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Understanding and Managing Corn Yield Potential

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UNDERSTANDING AND MANAGING CORN YIELD POTENTIAL

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TRENDS IN CORN YIELDS AND NUTRIENT USE

Rainfed and irrigated systems in which corn is grown either in rotation with soybean or as a continuous monocrop are the predominant cropping systems in North America. About 30 million ha of corn are harvested annually for grain in the USA, of which eleven states in the Corn Belt produce more than 210 million tons or 35% of the global corn supply (Dobermann and Cassman, 2002). During the past 35 years, average corn yields have increased linearly at a rate of 1.7 bu/acre per year (109 kg ha^{-1} per year, Fig. 1). Average corn yields now approach 140 bu/acre (8.8 t ha^{-1}), but progressive farmers routinely harvest 160 to 220 bu/acre (10 to 14 t ha^{-1}).

Average fertilizer rates used on corn are 130-140 lb N/acre, 45 to 50 lb P_2O_5/acre, and 50 to 60 lb K_2O/acre, but large differences exist among states and among farms within each state (Padgitt et al., 2000). Commercial fertilizer use rose sharply in the 1960s and 1970s in response to the adoption of responsive corn hybrids and favorable economic forces. However, corn yield increases since 1980 were achieved with stagnating fertilizer-N use and declining rates of P and K, leading to significant increases in nutrient use efficiency (bu yield per lb nutrient applied) of these macronutrients (Fig. 1). Average grain output per unit N applied increased from about 0.75 bu/lb N in 1980 to more than 1 bu/lb N in 2000. Since the late 1970s, USA corn farmers have been taking advantage of residual soil P and K reserves built up by previous nutrient applications (Uri, 1998). Average P use has declined at a rate of 0.6 lb P_2O_5/acre per year, average K use by 0.9 lb K_2O/acre per year (Dobermann and Cassman, 2002). Average fertilizer P rates used by corn farmers still exceed the net P nutrient removal, but the difference is declining in recent years. The average P surplus decreased from 33 lb P_2O_5/acre per crop in 1980-1984 to 10 lb P_2O_5/acre per crop in 1996-2000 and areas with negative P balances have become more widespread in recent years.

Three factors have probably contributed most to the improvement in yields and N fertilizer efficiency: (i) more vigorous crop growth associated with increased stress tolerance of modern hybrids (Duvick and Cassman, 1999; Tollenaar and Lee, 2002), (ii) improved crop management (conservation tillage, seed quality and higher plant densities), and (iii) improved N management. Improvements in N management include some reductions in fall-applied N fertilizer with a shift to applications in spring or at planting, greater use of split N fertilizer applications rather than a single large N application, and development and extension of N fertilizer recommendations that give N 'credits' for manure, legume rotations, and residual soil nitrate (Shapiro et al., 2001).

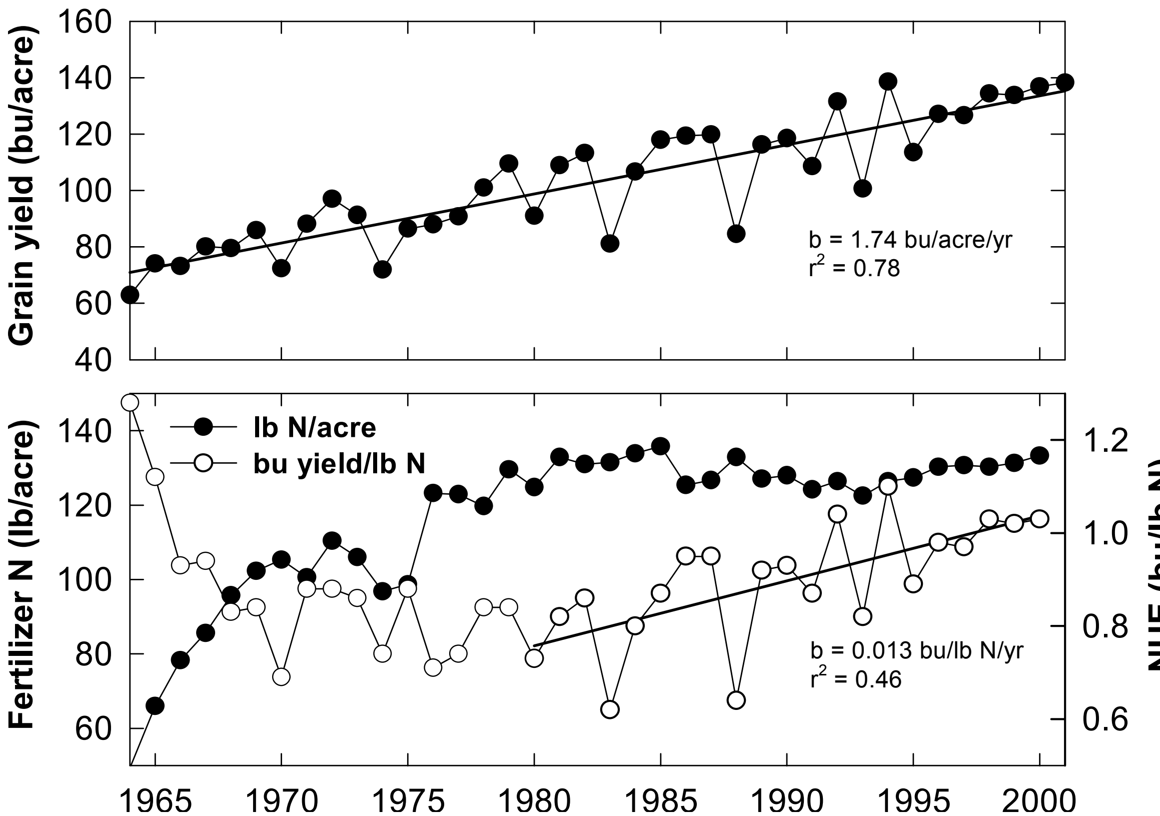

Figure 1. Trends in grain yield, nitrogen use, and N use efficiency (NUE) in corn grown in the USA. Yield data: mean annual yields, National Agricultural Statistics Service, USDA; Fertilizer data: mean N amounts applied, based on USDA Annual Cropping Practices Surveys of more than 2000 farms representing 80 to 90% of the maize area (http://www.ers.usda.gov).

POTENTIAL FOR INTENSIFICATION OF CORN SYSTEMS

Can we be satisfied with what has been achieved and will it be easy to maintain the yield growth rates achieved in the past? Highest corn yields have been reported in yield contests, and the winning yields have been used as a proxy for estimating yield potential and yield potential trends (Evans, 1993; Waggoner, 1994). In leading corn producing states such as Iowa and Nebraska, current average yields are only 40-50% of the yield achieved by contest winners (Fig. 2). What the real yield potential is remains a controversial subject because of the paucity of data from well-designed field experiments in which corn yields approach those reported in the yield contests. The linear increase in winning yields in Iowa beyond 400 bu/acre may suggest that there is no known limit to corn yield potential, whereas the stagnating winning yield of irrigated corn in Nebraska may reflect a yield potential of about 300 bu/acre in that environment.

Despite the progress made in increasing N use efficiency (Fig. 1), recent on-farm data indicate that, on average, only 37% of the applied fertilizer-N is taken up by corn (Cassman et al., 2002). Recovery efficiencies of applied N (lb increase in plant N accumulation per lb N applied) also are highly variable because almost 80% of the N is applied before crop emergence, which makes it vulnerable to losses during the crop establishment phase before the crop can establish an active root system. Only 14% of the corn area receives split applications of N after planting (Padgitt et al., 2000).

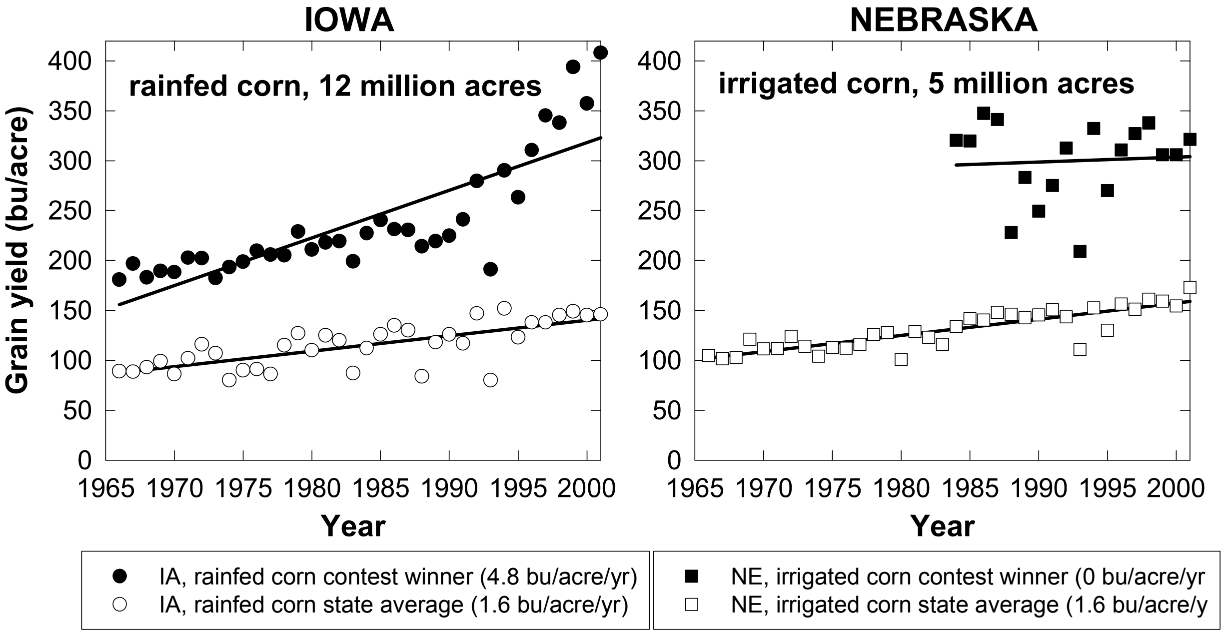

Figure 2. Trends in average grain yield and yields achieved by yield contest winners for rainfed corn in Iowa and irrigated corn in Nebraska.

Crop yield improvement must continue well into the 21st century to meet the world's food and fiber needs and to minimize the conversion to agriculture of land now spared for nature (Waggoner, 1994; Evans, 1998; Young, 1999). Corn yields must continue to increase at a rate of at least 1% per year to keep pace with population growth and dietary shifts associated with increased standards of living (Rosegrant et al., 2001). Globally important intensive agricultural systems such as rainfed and irrigated continuous corn or corn-soybean grown on prime agricultural land will play a key role in sustaining the future global food supply because of their large exploitable gaps in yield and nutrient use efficiency.

The yield gap (Fig. 2) will not be closed by genetic technology. At the farm level, rapid producer adoption of genetic and agronomic technologies has fueled past improvements in harvest index and crop biomass per unit area. However, harvest index in many seed crops is now approaching its natural asymptotic limit, making future seed yield improvement substantially dependent upon increases in crop biomass. Intensified, locally fine-tuned crop and soil management will be necessary to coax more out of the crop biomass potential. There is need to develop integrative scientific understanding of the relationships between soil productivity, crop yield potential, input use efficiency, nitrate leaching, C-sequestration, greenhouse gas fluxes and energy use in corn-based cropping systems (Cassman, 1999). A key challenge is to improve the prediction of soil nutrient supply, fertilizer efficiency, plant nutrient accumulation, and its effect on yield in absolute terms (Dobermann and Cassman, 2002).

THE ECOLOGICAL INTENSIFICATION EXPERIMENT AT LINCOLN, NEBRASKA

A long-term experiment was established in 1999 at Lincoln, Nebraska to address these issues in a high yield setting. The central hypothesis in this study is that intensive corn-based systems can be designed to achieve an optimal balance of productivity, profitability, energy use, and soil C sequestration with minimal nitrate leaching and emission of greenhouse gases by improved management that achieves greater input use efficiency at yield levels that approach yield potential ceilings. The specific objectives of this research are to (1) quantify the yield potential of irrigated corn and soybean and understand the physiological processes determining it, (2) identify cost-effective and environmentally friendly crop management practices to achieve yields that approach attainable levels, (3) determine how changes in soil quality affect the ability to achieve high yields, (4) quantify the nitrate leaching potential, energy use efficiency, soil C-sequestration and net radiative forcing potential of intensive corn-based systems at different levels of management, and (5) develop improved crop and ecosystem simulation models for accurate prediction of yield potential, nutrient efficiency, and carbon sequestration potential under different management scenarios.

Experimental details are described elsewhere (Dobermann et al., 2002). The experiment is conducted on a deep Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludoll). Average initial soil test values in 0 to 20 cm depth were pH 5.3, 2.7% soil organic matter, 67 ppm Bray-P, and 350 ppm exchangeable K. The experiment is conducted with crop rotations as main plots (CC – continuous corn, CS – corn-soybean, SC – soybean-corn), plant population density as sub-plots (corn: P1 - 28-31,000 plants/acre, P2 - 35-41,000 plants/acre, P3 - 38-47,000 plants/acre), and level of fertilizer nutrient management as sub-subplots (M1 - recommended best management practice based on soil testing and a yield goal of 200 bu/acre (Shapiro et al., 2001), M2 - intensive management aiming at yields close to yield potential). The field was fall moldboard plowed in each year to create a deeper topsoil layer. Irrigation was supplied to fully replenish daily crop evapotranspiration via a drip tape system (surface drip tape in 1999 and 2000, sub-surface drip system in 2001-2002, 30 cm deep).

From 1999 to 2002, N rates applied to corn in M1 treatments averaged 116 lb N/acre (130 kg/ha) for CS and 174 lb N/acre (195 kg/ha) for CC rotations, applied pre-plant (50% for CC, 75% for CS) and at V6 stage (remaining amount). No nutrients other than N were applied in the M1 treatments to both crops because soil test values were above currently suggested critical levels of sufficiency. Nutrient rates in M2 were calculated for a yield goal of 300 bu/acre and averaged 219 lb N/acre (245 kg/ha) for CS and 283 lb N/acre (317 kg/ha) for CC rotations, applied pre-plant (30-50%), at V6, V10, and VT stages. In M2, 92 lb P_2O_5/acre (45 kg P/ha) and 93 lb K_2O/acre (85 kg K/ha) were applied to both soybean and corn crops. Key measurements include:

- canopy environmental conditions (climate and intercepted solar radiation,
- crop development rates, aboveground biomass and biomass partitioning, NPK uptake,
- grain and biomass yield, harvest index, components of yield,
- plant C, N, P, K, Ca, Mg, S uptake in aboveground biomass,
- soil physical and chemical characteristics, residual soil nitrate,
- root length density and dry matter,
- soil surface CO_2, N_2O and CH_4 fluxes, and
- total soil microbial biomass, microbial community composition.

CORN PERFORMANCE AT HIGH YIELD LEVELS

Plant density and nutrient management levels significantly affected yield, harvest index, stover yield, components of yield, and nutrient uptake of corn. Intensive fertilizer management (M2) significantly increased yield in all four years over the recommended best management practice (M1, Fig. 3). Average corn yield in the treatment that represents the currently recommended best management practice (CS-P1-M1) was 224 bu/acre, 38% larger than the average irrigated corn yield in Nebraska (162 bu/acre) during the same period.

Maximum grain yields were achieved with M2 nutrient management at final plant densities of 37,000 plants/acre in 2000 (P2), 38,000 plants/acre in 2002 (P3) or 44-46,000 plants/acre in 1999 and 2001 (P3). Highest yields of corn grown after soybean consistently ranged from 243 to 257 bu/acre during 1999 to 2002 (average of 250 bu/acre). This represents a 12% yield increase over the CS-P1-M1 treatment or roughly 50% more than current average farm yields. Interestingly, continuous corn yields were below those obtained in the corn-soybean rotation at the recommended level of nutrient management (M1), but the differences diminished for M2 nutrient management. Because nutrient supply was fine-tuned to each of the two cropping sequences, highest yields obtained under continuous corn cropping were the same as those obtained for corn grown after soybean in both 2001 and 2002 (Fig. 3).

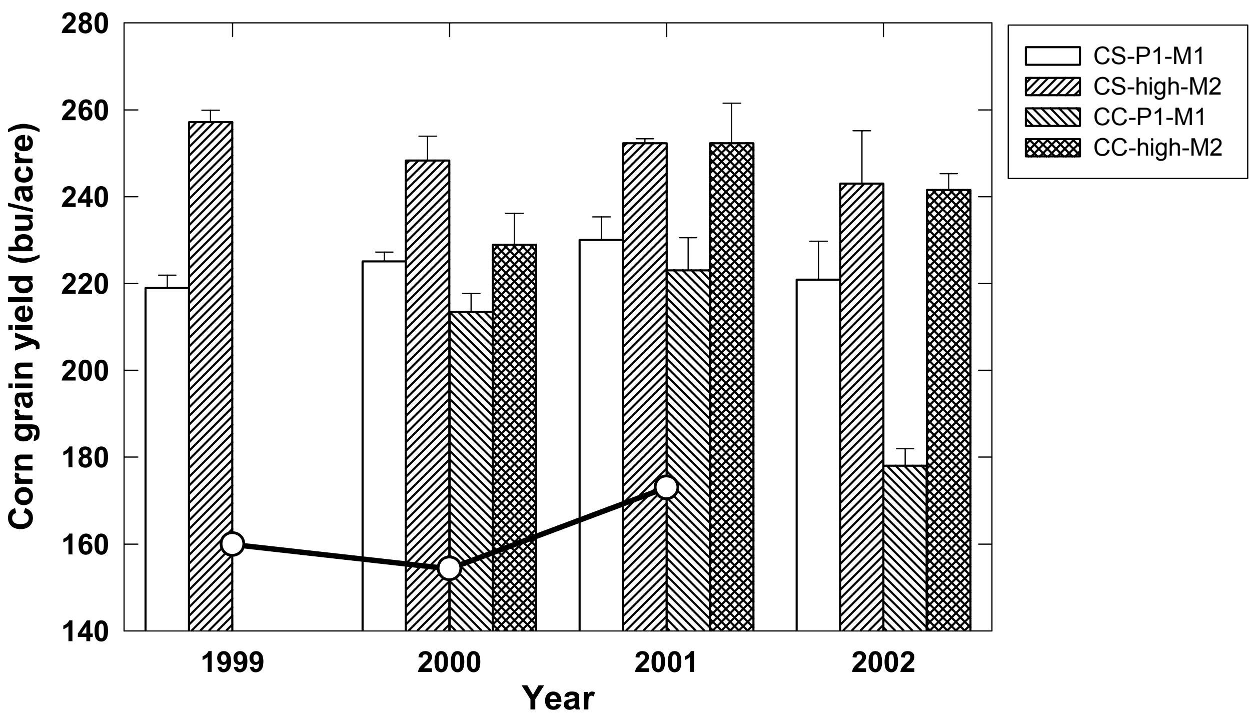

Fig. 3. Corn grain yield (15.5 % moisture) trends in the Ecological Intensification experiment at Lincoln, NE as affected by crop rotation (CC-continuous corn; CS – corn-soybean), fertility management (M1 – recommended; M2 – intensive), and plant population density (P1 – 28-31,000 pl./ac; high –37-46,000 pl./ac). Due to variation of final plant densities at P2 and P3 levels among years, the M2 treatments shown refer to the plant density with the highest yield (P3 in 1999, 2001, and 2002; P2 in 2000). For comparison, the line shows the average irrigated corn yield in Nebraska during the same years.

The consistently high corn yields in M2 treatments were achieved despite large climatic variability during 1999 to 2002, including years with less favorable conditions. Of the four experimental years, three (2000-2002) were characterized by long periods of high temperature and drought. Both 2000 and 2001 were hot and dry during July and August and grain filling mostly took place in August, when the average minimum daily air temperature as well as soil temperature exceeded normal levels by 1.3 to 1.9 ºC (Dobermann et al., 2002). As a result, the grain filling period of corn in 2000 and 2001 was shorter than in normal years. In 2002, average daily maximum temperature throughout the whole growing season was 30.9 ºC, about 2 ºC higher than in the previous years and the long-term average. Average relative humidity in 2002 was 59% as compared to about 65 to 70 % in most years.

These climatic stresses as well as variation in crop establishment and final plant density explained why crop response to plant density and nutrient management levels varied somewhat from year to year. Only in 1999 were the target populations reached and weather was near the long-term average, so that crop responses to plant density and nutrients were most clearly expressed. Grain yield (Fig. 4), plant biomass, and plant uptake of N, P and K (data not shown) increased with increasing plant density and fertilizer management intensity, with a high of 258 bu/acre for the CS-M2-P3 treatment. Grain yield in CS-P3-M2 was 97% of the simulated climatic yield potential, whereas it ranged from 82 to 87% in the M1 treatments. Increasing plant density had no significant effect on yield under M1 management, but increased yields at the M2 level. The yield gap between M1 and M2 increased with increasing plant density (Fig. 4). Crop intensification to close existing yield gaps is likely to require both increases in plant density and nutrient amounts to exploit significant interactions among these two yield determinants.

Across all years, the harvest index of corn decreased with increasing plant density due to greater vegetative biomass accumulation. Stover yield (stalks, leaves, cobs, tassels) increased with both an increase in population and fertility management. For example, averaged over three years, stover yield was 12.2 Mg dry matter/ha in corn after soybean at the currently recommended plant density (P1) and fertilizer management level (M1). In contrast, stover yield at very high density (P3) and intensive fertilizer management (M2) averaged 14.1 Mg/ha. Sink size (no. of kernels/m^2) and the 100-seed weight were about 4% larger in M2 treatments than in M1, but decreased with increasing plant density. Grain weight of individual ears decreased with increasing plant density in both M1 and M2 treatments, but ears in M2 were consistently larger than those in M1, demonstrating the importance of adequate nutrient supply for kernel filling at high yield levels (Fig. 5).

DEVELOPING TOOLS FOR UNDERSTANDING YIELD POTENTIAL

One of the key functions of field experiments such as the one at Lincoln is to provide detailed data sets for developing and validating quantitative tools such as a crop simulation models. If a crop growth model is able to correctly simulate growth dynamics and yields measured under near-optimum field conditions, it is likely to adequately represent the key physiological processes involved. If so, it can be used to develop and test hypotheses about the effects of climate and crop management on yield-forming processes. Extrapolation to other environments then becomes feasible and variations in yield potential due to climate, planting date, hybrid choice (maturity group) and plant density can be studied without laborious experimentation, leading to locally fine-tuned management recommendations.

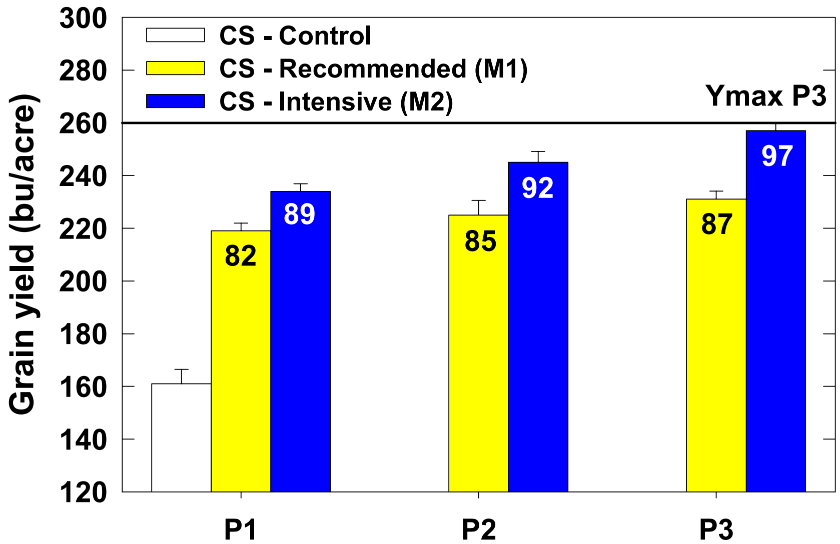

Fig. 4. Corn grain yield in 1999 as affected by the final plant density (P1 – 28,300; P2 – 35,700; P3 – 44,200 plants/acre) and management (M1 – recommended; M2 – intensive). The Ymax line indicates the simulated crop yield potential at P3 plant density (Hybrid-Maize model simulations). Numbers within the bars are the actual yield expressed as percentage of Ymax.

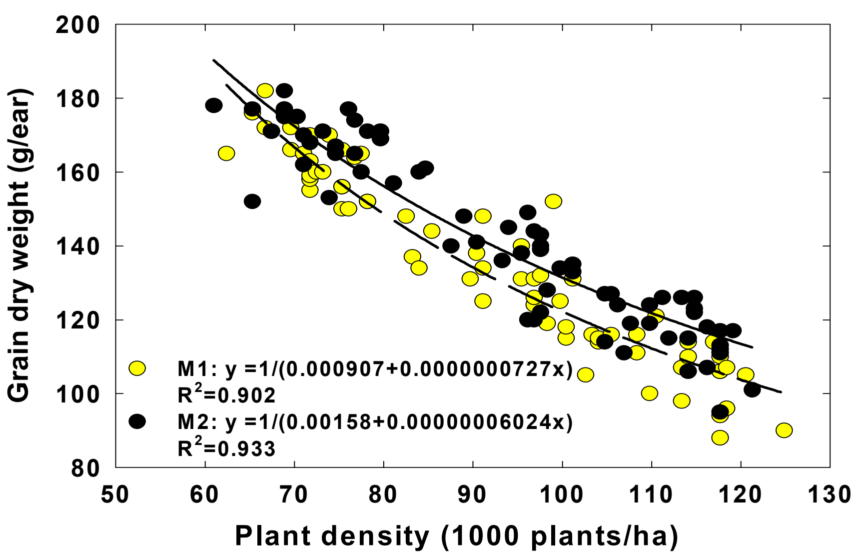

Fig. 5. Corn grain weight per ear as affected by plant density and nutrient management (M1 – recommended fertilizer management; M2 – intensive fertilizer management). Data shown are from both continuous corn and corn-soybean rotation, 1999 to 2001.

However, most corn growth models have so far been evaluated at moderate grain yields of 150 to 200 bu/acre, although yields of 300 bu/acre or more have been reported in the north-central USA. Published versions of existing corn models, Ceres-Maize (Jones and Kiniry, 1986), Muchow-Sinclair (Muchow et al., 1990), and Intercom (Lindquist, 2001), were used to simulate the climatic-genetic yield potential for all three experimental years at the Lincoln site (Table 1). Because there were no obvious abiotic (water, nutrients) or biotic stresses that limited crop growth, all functions for these stresses in the models were ‘turned off’ so that the simulations would reflect cop growth under non-limiting conditions driven by climate (temperature, solar radiation) for a specific planting date and plant density.

The general pattern of simulated aboveground biomass accumulation was in good agreement among the models, but the simulated leaf area index (LAI) varied considerably. The models accurately tracked the actual dry matter accumulation during the establishment phase of corn, but underestimated actual growth rates during the linear growth phase. As a result, the models underestimated the measured grain yield at near-optimal growth by an average of 6 to 26% across all three plant densities. Underestimation of total biomass at maturity was even larger than that (11 to 29%) and the models mostly failed to account for the measured decrease in harvest index (HI) at higher plant populations. Accuracy of simulating vegetative biomass is a concern when modeling long-term carbon balances because of cumulative effects of underestimating crop residue inputs.

Table 1. Simulations of corn grain and stover yields and harvest index at maturity relative to the actual measurements of these parameters in the field experiment at Lincoln, NE. Values shown are average of the CS-P2-M2 treatment for 1999 to 2001 (H. Yang et al., unpublished data).

Crop model	Grain	Stover	Total biomass	HI
	---------------- Mg dry matter/ha		----------------	
Measured (EI trial)	13.2	13.2	26.4	0.50
Ceres-Maize	12.4	11.0	23.4	0.53
Muchow-Sinclair	11.4	11.4	22.8	0.50
Intercom	9.7	9.0	18.7	0.52
Hybrid-Maize	13.1	13.2	26.3	0.50

Efforts were therefore made to develop a new corn model, Hybrid-Maize. This model combines components of several of the crop models tested as well as unique formulations that were derived from the literature and data collected in the UNL Ecological Intensification experiment (H. Yang et al., unpublished). Initial validation suggests that Hybrid-Maize simulated yield, biomass, harvest index, and LAI in near yield potential situations more accurately than other corn models (Table 1). Other advantages include a greater sensitivity to plant density, the ability to simulate maturity based on cumulative growing degree days rather than as a user-defined date, and a user-friendly software.

Hybrid-Maize simulations done for each experimental year and plant density suggested that (i) simulated yield potential in normal plant density treatments (P1) was matched by the measured yields in both rotations and at both nutrient management levels, (ii) measured yields were typically below the simulated yield potential at increased plant density (P2 and P3), but the difference was largest for M1 treatments. The latter suggests a resource limitation, which was at least partially overcome by applying more nutrients in the M2 treatments.

Ongoing applications of the Hybrid-Maize include (i) simulation of planting date scenarios and their effect on yield potential at different locations, (ii) assessment of the inter-annual variability in yield potential based on long-term climate records, (iii) mapping of corn yield potential, optimal planting dates, and best maturity group choices for the whole state of Nebraska, and (iv) yield potential simulations for other locations in the Corn Belt.

NUTRIENT REQUIREMENTS OF CORN

Higher plant density and intensive nutrient management resulted in greater plant accumulation of N and K per unit grain yield, whereas no such differences were observed for P, Ca, Mg, and S (Table 2). Average crop nitrogen accumulation in aboveground biomass was 1.05 lb N/bu yield in the recommended management treatment (CS-P1-M1), but increased to 1.10 lb/bu under CS-P2-M2 management. Similarly, average crop potassium accumulation in aboveground biomass increased from 1.57 lb/bu to 1.86 lb/bu. In contrast, nutrient removal with grain alone did not differ significantly among the nutrient management and plant density levels, except for a slight decrease in grain N removal with increasing cropping intensity (Table 2).

Table 2. Plant nutrient accumulation per unit grain yield as affected by nutrient management and plant density. Averages of 1999 and 2001, corn grown after soybean.

Density	Fertilizer	Yield	N	P_2O_5	K_2O	Mg	S
		bu/acre	lb nutrient per bushel/acre yield				
P1	M1 Recommended		1.05	0.42	1.57	0.12	0.12
P2	M2 intensive	248	1.10	0.41	1.86	0.12	0.11
P1	M1 Recommended	224		0.32	2	0.06	
P2	M2 Intensive	248		0.32	2	0.06	

The measured numbers of total plant nutrient uptake per unit yield shown in Table 2 compare to simulated optimal nutrient requirements at near yield potential level of about 1.08 lb N, 0.46 lb P_2O_5, and 1.40 lb K_2O per bushel yield (Dobermann, 2001). As yields approach existing ceilings internal plant nutrient requirements increase to sustain the physiological functions of a vastly increased amount of aboveground biomass (Witt et al., 1999). This is particularly true for nutrients such as potassium, which has both non-specific and specific plant functions and can be stored in large amounts in the vacuoles of cells. However, potassium uptake in our experiment appears to have exceeded the levels that are typically required for optimal growth (Dobermann, 2001). Future research must clarify what the true crop K requirements for achieving yield potential are and whether the increased K uptake is due to passive influx of K^+ ions with the transpiration stream, which may result from increased plant competition under high-yielding conditions and/or heat stress in some years.

NITROGEN USE EFFICIENCY

Average N use efficiency (NUE) defined as the amount of grain produced per unit fertilizer N varied among cropping systems (Table 3). In the recommended best management practice (CS-P1-M1), NUE of corn averaged 1.91 bu grain per lb N applied, which compares to average NUE in farmers' fields of about 1.03 bu/lb (Fig. 1). Nitrogen use efficiency declined to 1.16 bu/lb in the intensive CS-P2/3-M2 treatment, but remained above typical farm levels. In CC-P2/3-M2, however, NUE was slightly below 1 bu/lb, indicating that N management was not yet fine-tuned enough to achieve good congruence between the dynamics of N supply and crop N demand.

Table 3. Nitrogen use efficiency of corn expressed as bushels yield per lb N applied.

Density	Fertilizer	1999	2000	2001	2002	Mean
			bushel yield/ lb N applied			
Continuous corn						
P1	M1 Recommended	-	1.18	1.25	1.11	1.18
P2/3 [1]	M2 intensive	-	0.71	0.94	0.94	0.86
Corn - soybean						
P1	M1 Recommended	1.89	1.83	1.86	2.06	1.91
P2/3 [1]	M2 Intensive	1.28	0.93	1.16	1.28	1.16

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

Nitrogen use efficiency was highest in 1999, when corn growth mostly occurred under near-normal weather conditions and final plant stands closely matched target populations. In 1999, both agronomic N efficiency (increase in yield per unit N applied) and N uptake efficiency (% of fertilizer-N recovered in the plant) were high and increased with plant density, particularly in M2 treatments. Nitrogen uptake efficiency reached 81% in CS-P1-M1 and 75% in CS-P3-M2, which compares to current farm averages of about 40% (Cassman et al., 2002). This illustrates the potential that exists for improving N efficiency in corn-based cropping systems. More research is required to develop feasible real-time N management schemes that will allow consistently achieving such levels of N use efficiency through improved congruence of crop N demand and N supply.

CARBON SEQUESTRATION POTENTIAL AND GREENHOUSE GAS EMISSIONS

Corn production systems can contribute to solving environmental problems rather than being perceived to be the source of such problems. One such example is the potential of corn systems to fix atmospheric carbon dioxide (CO_2) in crop biomass, through the process of photosynthesis, and to sequester a portion of this fixed carbon (C) in soil organic matter. Corn-based cropping systems in the north-central USA are considered to have significant under-utilized C sequestration potential, but, at average or below average yield levels, potentially positive effects of sequestering C may be offset by high energy use or increased emissions of greenhouse gases such as nitrous oxide (Robertson et al., 2000).

At issue is to quantify the C sequestration potential of continuous corn and corn-soybean rotations as affected by different levels of yield and biomass production. Our over-arching hypothesis is two-fold: (1) through the use of innovative management practices, that increase plant primary production and minimize adverse environmental effects, the major agroecosystems in the north-central USA will substantially increase present rates of C sequestration and (2) by improving our understanding of biophysical controls on annual C balance we can predict the effects of various management practices on C sequestration in these agroecosystems.

The cumulative amount of crop residue C recycled varied widely among cropping systems, depending on crop rotation and primary biomass production as affected by nutrient management and plant densities levels (Fig. 6). In four years, 16.9 Mg C/ha were recycled in the recommended CS-P1-M1 treatment. This amount increased to 19.6 Mg C/ha in the intensified corn-soybean system (CS-P3-M2). However, net C recycling in all continuous corn treatments was larger than in any of the corn-soybean treatments, reaching 20.8 Mg C/ha in CC-P1-M1 and a maximum of 25.4 Mg C/ha in CC-P3-M2.

It remains to be seen how the different levels of C input will affect soil C stocks over time, i.e., what the net annual C sequestration rate is in these different systems and how it slows down over time as soil organic matter levels approach potential ceilings. A rough calculation suggests, however, a greatly increased annual soil sequestration rate under intensive continuous corn management. Compared to CS-P1-M1, 8500 kg C/ha more were added to the soil under CC-P3-M2 management during the 1999 to 2002 period (not including roots). Assuming that about 20% of the residue-C added will remain in the soil as soil organic matter, this net difference in C addition could result in an increase of the annual soil C sequestration by about 400 kg C/ha over the currently recommended management practice in our experiment, sustained at least for several years. It should be noted that, in our study, yields of CS-P1-M1 were already 35 to 40% larger than current farm averages (Fig. 1), suggesting that the relative gain in C sequestration as compared to farm averages is likely to be larger than 500 kg C/ha per year.

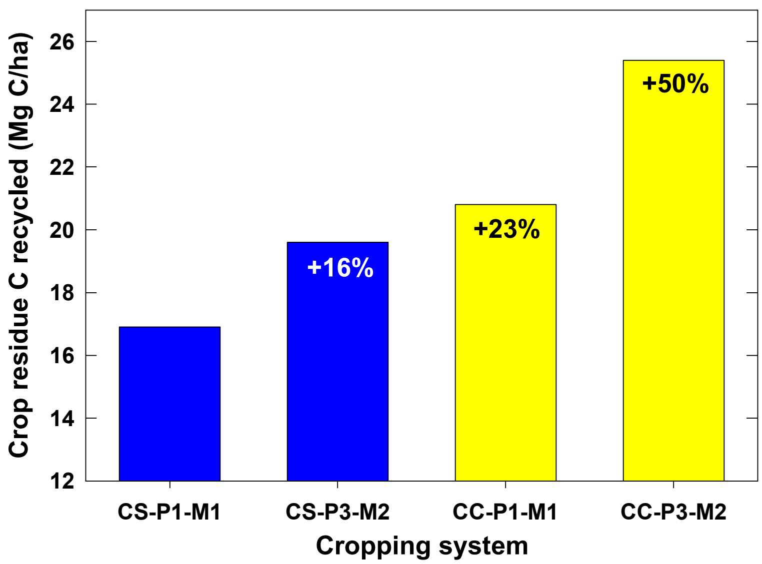

Fig. 6. Cumulative carbon input through aboveground crop residues remaining in the field for a four-year period (1999-2002), as affected by crop rotation, plant density, and nutrient management.

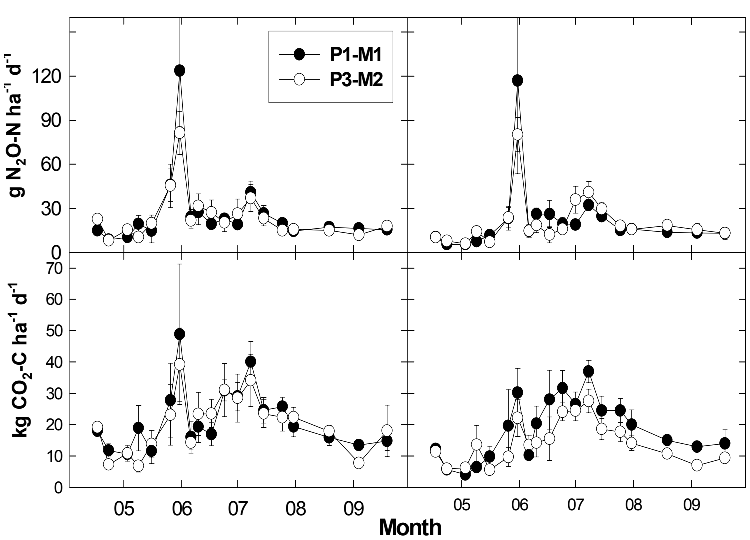

Fig. 7. Soil emissions of CO_2 and N_2O during the 2002 growing season.

Increased carbon sequestration will only have a net positive effect on the global environment if it can be achieved without increases in the emissions of CO_2 and other greenhouse gases such as N_2O or CH_4. Measurements in different continuous corn treatments during 1999 to 2001 showed no significant differences in soil CO_2 flux among different levels of nutrient management and plant populations (Dobermann et al., 2002). Fertility treatments resulted in significantly different CO_2 flux in only 5 out of 43 sampling dates, suggesting that, for the same crop rotation, increased biomass and crop residue production did not cause greater CO_2 losses. Whether soil surface CO_2 fluxes differ between continuous corn and corn-soybean rotations is being studied since 2001. In 2001, CC plots had significantly higher CO_2 flux than CS plots from mid June to mid July, but there was no significant difference thereafter (Dobermann et al., 2002).

While no significant differences in methane (CH_4) fluxes were seen among the treatments (not shown), soil surface N_2O flux was significantly higher in the M2 treatment in 2000 than in M1 or the unfertilized control. This was caused by high N rates in combination with the need to start irrigation in 2000 much earlier than normal because of dry weather. The surface drip tape caused wet conditions in the zone with highest soil N concentrations and soil temperature and thereby probably stimulated gaseous N losses due to nitrification-denitrification processes. However, although high levels of nitrogen were also applied in 2001, N_2O flux was not significantly different between M1 and M2 treatments. Compared to 2000, major differences included (i) splitting of N applications into 4 doses in the M2 treatment, (ii) use of sub-surface drip irrigation, and (iii) delayed start of irrigation.

In 2002, more continuous measurements of CO_2, N_2O and CH_4 fluxes were conducted in the four most contrasting cropping systems (Fig. 7). For most of the season, no significant differences were found in soil greenhouse gas fluxes among crop rotations or the different levels of management, despite large differences in past crops residue input (Fig. 6) and the amounts of fertilizer-N applied. To some degree this may have been due to the extremely dry weather during June and July and sub-surface water supply (drip tapes about 30 cm deep), leaving much of the soil surface dry and with reduced microbial activity and gas diffusion. More research will be conducted to understand management options for reducing soil greenhouse gas fluxes.

SUMMARY AND OUTLOOK

The experimental cropping systems established at Lincoln, NE illustrate that a large unutilized potential exists to increase yields and input use efficiency in the North American corn belt, potentially making farms more profitable, improving soil quality, and protecting the environment. More research is needed to conduct a complete systems analysis, study changes over longer time periods, conduct similar studies in other environments, and develop practical tools for crop management at elevated yield levels.

Greater quantitative knowledge about crop response to nutrients and balanced plant nutrition is required to manage crops at high yield levels. Unlike previous high-yield studies (Karlen et al., 1988), the ecological intensification experiment at Lincoln represents cropping systems with relatively moderate nutrient inputs. Rates of N were not excessive, NUE was high, there has been no indication of significant leaching losses, and the P and K amounts used in the M2 treatments were sufficient to maintain near neutral P and K input output budgets. Current fertilizer recommendations that are based on a yield goal that is well below the yield potential threshold do not allow expression of full attainable yield that is possible at higher plant densities and more intensive nutrient management. Compared to current recommendations, high corn yields require higher plant density (35,000 to 40,000 plants/acre) and greater N and K uptake per unit yield. More dynamic real-time approaches to N management are required to improve the congruence of N supply and crop N demand, thereby avoiding accumulation of residual soil nitrate and high peak rates of N_2O emission under intensive management.

The M2 treatments have shown high yield stability in years of widely varying climate, generally yielding more than 90% of the simulated climatic-genetic yield potential for this site in each year. The intensified systems are likely to be sustainable over the long run because increased biomass production will lead to increased crop residue inputs and, most likely, significant increases in soil organic matter content over time. Preliminary data indicate that intensive management schemes do not appear to cause increased soil surface CO_2 flux, which would offset their increased soil carbon sequestration potential. However, efforts to increase sequestered carbon through high N applications may lead to other problems such as increased nitrous oxide (N_2O) emission, which must be mitigated through more detailed forms of N management. More research must be conducted to establish full balances of the net radiative forcing potential and assess the energy use efficiency at the whole systems level.

Existing corn growth simulation models underestimate the actual dry matter production and yield measured at near-optimum growth conditions in the field. A new corn model, Hybrid-Corn, was developed to overcome some of these weaknesses, but requires further improvement. Model simulations suggest that yield potential varies across the Corn Belt and is likely to be higher at many other locations than that at Lincoln, where high temperatures appear to be the most limiting factor. Preliminary simulations based on long-term climate records for different agroecological zones in Nebraska suggest a range of the average corn yield potential from about 220 bu/acre in the northwest to 300 bu/acre in the south-central parts of the state. It remains unclear whether even this improved model is capable of simulating the true yield potential of corn. Key issues for model improvement are LAI prediction, radiation use efficiency (RUE), density effects on harvest index, and response to temperature, particularly during grain filling.

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