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Abstract

In 1999, an interdisciplinary research team at the University of Nebraska established a field experiment 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. Selected results for corn are presented.

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). 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 t or 35% of the global corn supply (Dobermann and Cassman, 2002). 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). This yield gap 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 (Sinclair, 1998), making future seed yield improvement substantially dependent upon increases in crop biomass. Intensified crop and soil management will be necessary to coax more out of the crop biomass potential.

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.

There is need to develop integrative scientific understanding of the relationships between soil productivity, crop yield potential, input use efficiency, nitrate leaching, C-sequestration, and greenhouse gas fluxes and energy use in corn-based cropping systems (Cassman, 1999). Therefore, in 1999, a group of researchers at UNL established a field experiment suitable 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 irrigated corn and soybean yields that approach attainable levels.
3. Determine how changes in soil quality affect the ability to achieve yields that approach yield potential levels.
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.
5. Develop improved crop and ecosystem simulation models for accurate prediction of yield potential and carbon sequestration potential under different management scenarios.

Initial focus during this period was on (1) exploring crop management practices for growing corn and soybean near optimal levels, (2) quantifying crop growth rates and dry matter distribution among various plant organs, (3) assessing and improving crop simulation models for corn, and (4) quantifying fluxes of greenhouse gases at different levels of management. First data were reported earlier (Arkebauer et al., 2001). In this paper we focus on a more detailed understanding of corn yields as well as soil processes at different cropping intensity.

Material and Methods

A long-term experiment was established in 1999 at the UNL 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.

Fertilizer N rates used are shown in Table 2. In M1 plots, N rates for corn were calculated using the current UNL N algorithm (Shapiro et al., 2001):

$$N = -35 + (1.2 \times YG) - (8 \times NO_3) - (0.14 \times YG \times SOM) - \text{other N credits}$$

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. 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. 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 (e.g., air and soil temperatures, wind speed, wind direction, precipitation, solar radiation, relative humidity), intercepted radiation, photosynthetically active 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.

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

Table 2. Fertilizer N applications to corn and soybean.

Crop rotation	Management	Growth Stage	N rate (lb/acre)		
			1999	2000	2001
Corn after soybean	M1	Pre-plant	58	92	89
		V6	58	31	27
		Total	**116**	**123**	**116**
	M2	Pre-plant	94	92	89
		V6	54	89	45
		V10	54	85	45
		VT			36
		Total	**201**	**266**	**214**
Corn after corn	M1	Pre-plant		92	89
		V6		89	89
		Total		**181**	**179**
	M2	Pre-plant		92	89
		V6		116	71
		V10		116	71
		VT			36
		Total		**324**	**268**
Soybean	M2	Pre-plant	36	92	-
		R3	49	45	36
		R5	49	-	36
		Total	**134**	**137**	**72**

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).

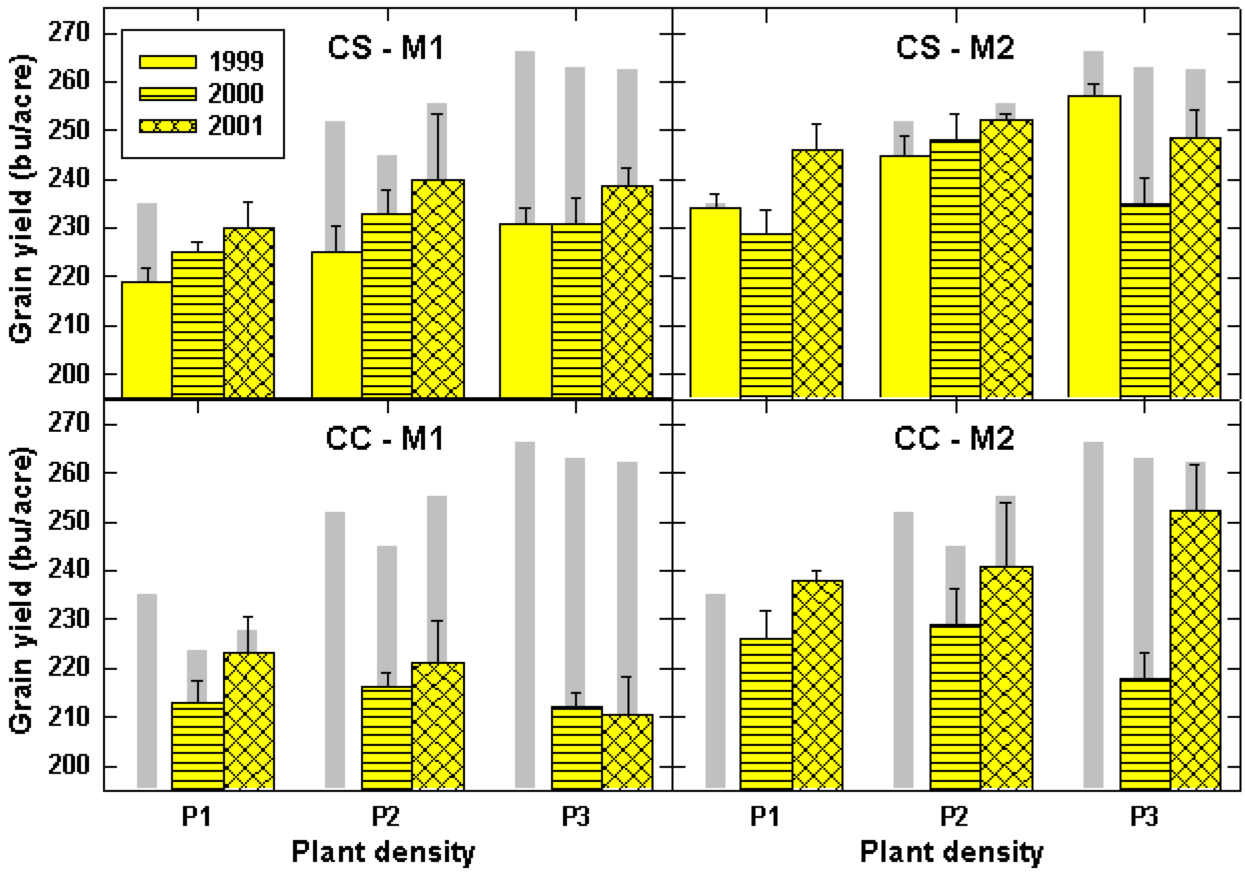


Fig. 1. Corn grain yield (15.5 m.c.) in 1999 to 2001 as affected by crop rotation (CC-continuous corn; CS – corn-soybean), fertility management (M1 – recommended; M2 – intensive), and final plant population density (P1 – 28-31,000 pl./ac; P2 – 36-41,000 pl./ac; P3 – 44-47,000 pl./ac). Values shown are 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).

Simulated Corn Yield Potential

Crop simulation modeling is a useful tool for gaining improved understanding of environmental controls on crop growth and development. It also can improve the efficiency of targeting research that seeks to develop improved management practices for optimizing crop performance, soil quality, and addressing environmental concerns, especially at yield levels that approach the yield potential ceiling. Before using a model as a tool to guide research, however, it must be evaluated comprehensively under circumstances similar to the intended applications. Most corn 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 four existing corn models were used to simulate the climatic-genetic yield potential for all three experimental years (Table 3). Neither model formulations nor

default values of parameters were modified except for those parameters that require site- and season-specific settings. The crop data from the EI field trial were obtained from the intensive nutrient management treatment in the corn-soybean rotation. 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% (Table 3). Underestimation of stover 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. Greater variability in the accuracy of simulating vegetative biomass compared to grain yield is a concern when modeling long-term C balances to predict C sequestration in high-yield systems 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 (Table 3). 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, making it easier to use for scenario analysis. 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, which appeared to be associated with climatic factors rather than resource limitation.

It remains unclear whether even this improved model is capable of simulating the true yield potential of corn because several fundamental relationships used in it will require better calibration using data sets collected at yield potential levels. Key issues for model improvement are LAI prediction, radiation use efficiency (RUE), density effects on harvest index, and response to temperature, especially during the reproductive growth phase.

Understanding Corn Performance at High Yield Levels

Climatic Variation and Yield Potential of Corn

The main value of quantitative tools such as a crop simulation model is probably to develop hypotheses about the effects of climate and crop management on yield-forming processes as a means for identifying most suitable mitigation options. 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. Below we attempt to understand those differences with the help of the Hybrid-Maize model.

Table 3. Actual corn grain yield and total aboveground biomass as measured in the field experiments conducted from 1999 to 2001, and the simulated values for these parameters using five corn simulation models. All values are derived from the M2 nutrient management treatment for corn following soybean at a plant population of 37,000 to 40,000 plants/acre (P2). Values in parenthesis are deviations (%) of model simulations from the actual values measured in the field (H. Yang, unpublished data).

Data/crop model	Year	Grain yield [1]		Total biomass [1]	
		bu DM/acre	%	ton DM/acre	%
Measured (EI trial)	1999	245		11.3	
	2000	249		11.9	
	2001	252		12.1	
Mean		**249**		**11.8**	
Ceres-Maize Kiniry	1999	217	(-11.4)	9.3	(-17.4)
(Kiniry et al., 1997)	2000	235	(-5.4)	10.5	(-11.8)
(Jones and Kiniry, 1986)	2001	252	(-0.3)	11.5	(-5.2)
	Mean	**235**	**(-5.6)**	**10.4**	**(-11.4)**
Ceres-Maize DSSAT	1999	190	(-22.3)	9.5	(-15.6)
(IBSNAT, 1994)	2000	215	(-13.7)	11.2	(-5.6)
	2001	190	(-24.7)	10.8	(-10.9)
	Mean	**198**	**(-20.2)**	**10.5**	**(-10.6)**
Sinclair-Muchow	1999	192	(-21.5)	9.1	(-19.3)
(Sinclair and Muchow, 1995)	2000	223	(-10.3)	10.6	(-11.3)
(Muchow et al., 1990)	2001	230	(-9.1)	10.9	(-10.4)
	Mean	**215**	**(-13.6)**	**10.2**	**(-13.6)**
Intercom	1999	189	(-22.7)	7.8	(-31.1)
(Kropff and van Laar, 1993)	2000	189	(-23.8)	9.6	(-19.4)
(Lindquist, 2001)	2001	169	(-32.9)	7.6	(-37.1)
	Mean	**183**	**(-26.5)**	**8.3**	**(-29.2)**
Hybrid-Maize	1999	252	(2.8)	11.4	(1.4)
(H. Yang et al., UN-L)	2000	245	(-1.5)	11.8	(-1.2)
	2001	255	(1.2)	12.2	(0.8)
	Mean	**251**	**(0.8)**	**11.8**	**(0.3)**

[1] Grain yield at 15.5% moisture content. Biomass: 1 ton = 2000 lb.

Table 4. 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 (^{o}C)	23.0	23.1	22.9	22.9
Average soil temperature, 10 cm (^{o}C)	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 (^{o}C)	21.8	23.1	22.9	20.7
Average soil temperature, 10 cm (^{o}C)	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 (^{o}C)	30.2	29.9	30.8	31.2
Average min. air temperature (^{o}C)	18.7	18.4	20.0	20.2
Average soil temperature, 10 cm (^{o}C)	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.

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 4), 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 ºC (70 ºF). However, both 2000 and 2001 were hot and dry years during July and August. Due to earlier planting of corn (emergence 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 ºC (Table 4). Moreover, relative humidity was 5% lower than normal. As a result, crops in 2000 and 2001 matured faster than in 1999 or normal years. Most noticeably, the grain filling period of corn in 2000 was about 10 days shorter than in normal years (Table 4).

Hybrid-Maize simulations of yield potential (Table 4) 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 these simulations total plant carbohydrate loss includes maintenance respiration, growth respiration (loss of carbon during translocation and conversion into structural carbohydrates) and root biomass loss. Temperature affects maintenance respiration, but the final grain yield and total biomass depend on the balance of gross assimilation and losses through respiration for both maintenance and conversion. 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.

Effects of Climate and Planting Date on Yield Potential of Corn

Validated crop models are also useful for assessing the long-term yield potential and identifying optimal planting windows at a particular site. Using the climate data for 1986 to 2001 at the Lincoln site, we simulated the inter-annual variation in corn yield potential (Fig. 2). Results showed that the yield potential for early emerging corn (May 1) at a density of 40,000 plants/acre fluctuated widely from year to year (204 to 288 bu/acre), but was typically in the 230 to 260 bu/acre range. As mentioned above, it is not known whether these numbers represent the true yield potential, but they suggest that yields of 300 bu/acre or more may be difficult to achieve at this location. Substantial variation in corn yield potential may, however, exist in the Corn Belt.

Related to this is the issue of optimal planting date with regard to yield potential and risk of early frost. Crop simulations for the Lincoln site suggested an increase in yield potential as corn planting is delayed until early June (Fig. 2). However, climate probabilities must be taken into account to avoid risk of high temperature during tasseling/silking as well as frost damage during late grain filling. Combining the model simulations with the historical temperature records for Lincoln (Fig. 3) suggests that corn emergence during May 10 to May 20 may provide the most desirable compromise in terms of yield potential and low risk. Delaying planting would

have little effect on maximum temperature during silking, but a significant part of the grain filling period would be moved to a period with cooler night temperatures (Fig. 3). Considering the observations discussed above (Table 4), the most likely result would be a shortened vegetative period, but prolonged grain filling and reduced respiration losses. Similar effects can be achieved to some degree by hybrid choice, but a combination of later-maturing hybrid with a one or two week delay in planting may offer the best compromise for this particular location.

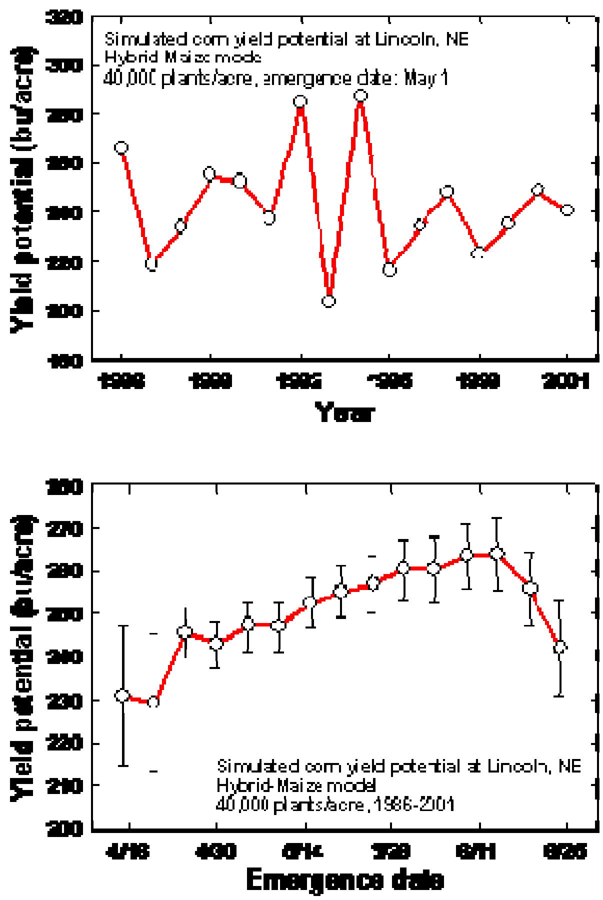


Fig. 2. Variability of corn yield potential at Lincoln, NE due to climatic factors. The left graph shows the simulated yield potential from 1986 to 2001 for a corn crop planted in late April. The right graph shows the effect of different planting (emergence) dates on the simulated corn yield potential (average climatic conditions and standard error). All simulations were done using the Hybrid-Maize model (H. Yang, unpublished data).

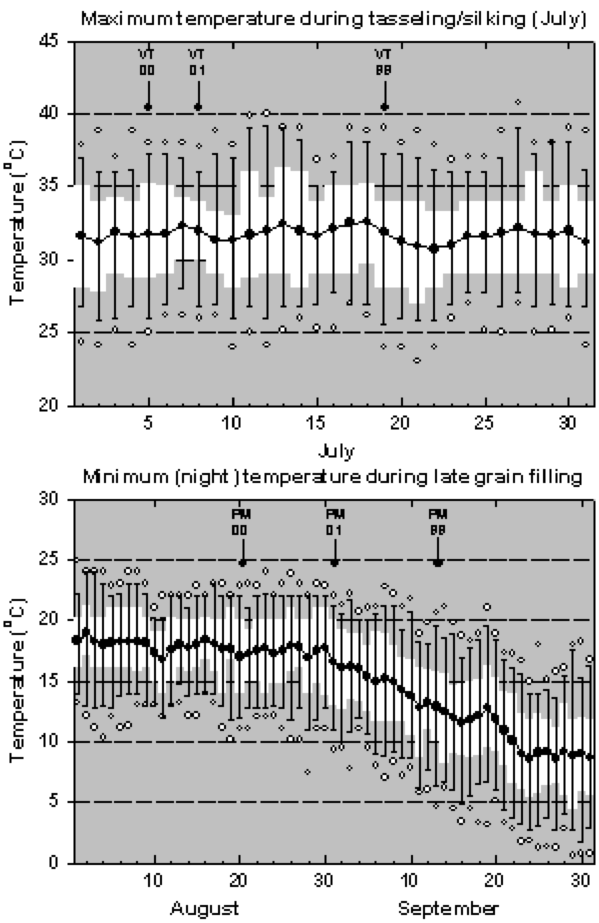


Fig. 3. Frequency distribution of maximum daily air temperature in July and minimum daily air temperature in August and September at Lincoln, NE. Values shown are mean (filled circles), 5 and 95% percentiles (open circles), 10 and 90% percentiles (error bars), and 25 and 75% percentiles (white boxes) of 53 years of historical climate data (1948-2000). Actual dates of tasseling (VT) and physiological maturity (PM) in 1999 to 2001 are shown for comparison.

Nonstructural carbohydrates

Although, during the past two decades significant attention has been paid to relationships between C and N metabolism in the productivity of corn, very little information is still available on ^{13}C and ^{15}N redistribution in this species. The contribution of pre-anthesis assimilate to grain filling is the product of a) the mass of pre-anthesis assimilate that is mobilized between anthesis and maturity, and b) the efficiency of mobilized pre-anthesis assimilate conversion into grain mass. Thus, knowledge about the actual contribution of pre-anthesis reserves by grain filling and on the efficiency of mobilized reserve conversion in grain mass is still limited. In order to follow the mobilization of carbon previously fixed through photosynthesis, from either the source leaves or the stalk, we determined the non-structural carbohydrate content in treatments with intensive management and normal density (M2-P1), recommended management and normal density (M1-P1), intensive management and high density (M2-P3), and recommended management and high density (M1-P3).

The data obtained with the leaf and stem samples at the end of the growing season, are consistent with data in the literature (Swank et al., 1982). Plants provided with increased amounts of N were better able to mobilize nonstructural carbohydrates. This is evidenced by decreases in both stalk and leaf nonstructural carbohydrate levels in high management plots, relative to those in normal management (Fig. 4). This was true in both the low density and high density populations. Final nonstructural carbohydrate concentrations in stalk and leaves were lowest in the most intensive treatment with high plant density (M2-P3).

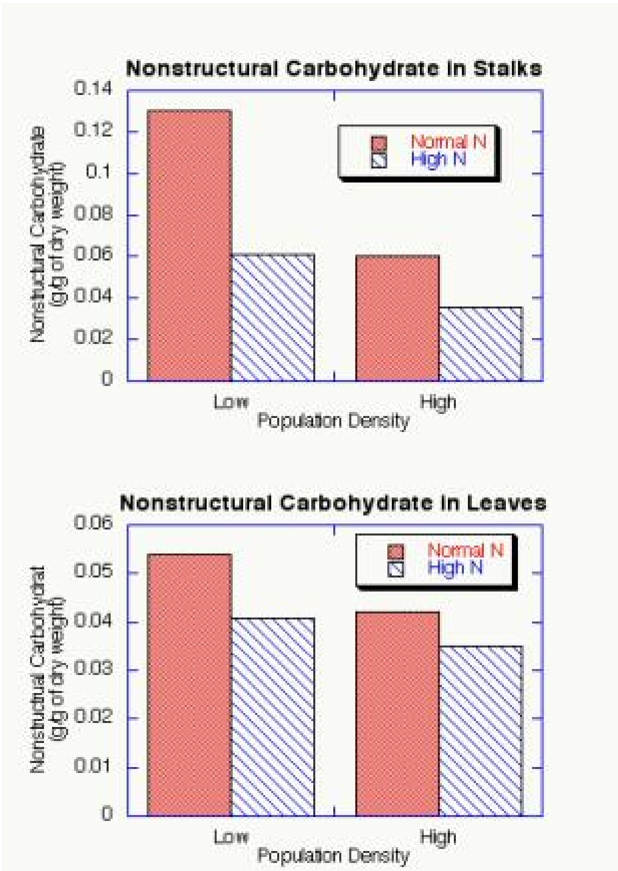


Figure 4. Nonstructural carbohydrate content in stem and leaf material harvested August 20, 2000. The data represent the mean of duplicate determinations (S. Madhavan and J. Markwell, unpublished data).

Studies using ^{13}C labeling techniques will be required to clarify whether this is the result of greater translocation to grain or whether it reflects increased respiration losses due to maintenance needs of a greatly increased amount of crop biomass. Clarifying this is expected to be a major issue for understanding yield potential as well as for improving corn models, which often assume a constant rate of conversion losses irrespective of factors such as plant density or 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 5). 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 5). Data for 2001 are not yet available to further confirm these numbers and also compare CC and CS rotations.

Table 5. 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.

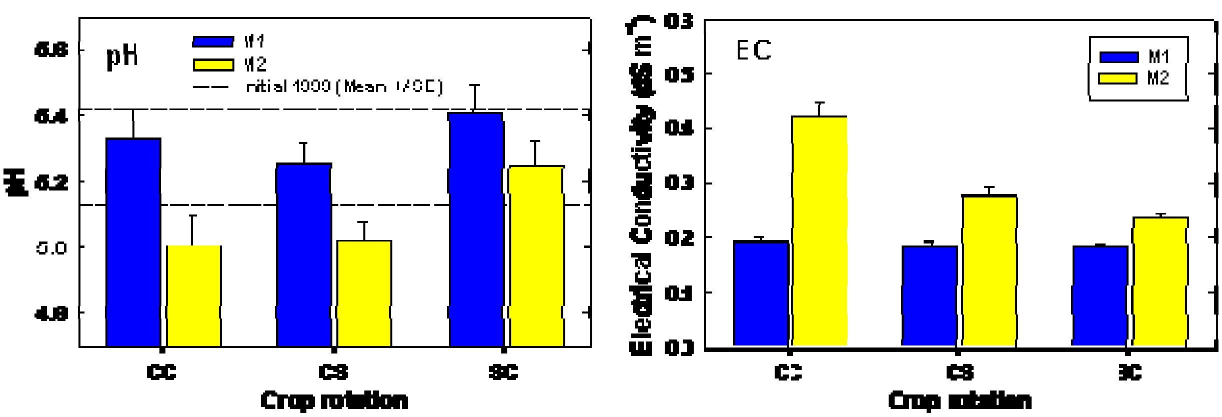
Plant pop	Fertilizer (N-P-K, lb/acre)	Yield	N	P_2O_5	K_2O	Mg	S
		bu/acre	lb nutrient per bushel/acre yield				
			Total aboveground nutrient uptake				
P1	M1 UN-L-rec. (120 - 0 - 0)	222	1.04	0.41	1.49	0.10	0.10
P2	M2 intensive (234 - 92 - 93	247	1.09	0.39	1.68	0.10	0.09
P3	M2 intensive (234 - 92 - 93)	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

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. 5). The pH decrease was largest in rotations with 2 or 3 corn crops grown from 1999 to 2001 (CC and CS). Measurements conducted during the 2001 growing season revealed that soil pH in the upper 4 inches decreased from 5.5 in May to 4.8 at the end of corn growth in M2 plots, whereas no or less change was observed in M0 and M1 plots (Table 6). The pH decline in M2 was associated with an increase in electrical conductivity (EC; Fig. 5 and Table 6), suggesting that it was mainly caused by greater fertilizer (N) use. Such pH and EC changes may affect microbial transformation processes such as nitrification and denitrification and thereby trace gas emissions (McCormick and Wolf, 1980; Weier et al., 1993). More research is needed to clarify the processes involved, but intensive management may change liming needs over the longer term. It is also unclear whether more vigorous root systems may contribute to soil acidification through cation uptake and excretion of organic acids. However, it is worthwhile to note that even at pH of 5 or less the M2 treatments still yielded 250 bu/acre or more.

Soil P and K levels remained unchanged in M2 treatments, but decreased under M1 management in both CC and CS rotations (Fig. 5). Despite the decreases in P and K, soil test levels in M1 treatments remain at levels that are above currently recommended levels for corn and soybean in Nebraska (Ferguson and De Groot, 2000). However, the corn yield data indicate that the fertilizer management in M1 has been insufficient to fully exploit the yield potential (Fig. 1). More research must be conducted to clarify to what extend this may have been caused by not applying and (fresh) P and K fertilizer for many years.



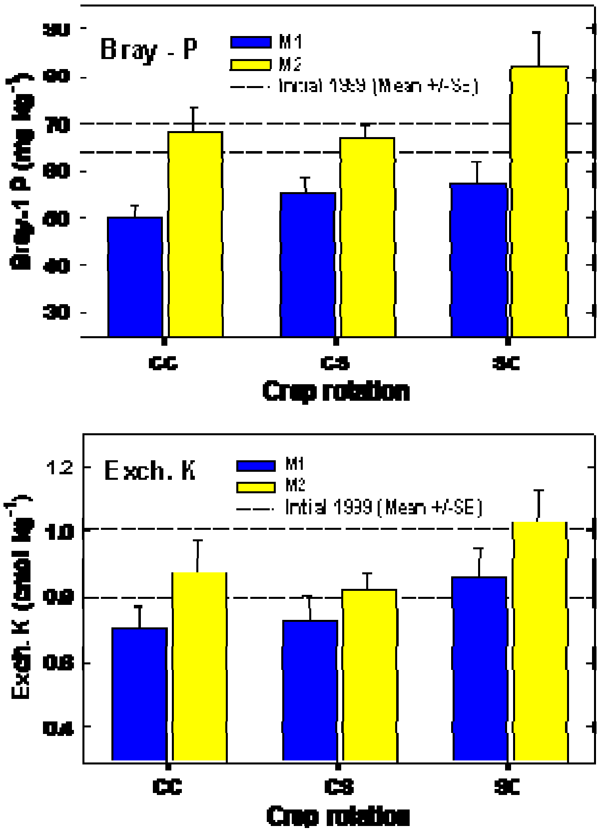


Fig. 5. Changes in soil test values (0-8" depth) after three crops grown under recommended (M1), and intensive (M2) fertility management. Crop rotation treatments refer to continuous corn (CC, 3 corn crops), corn-soybean rotation (CS, 2 corn, 1 soybean crop), and soybean-corn rotation (SC, 2 soybean, 1 corn crop). Samples were collected in Fall 2001. Values shown are means and standard errors across all three population densities.

Table 6. Changes in electrical conductivity and pH in 0-4" soil depth for the control (M0), recommended (M1), and intensive (M2) fertility treatments (all continuous corn at P2 density) over the 2001 growing season (B. Amos, unpublished data). [1]

Date	EC (dS m^{-1})			pH		
	M0	M1	M2	M0	M1	M2
May 17	0.26 a	0.34 a	0.41 a	5.8 a	5.5 a	5.5 a
July 24	0.12 a	0.27 a	0.65 b	5.9 a	5.5 a	5.0 b
August 22	0.12 a	0.28 a	1.00 b	5.6 a	5.2 b	4.8 c

[1] Electrical conductivity and pH were measured in a 1:1 mixture with distilled water. Measurements within the same row followed by the same letter do not differ significantly ($p > 0.05$) by Scheffe's procedure for analysis of variance.

Carbon Sequestration Potential and Greenhouse Gas Fluxes

Another justification for interest in optimal soil productivity are low commodity prices and the need for mitigating local and global environmental effects of human activities. 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. This C sequestration would contribute to reducing the rate of increase in greenhouse gases, and international negotiations are underway that may create markets for C storage. The annual C storage potential of corn production systems may range from 0.25-1.5 ton C/acre, depending on soil management and yield level, but no studies have been conducted to quantify this at near-optimal yield levels. 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 30% greater in continuous corn than in corn-soybean (Fig. 6), mainly due to less vegetative biomass production in soybean compared to corn. Total C input from recycled crop biomass was 1.5 t C/acre greater in CC compared to CS, and we expect the difference in C sequestration to be even greater because soybean residue decomposes much more rapidly than corn stover.

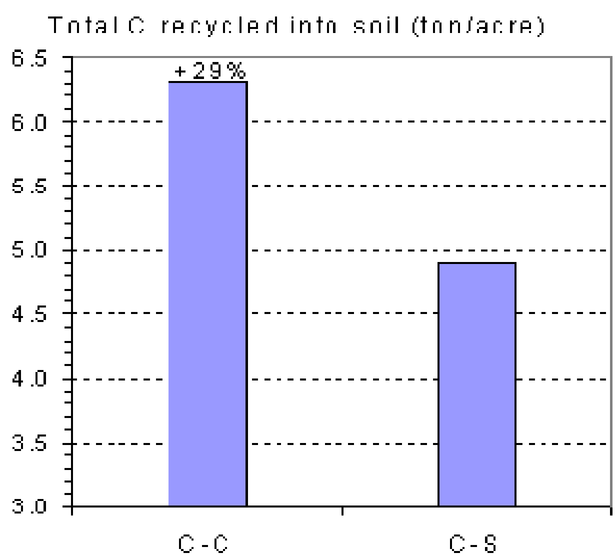


Figure 6. Comparison of estimated total C input to soil from aboveground crop residues (after grain harvest) and roots after a two-year period (1999 – 2000) in continuous corn (C-C) and a corn-soybean rotation (C-S) in the M2 nutrient management treatment at P2 plant densities.

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. Soil surface CO_2 flux is a measurement that reflects soil respiration. It is an indication of the total biological activity of all animal and plant life present in the soil, including microorganisms, macroorganisms (such as earthworms and nematodes), and plant roots (Parkin et al., 1996). While it has been shown that N fertilizer can significantly increase total soil C content, few studies have examined the effect of different fertility management regimes on soil surface CO_2 flux.

No significant differences in soil CO2 flux were seen among different levels of nutrient management (Table 7**)** and plant populations (not shown). 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 (Fig. 8).

Table 7. 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.

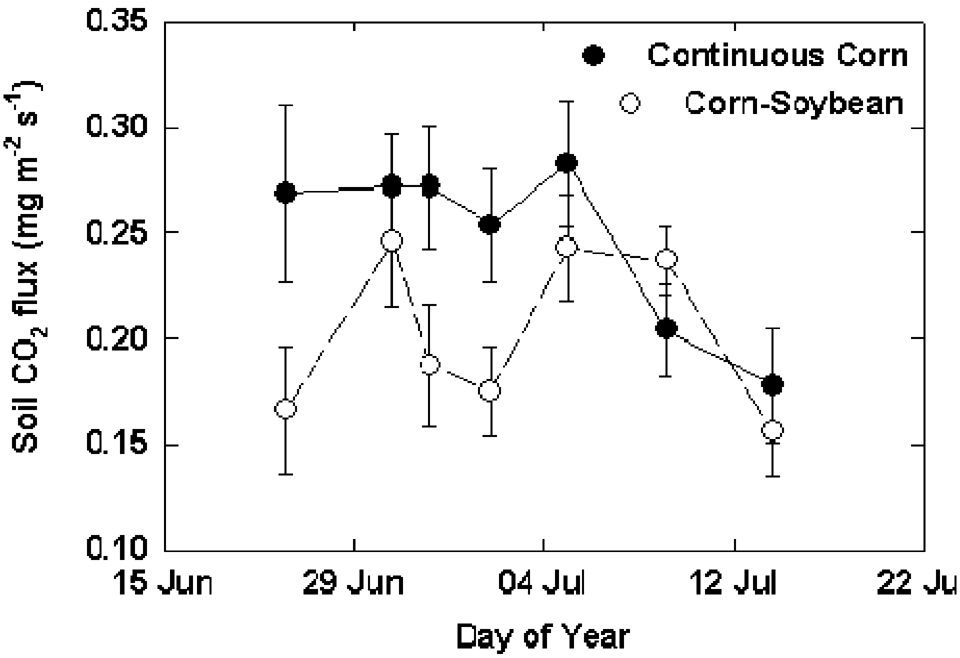


Fig. 8 Soil surface CO_2 flux measured during the 2001 growing season in continuous corn and corn-soybean rotation. Data shown are averages and standard errors of M1 and M2 treatments at P2 plant density (B. Amos and T. Arkebauer, unpublished data).

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 (Table 7). 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 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.

Microbial biomass in soils serves as a conduit through which major nutrient fluxes take place. First measurements of microbial signatures were conducted in 2000 to determine whether the amount, composition or activity of the microbial biomass differs among plant density or fertility treatments at corn silking and whether measured microbial parameters support observed differences in productivity. Microbial biomass at corn silking, quantified as total lipid phosphorus, was significantly different across replicate blocks indicating spatial variability of soil properties, but there were no significant differences among plant population levels. Microbial biomass decreased slightly, but significantly, with decreased fertility and increased soil depth. The failure of the microbial biomass to increase in size in response to higher plant populations suggests a more rapid "turnover" of the microbial biomass to cope with the greater influx of bioavailable carbon. This rapid turnover of the microbial biomass would signal increased nutrient flux in support of the higher plant populations. Significant shifts in microbial community composition (by FAME analysis) are not expected as the quality of C substrates would not differ among the treatments. We do expect; however, to see increased dehydogenase activity under higher plant populations to support the more rapid turnover of microbial biomass. Furthermore, this rapid turnover of the microbial biomass would be accompanied by increased production of microbial products that may foster stabilization of carbon in the soil, either as physically protected plant residues or as newly synthesized soil humus. This latter observation will be the focus of future studies and it relates strongly to the C sequestration potential of high-yield systems.

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.

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.
- Without specific calibration, 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-Maize, was developed to overcome some of these weaknesses, but requires further improvement to allow accurate simulation of yield potential.

- High nitrogen use efficiencies were achieved at both levels of crop management in 1999, but not in 2000 (data not shown). 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. The resulting increase in the amount of carbon added is likely to improve soil quality in future years. The potential to increase C sequestration is greatest in continuous corn systems with intensive management that supports high yield levels. With intensive management, crop residue C inputs increased by about 30%, without a detectable increase soil CO_2 flux.

Outlook

Experimental work in 2002 will focus on further fine-tuning of crop management to fully exploit the yield potential. Particular emphasis will be given to more accurate planting (density, spacing within rows, optimal planting date), reducing traffic and soil compaction, and fine-tuning of water and N management. We will complete the corn-soybean rotation in 2002 and then conduct a detailed 4-year comparison of the CC and CS systems, including aspects of yield, production economics, nitrogen efficiency, energy balance, soil C sequestration, and radiative forcing potential. Beginning in 2003, we will consider introducing changes in certain experimental treatments to compare crop management options such as narrower row spacing, different genotypes, or different strategies of N management.

Crop modeling research will continue to further improve the Hybrid-Maize model and validate it against data sets from other locations. The improved model will then be used to (i) create maps of yield potential and optimal planting dates and hybrid choice for corn in Nebraska and (ii) assess key scenarios for soil C sequestration in corn-based systems. Of particular interest is to assess the sensitivity of C sequestration to biomass production vs. tillage.

Accompanying research in the UN-L Carbon Sequestration Program (CSP) has started in 2001 to quantify soil C sequestration, greenhouse gas fluxes, and energy balances for whole production fields (1/4 sections). This project compares landscape-level fluxes and detailed soil and crop measurements of all components of the C balance in three systems, namely (1) continuous irrigated corn, (2) irrigated corn-soybean rotation, and (3) dryland corn-soybean. Knowledge, methods, and models derived from our high-yield studies are applied for conducting these studies irrigated yield levels of 220 to 240 bu/acre. Beginning in 2002, the Nebraska Soil Fertility Project (NSFP) will focus on statewide research on nutrient recommendations for high corn yields (>200 bu/acre) by establishing on-farm experiments across an agroecological gradient of 12 sites in Nebraska.

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