2002

Understanding Corn Yield Potential And Optimal Soil Productivity In Irrigated Corn Systems

A. Dobermann
University of Nebraska-Lincoln

Timothy J. Arkebauer
University of Nebraska-Lincoln, tarkebauer1@unl.edu

Kenneth G. Cassman
University of Nebraska-Lincoln, kcassman1@unl.edu

John L. Lindquist
University of Nebraska-Lincoln, jlindquist1@unl.edu

Daniel T. Walters
University of Nebraska-Lincoln, dwalters1@unl.edu

See next page for additional authors

Authors
A. Dobermann, Timothy J. Arkebauer, Kenneth G. Cassman, John L. Lindquist, Daniel T. Walters, Haishun Yang, Brigid Amos, Darren L. Binder, and Gregory J. Teichmeier

Proceedings of the Great Plains Soil Fertility Conference,
Denver, Colorado, March 5-6, 2002, ed. Alan J. Schlegel.

UNDERSTANDING CORN YIELD POTENTIAL AND OPTIMAL SOIL PRODUCTIVITY IN IRRIGATED CORN SYSTEMS

A. Dobermann, T.J. Arkebauer, K.G. Cassman, J.L. Lindquist,
D.T. Walters, H. Yang, B. Amos, D.L. Binder, G. Teichmeier
Department of Agronomy and Horticulture, University of Nebraska,
PO Box 830915, Lincoln, NE 68583-0915

ABSTRACT

In 1999, a field experiment was established to (1) quantify and understand the yield potential of corn and soybean under irrigated conditions, (2) identify efficient crop management practices to achieve yields that approach potential levels, and (3) determine the energy use efficiency, global warming and soil C-sequestration potential of intensively managed corn systems. The experiment compares systems that represent different levels of management intensity expressed as combinations of crop rotation (continuous corn, corn-soybean), plant density (low, medium, high) and nutrient management (recommended best management vs. intensive management). Detailed measurements include soil nutrient dynamics and C balance, crop growth and development, nutrient uptake and components of yield of corn and soybean, radiation use efficiency, soil surface fluxes of greenhouse gases, root biomass, C inputs through crop residues, translocation of non-structural carbohydrates, and amount, composition and activity of the microbial biomass. Data collected from 1999 to 2001 suggest that (i) current fertilizer recommendations do not allow expression of full attainable yield, (ii) high corn yields require higher plant density (37,000 to 44,000 plants/acre) and greater N and K uptake per unit yield, (iii) existing corn growth simulation models underestimate the actual dry matter production and yield measured at near-optimum growth conditions in the field, and (iv) the potential to increase C sequestration is greatest in continuous corn systems with intensive management.

RATIONALE AND OBJECTIVES

Crop yield improvement must continue unabated well into the 21st century, not only to meet the food and fiber needs of the nine billion people on earth the year 2050 (Evans, 1998), but also to minimize the conversion to agriculture of land now spared for nature (Waggoner, 1994; Young, 1999). Globally important intensive agricultural systems such as rainfed and irrigated continuous corn or corn-soybean will play a key role in sustaining the future global food supply because present average corn and soybean yields are only about 50% of the estimated climatic-genetic yield potential of these crops (Duvick and Cassman, 1999; Specht et al., 1999; Dobermann and Cassman, 2002).

Our hypothesis is that intensive agricultural systems can be designed to achieve an optimal balance of productivity, profitability, 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. Therefore, in 1999, a field experiment was established for making detailed measurements of crop, soil, and other system parameters in a high yield setting. The long-term objectives of this project 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 and carbon sequestration potential under different management scenarios. In this paper we present selected initial results, focusing on corn yields and soil changes at different cropping intensity.

MATERIAL AND METHODS

A long-term experiment was established in 1999 at the UN-L East Campus in Lincoln, NE on a deep Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludoll). Prior to 1999 the field was in a sorghum-soybean rotation without N fertilizer for the past 10 years. 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. Lime was applied in 1999 (2 t CCE/acre).

The 3x3x2 factorial experiment was conducted in a split-split plot randomized complete block design (4 replicates) with crop rotations (R) as main plots, plant population (P) density as sub-plots, and level of fertilizer nutrient management (M) as sub-subplots (Table 1). Sub-subplots were 6.1 m x 15.2 m (20' x 50') in size with 8 rows at 0.762 m (30'') row spacing. Four border rows adjacent to the main plots were used as unfertilized control plots (M0) in 1999 and 2000. In 2001, the experiment was modified to include one smaller M0 plot (4 rows x 10 ft) embedded within each M1 or M2 treatment plot. The field was fall moldboard plowed in each year to create a deeper topsoil layer. In the fall of 1999, the field was also ripped to a depth of about 45 cm. In 1999 and 2000, the experiment was irrigated to fully replenish daily crop evapotranspiration via a surface drip tape system, with the tape placed next to the plants in each row. In 2001, a permanent subsurface drip irrigation was installed with drip tapes in alternate rows at about 12 to 15" depth. Corn hybrid Pioneer 33A14 (Bt) was planted in 1999 and 2000 and hybrid 33P67 in 2001. In the corn-soybean rotation, a high-yielding, semi-determinate soybean cultivar, NE3001, was planted in all three years. Field cultivation of all plots was done at V6 stage of corn to incorporate N fertilizer and control weeds.

In M1 plots, nitrogen (N) rates for corn were calculated using the current UNL N algorithm (Shapiro et al., 2001):

$N = -35 + (1.2 \times YG) - (8 \times NO_3) - (0.14 \times YG \times SOM)$ – other N credits where N = recommended N rate (lb N/acre), YG = yield goal (200 bu/acre), NO_3 = soil test nitrate-N level in spring (ppm), SOM = soil organic matter content (%), and N credit = credit of 45 lb N/acre if previous crops was soybean. From 1999 to 2001, M1 rates ranged from 116 to 123 lb/acre for CS and 179 to 181 lb/acre for CC rotations, applied pre-plant (50% for CC, 75% for CS) and at V6 stage (remaining amount). In the M2 treatment, the N rate in 1999 was calculated by assuming 1 kg N uptake per bu yield for an expected yield of 250 bu/acre. In 2000 and 2001, the calculation assumed a yield goal of 300 bu/acre, an internal plant N requirement of 1.1 kg N uptake per bu yield, and an average recovery efficiency of applied N of about 60%. Measured values of indigenous N supply and residual soil nitrate were used to adjust N rates in M2 by crop rotations. From 1999 to 2001, M2 rates ranged from 201 to 266 lb/acre for CS and 268 to 324 lb/acre for CC rotations, applied pre-plant (30-50%), at V6, V10, and VT stages (2001 only). Nitrogen rates in the M2 in 2001 were 54 lb N/acre lower than in 2000 because high residual nitrate levels in soil resulting from a shortened 2000 growing season were taken into account.

Table 1. Treatment design for the Ecological Intensification of Maize Systems project.

Crop rotation (main plots)	
CC	Continuous corn
CS	Corn – Soybean (corn in odd years)
SC	Soybean – Corn (corn in even years)
Plant Population (subplots)[1]	
P1	Corn: 28-31,000 plants/acre Soybean: 1999-2000: 150,000 seeds/acre; 2001: 105,000 seeds/acre
P2	Corn: 35-40,000 plants/acre Soybean: 1999-200: 185,000 seeds/acre; 2001: 129,500 seeds/acre
P3	Corn: 44-47,000 plants/acre Soybean: 1999-2000: 220,000 seeds/acre; 2001: 154,000 seeds/acre
Management Intensity (sub-subplots)	
M1	recommended fertilizer management based on soil testing. Maize: UNL recommendation for 200 bu/acre yield goal
M2	intensive management aimed at yields close to yield potential. Maize yield goal 300 bu/acre, higher NPK rates, micronutrients, N in 3 splits

In both years, 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. In the M2 treatment, 92 lb P_2O_5/acre and 93 lb K_2O/acre were applied pre-plant in addition to N on both soybean and corn crops. In 1999 and 2000, those treatments also received 19 lb S/acre, 11 lb Fe/acre and 5 lb Zn/acre. Granular pre-plant fertilizer (blend of N, P, K, S, Fe and Zn fertilizers) was broadcast and disc-incorporated, whereas sidedress applications of ammonium nitrate were surface-banded in the plant row followed by a drip tape irrigation or field cultivation.

Key measurements in this field experiment include:

- Canopy environmental conditions (climate and intercepted solar radiation.
- Crop development rates, aboveground biomass and biomass partitioning, NPK uptake.
- Corn and soybean grain and biomass yield, harvest index, components of yield, barren and prolific plant population,
- Plant C, N, P, K, Ca, Mg, S uptake in aboveground biomass (grain, cobs, stover).
- Soil physical and chemical characteristics, potentially mineralizable nitrogen, soil C stocks, soil nitrate in spring, irrigation water composition.
- Root length density and dry matter (selected treatments).
- Soil surface CO_2, N_2O and CH_4 fluxes (selected treatments).
- Total soil microbial biomass, microbial community composition (selected treatments).
- Non-structural carbohydrates in stalks and leaves and their translocation to grain.

RESULTS AND DISCUSSION

Corn Grain Yield

Plant density and nutrient management levels significantly affected yield, harvest index, stover yield, components of yield, and nutrient uptake requirements of corn. Intensive fertilizer management (M2) significantly increased yield in all three years over the recommended fertility regime (Fig. 1). Maximum grain yields ranged from 249 to 257 bu/acre in all three years. In all three years, treatment CS-M2-P2 produced consistently high yields of 245 to 252 bu/acre that were close to the simulated yield potential for this plant density (Fig. 1). 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.

In 1999, corn was planted late (May 13) and grain yield increased with both increasing population density and management intensity, with a high of 258 bu/acre for the CS-M2-P3 treatment. At the M2 level of nutrient management, the harvest index of maize decreased with increasing plant density due to greater vegetative biomass accumulation. Sink size (no. of kernels/m^2) and nutrient uptake also increased with increasing plant density and nutrient management level (Arkebauer et al., 2001). The 100-seed weight was about 4% larger in M2 treatments than in M1, but decreased with increasing plant density.

In 2000 and 2001, corn was planted in late April and growth was much affected by hot temperatures during grain filling. Highest yield was 249 bu/acre in 2000 (CS-M2-P2 treatment) and 252 bu/acre in 2001 (CS-M2-P2 and CC-M2-P3 treatments). In 2000, at all population and nutrient management levels, grain yield in continuous corn was below that of corn grown after soybean, but the difference was smallest in M2 treatments. Similar observations were made for M1 treatments in 2001, but corn yield in M2 treatments with high plant density was similar in the CC and CS rotations (Fig. 1). Increasing plant density beyond the P2 level did not significantly increase yield and plant nutrient accumulation in 2000 and 2001, or even led to a decrease observed in 2000. Actual plant densities in the P3 treatment were about 5% greater than in 1999 (P3: average of 46,500 plants/acre in 2000 and 2001 vs. 44,200 plants/acre in 1999), which may have further accelerated crop stress under high temperatures during grain filling. Biomass x temperature interactions on crop respiration losses (see below) may explain why in 2000 and 2001 yields did not increase in the highest density treatment because the actual plant density in P3 was probably excessive, whereas it was already near optimal (37-41,000 plants/acre) in the P2 treatment.

At intensive level of nutrient management, the harvest index of maize 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, 30,000 plants/acre) and fertilizer management level (M1). In contrast, stover yield at very high density (P3) and intensive fertilizer management (M2) averaged 14.1 Mg/ha. In continuous corn, annual stover yield averaged 11.7 Mg/ha for the M1-P1 treatment vs. 14.0 Mg/ha under very intensive management (M2-P3).

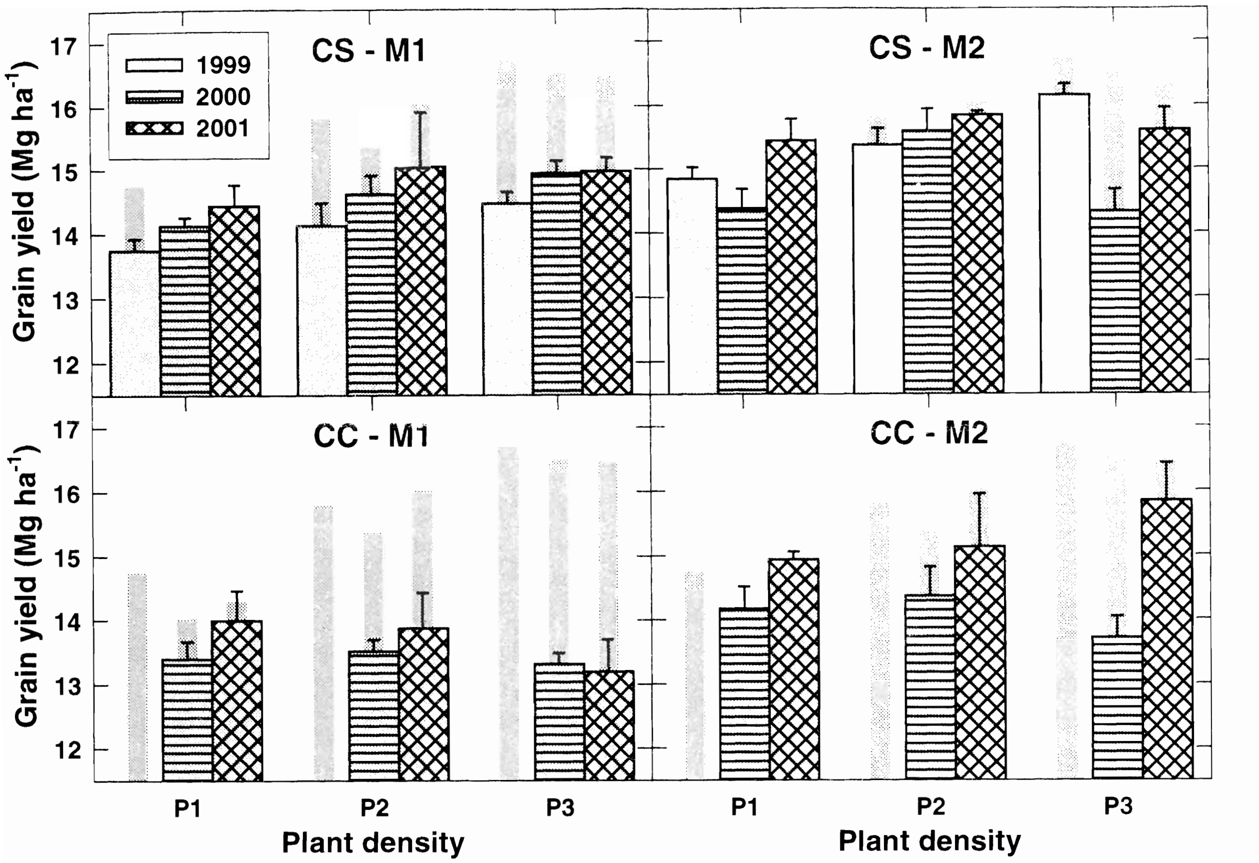

Fig. 1. Corn grain yield (15.5 m.c.) in 1999 to 2001 as affected by crop rotation (CC-continuous corn; CS – corn-soybean), fertility management (M1 – recommended; M2 – intensive), and final plant population density (P1 – 28-31,000 pl./ac; P2 – 36-41,000 pl./ac; P3 – 44-47,000 pl./ac). Values shown are treatment means and standard errors. The thin gray bars in the background show the simulated corn yield potential for each plant density – year combination (Hybrid-Maize simulations, H. Yang, unpublished data).

Understanding Corn Performance at High Yield Levels

Quantitative tools such as a crop simulation models can be used to develop hypotheses about the effects of climate and crop management on yield-forming processes. 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; Kiniry et al., 1997), Sinclair-Muchow (Muchow et al., 1990; Muchow and Sinclair, 1995), and Intercom (Lindquist, 2001), were used to simulate the climatic-genetic yield potential for all three experimental years at the Lincoln site. Crop data were obtained from the intensive nutrient management treatment in the corn-soybean rotation (CS-P2-M2). There were no obvious abiotic (water, nutrients) or biotic stresses that limited crop growth. Hence, 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 reasonable 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 the crop, 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%. 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 C balances because of cumulative effects of underestimating crop residue inputs. Efforts were 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 UN-L ecological intensification experiment (H. Yang et al., UN-L, 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 (within ±2% of measured grain yield and total biomass). Other advantages include a greater sensitivity to plant density and the ability to simulate maturity based on cumulative growing degree days rather than as a user-defined date.

The experimental years differed markedly in their climatic conditions, which caused significant differences in plant responses such as rate of plant development, leaf emergence, respiration, grain filling, and senescence as well as soil processes. Hybrid-Maize simulations done for each experimental year (Fig. 1) and plant density suggest 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. However, the model was unable to predict the decrease in yield in the M2-P3 treatments in 2000, for reasons that are not yet understood.

Overall, 2000 and 2001 were comparable in terms of climate and corn performance, but they differed significantly from 1999. Climatic conditions during 1999 were near-normal for most of the season (Table 2), and, due to late corn emergence (May 21), most of the grain filling took place during late August and early September, when minimum (night) temperatures seldom exceeded 21 °C (70 °F). However, 2000 and 2001 were hot and dry during July and August. Due to earlier emergence of corn (April 30 to May 2), grain filling mostly took place in August, when the average minimum air temperature as well as soil temperature exceeded normal levels by 1.3 to 1.9 °C (Table 2). As a result, crops in 2000 and 2001 matured faster than in 1999 or normal years. The grain filling period of corn in 2000 was about 10 days shorter than in normal years.

Hybrid-Maize simulations (Table 2) suggested that (i) for the whole season, 1999 had higher grain yield potential but lower total biomass (including root) than 2000 and 2001, (ii) for the vegetative growth period, 1999 had lower total duration, total solar radiation, gross assimilation, maintenance respiration, total carbohydrate loss, and net dry matter (DM) production than 2000 and 2001, and (iii) for the reproductive phase, 1999 had lower total radiation, gross assimilation, maintenance respiration, and total loss than 2000 and 2001, but the net DM production was higher. In 2000 and 2001, longer and more vigorous vegetative growth produced a large amount of vegetative dry matter, but at the cost of greater carbohydrate losses during grain filling, resulting in a slightly decreased yield.

Table 2. Measured climatic conditions and simulated growth during the whole growing season, vegetative and reproductive phases of corn as compared to the 15-year average at Lincoln, NE.

	1986-2000[1]	1999[2]	2000[2]	2001[2]
Whole season (VE to PM)	5/10-9/4	5/21-9/13	4/30-8/20	5/2-8/31
Duration (d)	117	115	112	121
Total solar radiation (MJ m^{-2})	2399	2247	2526	2618
Precipitation (mm)	351	333	312	410
Evapotranspiration (mm)	673	641	721	740
Average air temperature (^oC)	23.0	23.1	22.9	22.9
Average soil temperature, 10 cm (^oC)	25.0	24.3	25.4	24.6
Gross assimilation (Mg glucose ha^{-1})	62.5	56.4	64.2	65.1
Maintenance respiration (Mg glucose ha^{-1})	9.7	8.3	9.4	9.6
Total loss (Mg glucose ha^{-1})	30.9	27.1	31.9	33.3
Net dry matter production (Mg ha^{-1})	31.8	29.4	32.3	31.9
Stover+cob+root dry matter (Mg ha^{-1})	17.3	15.2	18.4	18.0
Grain dry matter (Mg ha^{-1})	14.5	14.1	13.9	13.9
Vegetative phase (VE to VT)	5/10-7/10	5/20-7/19	4/30-7/5	5/2-7/8
Duration (d)	61	59	66	67
Total solar radiation (MJ m^{-2})	1305	1201	1506	1456
Precipitation (mm)	199	225	201	331
Average air temperature (^oC)	21.8	23.1	22.9	20.7
Average soil temperature, 10 cm (^oC)	23.5	23.1	23.1	21.8
Gross assimilation (Mg glucose ha^{-1})	28.1	23.0	28.6	29.0
Maintenance respiration (Mg glucose ha^{-1})	2.6	2.1	2.5	2.8
Total carbohydrate loss (Mg glucose ha^{-1})	11.5	9.3	11.6	11.9
Net dry matter production (Mg ha^{-1})	17.0	13.8	17.1	17.1
Reproductive phase (VT to PM)	7/10-9/4	7/19-9/13	7/5-8/20	7/8-8/31
Duration (d)	56	56	46	54
Total solar radiation (MJ m^{-2})	1094	1046	1021	1162
Precipitation (mm)	152	108	111	78
Average max. air temperature (^oC)	30.2	29.9	30.8	31.2
Average min. air temperature (^oC)	18.7	18.4	20.0	20.2
Average soil temperature, 10 cm (^oC)	26.6	25.6	28.5	28.0
Gross assimilation (Mg glucose ha^{-1})	34.5	33.4	35.5	36.1
Maintenance respiration (Mg glucose ha^{-1})	7.1	6.2	6.9	6.8
Total carbohydrate loss (Mg glucose ha^{-1})	19.4	17.9	20.3	21.4
Net dry matter production (Mg ha^{-1})	14.8	15.6	15.3	14.8

[1] Hybrid-Maize model simulations for 1986-2000: emergence date May 1, 40,000 plants/acre.

[2] Hybrid-Maize model simulations for 1999-2001: actual emergence date (P3 (44-46,000 plants/acre). Reproductive phase in the model refers to silking (R1) to PM. Total loss = maintenance respiration + growth respiration (conversion loss) + loss of root biomass.

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 3). Average crop nitrogen accumulation in aboveground biomass (corn after soybean) was 1.04 lb N/bu yield in M1 treatments at normal plant density (P1), but 1.09 lb/bu under M2-P2/P3 management. Average crop potassium accumulation in aboveground biomass was 1.5 lb/bu in M1, but increased to 1.7 lb/bu under M2 management at high plant density. 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 3).

Table 3. Nutrient accumulation per unit grain yield as affected by fertility management (M), and plant density (P). Averages of 1999 and 2000, corn grown after soybean.[1]

Plant pop	Fertilizer (N-P-K, lb/acre)	Yield	N	P_2O_5	K_2O	Mg	S
		bu/acre	lb nutrient per bushel/acre yield				
			Total aboveground nutrient uptake				
P1	M1 UN-L-rec. (120 - 0 - 0)	222	1.04	0.41	1.49	0.10	0.10
P2	M2 intensive (234 - 92 - 93	247	1.09	0.39	1.68	0.10	0.09
P3	M2 intensive (234 - 92 - 93)	246	1.09	0.37	1.74	0.10	0.10
			Nutrient removal with grain				
P1	M1 UN-L-rec. (120 - 0 - 0)	222	0.69	0.29	0.22	0.05	0.06
P2	M2 intensive (234 - 92 - 93	247	0.67	0.28	0.22	0.05	0.05
P3	M2 intensive (234 - 92 - 93)	246	0.65	0.27	0.20	0.05	0.05

[1] Due to the short grain filling period in 2000 nutrient removal per unit yield values were generally lower in 2000 than in 1999.

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 vacuole. However, potassium uptake in our experiment appears to have exceeded the levels that are typically required for optimal growth (Dobermann, 2001) so that it remains unclear what the true crop requirements for achieving yield potential under non-stress conditions are.

Changes in Soil Properties

Compared to the initial status, soil pH decreased from about 5.3 to 5.0 in the most intensively managed treatments (M2), whereas it remained unchanged under M1 fertilizer management (Fig. 2). The pH decrease was largest in rotations with two or three corn crops grown from 1999 to 2001 (CC and CS). The pH decline in M2 was associated with an increase in electrical conductivity (EC), suggesting that it may have been caused by greater fertilizer (N) use. Measurements conducted during the 2001 growing season also revealed within-season changes in soil pH and EC measured in 1:1 soil:water suspension. In the upper 4 inches, pH decreased from 5.5 in May to 4.8 at the end of corn growth in M2 plots, whereas EC increased from 0.4 to 1.0 dS

Carbon Sequestration Potential and Greenhouse Gas Fluxes

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 carbon sequestration potential (Collins et al., 1999), but they also contribute significantly to global greenhouse gas emissions. Potentially positive effects of sequestering C in such agricultural systems may be offset by increased emissions of greenhouse gases such as nitrous oxide (N_2O) or high energy use (Robertson et al., 2000).

Soil samples collected after the first year indicated no significant differences in soil C and N stocks among treatments. As a baseline, average total soil C stored in 0 to 30 cm depth was 46.6 Mg C ha^{-1}, average total soil N was 3.6 Mg N ha^{-1}. Average concentrations were 14.8 g C kg^{-1} and 1.14 g N kg^{-1}. However, depending on the nutrient management and plant densities levels, total C input in two years (1999 – 2000), was 15 to 32% greater in continuous corn than in corn-soybean, mainly due to less vegetative biomass production in soybean compared to corn. For the 2-yr period from 1999 to 2000, total C input from recycled crop biomass (including roots) was 5.7 Mg C/acre in CC as compared to 4.3 Mg C/acre in CS (both at P2 and M2 treatment levels). It remains to be seen how the different levels of C input will affect soil C stocks over the medium and long term and whether the potentially greater sequestration of C can be achieved without increases in emissions of CO_2 and other greenhouse gases.

From 1999 to 2001, we conducted soil CO_2 flux measurements in continuous corn treatments with different level of nutrient management. No significant differences in soil CO2 flux were seen among different levels of nutrient management (Table 4) and plant populations (not shown) for the CC rotation. Fertility treatments resulted in significantly different CO_2 flux in only 5 out of 43 sampling dates throughout the entire study, 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 (data not shown).

While no significant differences in methane (CH_4) fluxes were seen among the treatments (data not shown), soil surface N_2O flux was significantly higher in the M2 treatment in 2000 than in M1 or the unfertilized control (Table 4). It is likely that this was caused by high N rates in combination with the need to start irrigation much earlier than normal because of dry weather. The surface drip tape cause wet conditions in the zone with highest soil N concentrations and soil temperature and thereby 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) lower N rates and splitting of N applications into four doses in the M2 treatment, (ii) use of sub-surface drip irrigation, and (iii) delayed start of irrigation.

In summary, 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.

Table 4. Mean soil surface fluxes of CO_2 and N_2O for the P3 (44,000 plants/acre) control areas (M0-CC) and the recommended (M1-CC) and intensive (M2-CC) fertility management treatments at the P2 (37-40,000 plants/acre) population for different sampling days during the 2000 and 2001 growing seasons (B. Amos and T. Arkebauer, unpublished data).

	N_2O flux			CO_2 flux		
Date	M0	M1	M2	M0	M1	M2
	---------- g N ha^{-1} d^{-1} ----------			---------- kg C ha^{-1} d^{-1} ----------		
23 May 2000	0.0 a*	1.7 ab	6.5 b			
	*0.0***	*3.3*	*7.5*			
12 July 2000	0.3 a	10.2 a	47.9 b	49.0 a	31.4 a	53.6 a
	0.8	*16.0*	*39.5*	*27.6*	*20.5*	*40.9*
24 August 2000	0.2 a	14.6 a	41.3 b	24.0 a	14.6 a	12.8 a
	0.6	*17.5*	*22.8*	*24.6*	*10.8*	*6.2*
17 May 2001	17.6 a	39.3 a	38.9 a	25.4 a	30.8 a	23.1 a
	13.8	*34.6*	*28.2*	*13.5*	*23.9*	*18.7*
24 July2001	1.9 a	4.5 a	35.7 a	27.8 a	29.8 a	27.0 a
	2.6	*3.5*	*85.1*	*10.0*	*25.2*	*17.4*
22 August 2001	1.3 a	1.0 a	4.3 a	14.8 a	15.4 a	16.2 a
	2.4	*2.3*	*4.0*	*8.8*	*13.2*	*4.0*

* Values within each row and gas measurement followed by the same letter do not differ significantly ($p > 0.05$) by Scheffe's procedure for analysis of variance.
** Number in small italic font is standard deviation.

CONCLUSIONS

A preliminary summary of data collected from 1999 to 2001 suggests that:

- 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 (40,000 to 44,000 plants/acre) and greater N and K uptake per unit yield.
- Corn growth in 2000 and 2001 was affected by hot weather during grain filling, but more research is needed to understand the interactions between plant density, nitrogen status, climatic stress at sensitive crop development stages, and yield potential, particularly during the grain filling period.
- Existing corn growth simulation models underestimated the actual dry matter production and yield measured at near-optimum growth conditions in the field. A new corn model, Hybrid-Maize, was developed to overcome some of these weaknesses, but requires further improvement. 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.

- A more dynamic approach to N management may be required to improve the congruence of N supply and crop N demand and thereby avoid accumulation of residual soil NO_3 and high rates of N_2O emission under intensive management, particularly in years with high air and soil temperatures.
- High-yielding corn systems significantly increased the amount of crop residue added to the soil. With intensive management, crop residue C inputs increased by about 30%, without a detectable increase soil CO_2 flux. The resulting increase in the amount of carbon added is likely to improve soil quality in future years.

ACKNOWLEDGMENTS

This project is supported by the Fluid Fertilizer Foundation (FFF), the Foundation for Agronomic Research (Potash & Phosphate Institute and IMC Global, Inc.) and the Nebraska Corn Board. We wish to acknowledge the contributions made by numerous other researchers and support staff involved in other aspects of this research, including R. Caldwell, R. Drijber, L. Nelson, J. Markwell, S. Madhavan, W. Powers, K. Russell, J. Specht, and C. Murphy.

REFERENCES

Arkebauer, T., K.G. Cassman, A. Dobermann, R.A. Drijber, J. Lindquist, Nelson.L., W.L. Powers, K. Russel, J.E. Specht, and D.T. Walters. 2001. Annual report to the Fluid Fertilizer Foundation: Yield potential and optimal soil productivity in irrigated corn systems of the North Central USA. p. 44-54. *In* L.S. Murphy (ed.) Proceedings of 2001 Fluid Forum, Vol. 18. Fluid Fertilizer Foundation, Manhattan,KS.

Collins, H.P., R.L. Blevins, L.G. Bundy, D.R. Christenson, W.A. Dick, D.R. Huggins, and E.A. Paul. 1999. Soil carbon dynamics in corn-based agroecosystems: results from carbon-13 natural abundance. Soil Sci. Soc. Am. J. 63:584-591.

Dobermann, A. 2001. Crop potassium nutrition – implications for fertilizer recommendations. *In* Proc. of the 31st North-Central Extension-Industry Soil Fertility Conference, November 14-15, 2001, Des Moines, IA. Potash & Phosphate Institute, Brookings, SD.

Dobermann, A., and K.G. Cassman. 2002. Plant nutrient management for sustaining productivity gains in intensive grain production systems of Asia and the United States. Plant Soil (rev)

Duvick, D.N., and K.G. Cassman. 1999. Post-green revolution trends in yield potential of temperate maize in the North-Central United States. Crop Sci. 39:1622-1630.

Evans, L.T. 1998. Feeding the ten billion: plants and population growth. Cambridge University Press, New York.

Ferguson, R.B., and K.M. De Groot. 2000. Nutrient management recommendations for agronomic crops in Nebraska. University of Nebraska, Lincoln, NE.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station, TX.

Kiniry, J.R., J.R. Williams, R.L. Vanderlip, J.D. Atwood, D.C. Reicosky, J. Mulliken, W.J. Cox, H.J. Mascagni, S.E. Hollinger, and W.J. Wiebold. 1997. Evaluation of two maize models for nine U.S. locations. Agron. J. 89:421-426.

Lindquist, J.L. 2001. Performance of INTERCOM for predicting corn-velvetleaf interference across north-central United States. Weed Science 49:195-201.

McCormick, R.W., and D.C. Wolf. 1980. Effect of sodium chloride on CO_2 evolution, ammonification, and nitrification in a Sassafras sandy loam. Soil Biol. Biochem. 12:153-157.

Muchow, R.C., and T.R. Sinclair. 1995. Effect of nitrogen supply on maize yield. I. Modeling physiological responses. Agron. J. 87:632-641.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yields across locations. Agron. J. 82:338-342.

Robertson, G.P., E.A. Paul, and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922-1925.

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

Specht, J.E., D.J. Hume, and S.V. Kumudini. 1999. Soybean yield potential - a genetic and physiological perspective. Crop Sci. 39:1560-1570.

Waggoner, P.E. 1994. How much land can ten billion people spare for nature? Task Force Report No. 121. Council for Agricultural Science and Technology, Ames,IA.

Weier, K.L., J.W. Doran, J.F. Power, and D.T. Walters. 1993. Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci. Soc. Am. J. 57:66-72.

Witt, C., A. Dobermann, S. Abdulrachman, H.C. Gines, G.H. Wang, R. Nagarajan, S. Satawathananont, T.T. Son, P.S. Tan, L.V. Tiem, G.C. Simbahan, and D.C. Olk. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63:113-138.

Young, A. 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. Environment, Development and Sustainability 1:3-18.