.61
Grain yield of soybean, Mg/ha	–	–	4.89	5.02

[1]C and S indicate corn and soybean crops, respectively.

Average crop yields in this long-term experiment (**Table 1**) were close to the yield potential of soybean and corn at the location and significantly higher than national or state averages. Corn yields were generally in the 13.5 to 18 Mg/ha (215 to 287 bu/A) range or within 84 to 97% of the simulated yield potential. Corn following soybean (CS) yielded about 5 to 11% higher than continuous corn (CC), primarily due to fewer problems with crop establishment and some insect pests. Soybean yields averaged about 5 Mg/ha (74 bu/A), with a maximum yield of 5.9 Mg/ha (88 bu/A) measured in 2001. Nitrogen use efficiency in corn grown in 2003-2004, calculated as amount of grain produced per kg N applied, increased in the order CC-int (62) < CS-int < CC-rec < CS-rec (123 kg/kg), which is significantly higher than national averages of about 58 to 60 kg/kg achieved in recent years.

Since the start of this experiment in 1999, 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 (**Figure 1**). 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 (**Figure 2a**). 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%.

Changes in SOC

Despite the large biomass production in our high-yielding maize systems, peak growing season (about 40 to 60 kg/ha/day) or annual (4,300 to 10,200 kg C/ha/yr) 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 (2004 – 2005), soil CO_2 efflux in the continuous corn systems was 22% larger than in corn-soybean rotations at both levels of management intensity. Within each crop rotation, however, intensified management did not cause a significant increase in CO_2 emissions as compared to the recommended practice. Hence, increasing crop productivity is a key measure for increasing the soil C sequestration potential.

Both SOC and TSN increased in the two CC systems, but decreased in CS-rec or remained unchanged in CS-int (**Figure 2b**). On average, SOC declined at an annual rate of 300 kg C/ha/yr in CS-rec, whereas it increased at a rate of 620 kg C/ha/yr in CC-int. Similar trends were observed for TSN. The different changes in SOC and TSN largely reflected the differences in crop residue amounts and composition (**Figure 2a**). 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 a few years. Although corn yields and N use efficiency were highest in the intensive corn-soybean system (**Table 1**), this excellent performance was achieved at the cost of exploiting soil C and N reserves.

Our results confirm those of recent eddy covariance studies at other sites, showing that significant net C losses during the soybean phase limit the soil C sequestration potential in corn-soybean rotations of North America (Baker and Griffis, 2005; Verma et al., 2005). Large grain N removal, less residue input, and rapid cycling of soybean residue through young organic matter fractions were observed in the CS rotation, leading us to conclude that the N-credit attributed to corn-soybean rotations

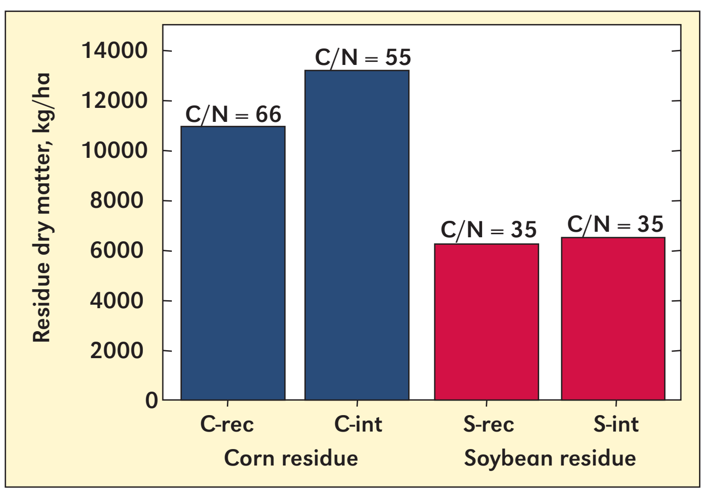

Figure 1. Average annual input of crop residues in recommended (-rec) and intensively managed (-int) systems at Lincoln, Nebraska.

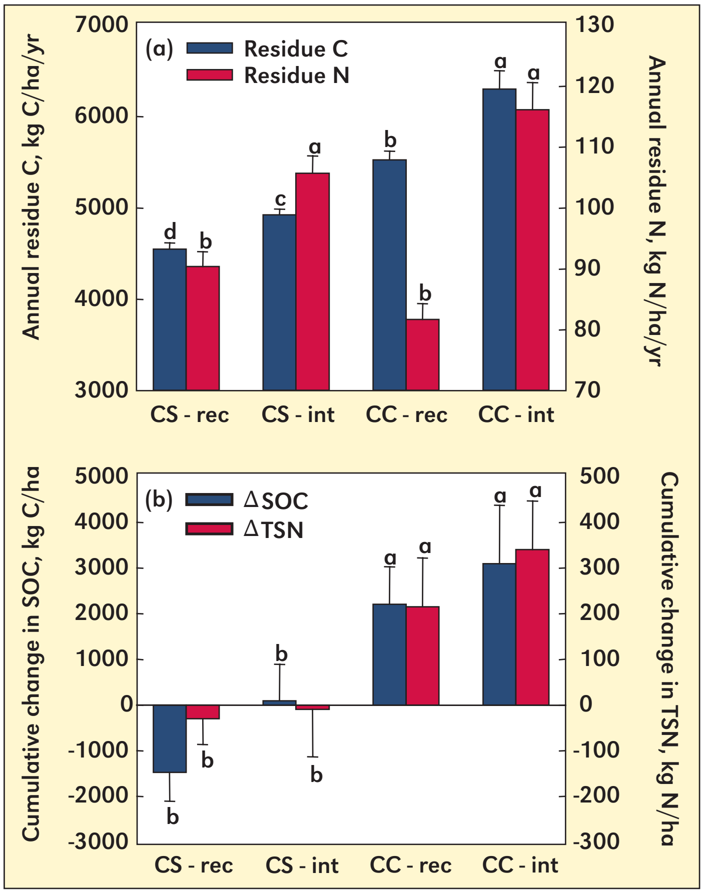

Figure 2. Average annual input of C and N with aboveground crop residues during 1999-2004 (a) and changes in soil organic C (SOC) and total soil N (TSN) for the corresponding period (b) in continuous maize (CC) and maize-soybean (CS) systems at Lincoln, Nebraska. Means and standard errors of two population densities for each management system. Letters indicate statistical significance ($p<0.05$) of treatment differences (Holm-Sidak test).

appears to be due to "mining" of soil N reserves. Soybean has the effect of temporarily storing more N and labile C in the light and mobile humic acid fractions of SOM, which is then lost in the corn year due to mineralization to satisfy crop N demand. Under intensive management with very high crop N demand, this can result in a net decline of soil C and N over time.

Significant potential for sequestration of atmospheric C exists in intensively managed continuous corn systems. In CC-int, 14% more crop residue C was returned to the soil than in CC-rec, but there was no significant difference in soil CO_2 fluxes. Likewise, residue C amounts in CC-int were 28 to 39% larger than in the two corn-soybean systems, but the soil CO_2 efflux increase was only about 20%. Conditions for humification and accumulation of C and N in more recalcitrant SOM fractions appear to be more favorable in continuous corn systems, particularly when residue is incorporated in the soil and sufficient N is available to support the humification process. Applying N fertilizer in fall on corn residue followed by relatively deep but non-inverting incorporation probably enhanced the formation of more stable humus compounds resulting from residue decomposition during the fall to spring period. This seems to contradict the widespread notion that conservation tillage is required for sequestering atmospheric CO_2 in agricultural soils. Recent studies suggest, however, that when sampling is done deep enough and SOC stocks are properly expressed on an equivalent soil dry mass basis, the potential for no-till systems to sequester atmospheric CO_2 in SOC seems limited (VandenBygaart and Angers, 2006; Baker et al., 2007). Particularly in high-yielding systems with large amounts of crop residue, no-till cropping is not necessarily the best management strategy because of high CO_2 respiration losses from the soil surface (Verma et al., 2005).

Global Warming Potential

With conventional use of corn and soybean grain, all four cropping systems where net sources of GHG, with GWP ranging from 540 to 1,020 kg CO_2-C/ha/yr (**Table 2**). 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, whereas CH_4 oxidation added only little mitigation capacity. 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 the agricultural production. Despite higher C cost associated with crop production and also higher N_2O emissions, net GWP in continuous maize systems was lower than that of the corn-soybean systems because sequestration of atmospheric CO_2 in SOC was observed in both CC systems (**Table 2**). Within each crop rotation, intensification of management practices increased production C costs and also N_2O emissions, but when combined with the net change in SOC resulted in only slightly higher GWP for CC-int as compared to CC-rec or no change in GWP for CS-int as compared to CS-rec.

Large variations in N_2O emissions among years caused, however, large inter-annual variation in the GWP of these systems. In the CC-rec system, annual N_2O emissions during 2003 to 2005 ranged from 1.28 to 3.92 kg N_2O-N/A, which is equivalent to a GWP range of 320 kg CO_2-C/ha/yr. In the CC-int system, annual N_2O emissions ranged from a low of 1.8 kg N_2O-N/ha in 2005 to a high of 9.24 kg N_2O-N/ha in 2003, or a GWP range of 94 kg CO_2-C/ha/yr. Seasonal variations in soil CO_2 and N_2O fluxes were principally dependent upon temperature, soil water status associated with precipitation and irrigation events, crop growth, and, to a lesser extent soil NO_3-N content. Although the amount of fertilizer N applied to corn grown in the intensive cropping systems was 40% (CC) or 64 to 92% (CS) greater than in the recommended cropping systems, N_2O losses were not directly related to the level of N input only. This contradicts the assumptions made in the current IPCC method, which calculates the contributions of N fertilizer to global anthropogenic N_2O fluxes by assuming that on average 1.25±1% of the N amount applied is lost as N_2O (IPCC, 2001). In our study, N_2O emissions from N fertilizer applied to corn ranged from 1.9 to 3.5% in 2003, 0.8 to 1.5% in 2004, and 0.4 to 0.5% in 2005, with no consistent differences among the four systems. Low N_2O fluxes in 2004 and 2005 illustrated the potential to reduce N_2O emissions from intensively managed agricultural systems.

Table 2. Estimated net global warming potential (GWP) in corn-based cropping systems with recommended and intensive management.

GWP components		Continuous corn (CC) Recomm.	Continuous corn (CC) Intensive	Corn-soybean (CS) Recomm.	Corn-soybean (CS) Intensive
		------------ kg CO_2-C equivalents/ha/yr ------------			
Agricultural Production[1]	N fertilizer	220	330	80	180
	P, K, fertilizer	0	60	0	60
	Lime	60	90	60	90
	Seed, pesticides	50	60	50	60
	Machinery, transport	20	30	20	30
	Diesel	90	90	80	80
	Irrigation	140	140	110	110
	Grain drying	110	120	90	100
	Total	690	920	490	710
Δ Soil C[2]		-440	-620	300	-20
Soil N_2O[3]		320	570	250	340
Soil CH_4[3]		-30	-30	-20	-10
GWP[4]		540	840	1,020	1,020

[1] Carbon cost associated with crop production. Average for corn and soybean crops grown during 2000-2005.
[2] Average annual change in SOC, based on measurements of SOC conducted in June 2000 and June 2005.
[3] Radiative forcing potential for 100 year time frame. CC systems: average of three corn crops (2003-2005); CS systems: weighted average of two corn crops (2003-2004) and one soybean crop (2005).
[4] GWP = Agricultural production + ΔSOC + soil N_2O + soil CH_4.

Reduced N_2O losses may not be the only or most important environmental consequence. Direct measurements of NO_3 leaching and its impact on water quality were beyond the scope of our study, but it is likely that the management practices employed resulted in both reduced N_2O and NO_3 leaching losses. BC

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Conclusions

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. High-yielding continuous corn systems have significant potential for GHG mitigation, particularly when corn is converted to bio-ethanol. Managing a crop at high yield levels creates large sinks for CO_2 and mineral N, thereby providing the prerequisite for sequestering atmospheric CO_2 and avoiding large N_2O emissions that could results from inefficient utilization of soil or fertilizer N.

Major components for improving crop management to reduce GWP are (i) choosing the right combination of adopted varieties, planting date and plant population to maximize yield potential, crop biomass productivity and residue input, (ii) tactical water and N management decisions that minimize energy use, achieve high N use efficiency and avoid high N_2O emissions, and (iii) a tillage and residue management approach that can handle the large amounts of residue produced and favors the build-up of SOM.

Policies that favor greater adoption of such management practices would not only satisfy the increasing demands for crops such as corn and soybean, but may also mitigate GHG emissions from agriculture. Future research should concentrate on demonstrating the potential impact of such management practices at production scale, particularly to determine whether it is possible to reduce the large seasonal fluctuations in N_2O and CO_2 emissions from the soil surface.

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