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# Understanding Corn Yield Potential in Different Environments

Achim R. Dobermann
*University of Nebraska - Lincoln*, adobermann2@unl.edu

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

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

Rhae A. Drijber
*University of Nebraska - Lincoln*, rdrijber1@unl.edu

J. Lindquist
jlindquist1@unl.edu

***See next page for additional authors***

**Authors**
Achim R. Dobermann, Timothy J. Arkebauer, Kenneth G. Cassman, Rhae A. Drijber, J. Lindquist, James E. Specht, Daniel T. Walters, Haishun Yang, D. Miller, Darren L. Binder, Gregory Teichmeier, Richard B. Ferguson, and Charles S. Wortmann

*2003 Annual Report to the Fluid Fertilizer Foundation on grant "Yield potential and optimal soil productivity in irrigated corn systems of the north-central USA"*

# Understanding Corn Yield Potential in Different Environments

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Department of Agronomy and Horticulture, University of Nebraska, PO Box 830915, Lincoln, NE 68583-0915

## YIELD POTENTIAL AND YIELD GAPS

The UNL research program on *Ecological intensification of irrigated maize-based cropping systems* aims to (i) improve understanding of the yield potential of corn and soybean and how it is affected by management, (ii) develop a scientific basis for evaluating yield potential at different locations, (iii) develop practical technologies for managing intensive cropping systems at 70-80% of the yield potential, and (iv) conduct integrated assessment of productivity, profitability, input use efficiency, soil carbon sequestration, energy and carbon budgets, and trace gas emissions. Results of this work have been reported earlier (Arkebauer et al., 2001; Dobermann et al., 2002). In this paper we discuss examples of progress made in 2002, focusing on obtaining additional data sets from high-yield environments and on using crop simulation modeling for understanding yield potential.

Yield potential (or potential crop production, Ymax) can be defined as the maximum yield that can be achieved in a given environment for a certain plant species. Thus, yield potential refers to a situation of unlimited water and nutrient supply, where potential plant production is solely determined by growth-defining factors such as genetic characteristics, solar radiation, temperature, and $CO_2$ concentration (van Ittersum et al., 2003). Management of Ymax is only possible through breeding and tactical decisions such as selecting the right cultivar, sowing date, and plant density in relation to variation in Ymax that is due to the seasonal pattern of radiation and temperature.

Approaches used to quantify Ymax include (i) theoretical calculations from components of yield and radiation use efficiency, (ii) measurements in well-controlled, small-scale experiments in which elimination of biotic and abiotic stresses (water, nutrients, pests) is attempted, and (iii) estimation by crop simulation models. Much debate is ongoing about what the yield potential of corn is. Highest corn yields have been reported in yield contests, and the winning yields have been used as a proxy for estimating corn yield potential and yield potential trends. For example, Waggoner (1994) and Evans (1993) speculate that there is no limit to corn yield potential in the foreseeable future based on the linear increase in winning yields in yield contests and the increasing size of the yield gap between average farm yields and contest-winning yields. In contrast, Tollenaar and Lee (2002) argue there has been little improvement in corn yield potential under optimal growth conditions and that most of the improvement in yield has resulted from increased stress resistance. The paucity of data from well-designed field experiments in which yields approach those reported in the yield contests makes it difficult to test these conflicting hypotheses (Duvick and Cassman, 1999). It also makes it difficult for crop scientists to validate the ability of corn growth models to simulate potential yield.

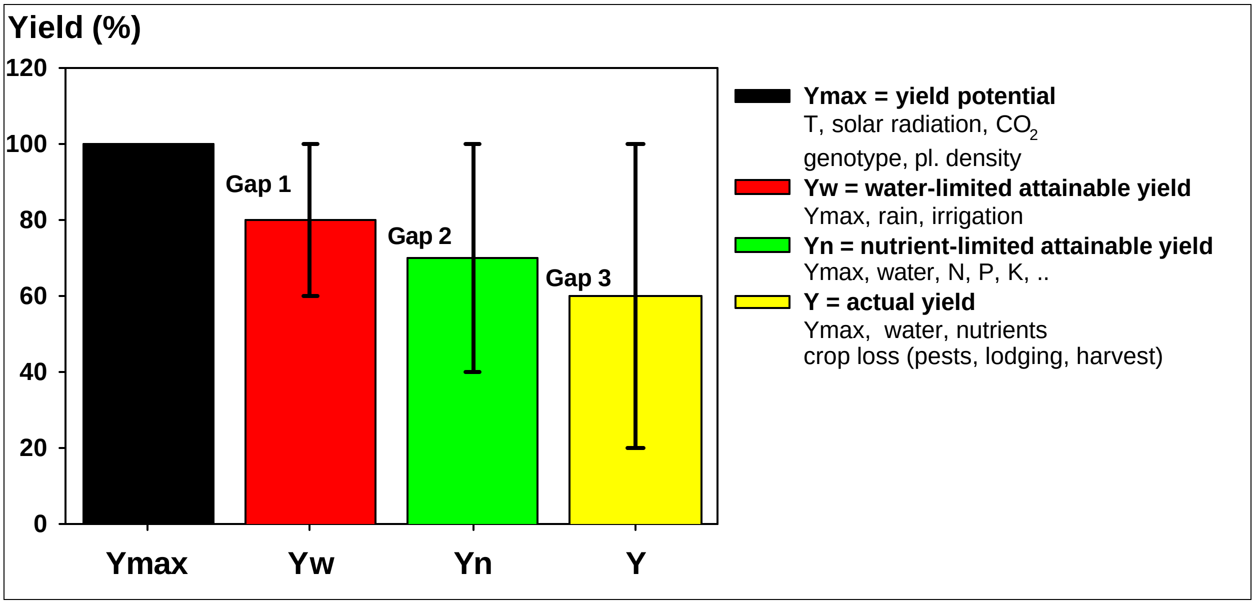



**Fig. 1.** Climatic-genetic yield potential and yield gaps in agricultural systems. Improved location-specific management involves managing all three yield gaps.

Growth-limiting factors (water, nutrients) and growth-reducing factors (weeds, insect pests, diseases) cause yield gaps of unrealized attainable yield potential (Fig. 1). Such yield gaps may vary widely and understanding their causes is at the heart of improving crop management. However, many management decisions are often based on relative assessment of the attainable yield, with little use of tools that allow quantifying the yield potential as well as the attainable water- and nutrient limited yields. Comparisons are often made with some "reference treatment", but without knowing Ymax in absolute terms it becomes difficult to judge what can be achieved in a given environment.

In Nebraska, for example, agroecological zones have been mapped along a northwest to southeast gradient, which mainly represents increasing growing degree days, summer water balance, and root zone available water-holding capacity across the state (Fig. 2). Average county-level yields of rainfed corn roughly follow a similar trend (Fig. 2) because they mainly represent the water-limited attainable yield (Yw) as defined in Fig. 1. In contrast, county mean yields of irrigated corn show a different pattern and are highest in the south-central part of the state, particularly along the Platte River (Fig. 2). Because water is less limiting the growth of irrigated corn, the map of irrigated yields may mainly reflect spatial variation in Ymax associated with temperature and solar radiation regimes. These differences are currently not considered in most management recommendations. Moreover, even in the highest-yielding counties average yields rarely exceed 200 bu/acre, as compared to irrigated corn contest winner yields that have reached around 300 bu/acre (Duvick and Cassman, 1999).

In the future, management recommendations must be considerably more robust and accurate than current approaches and they should take into account the spatio-temporal variation in yield potential. Quantitative approaches are particularly suitable for favorable production environments, because in most years the yield response to nutrients is not severely confounded by other abiotic or biotic stresses. Crop - ecosystems modeling is likely to play a key role in this.

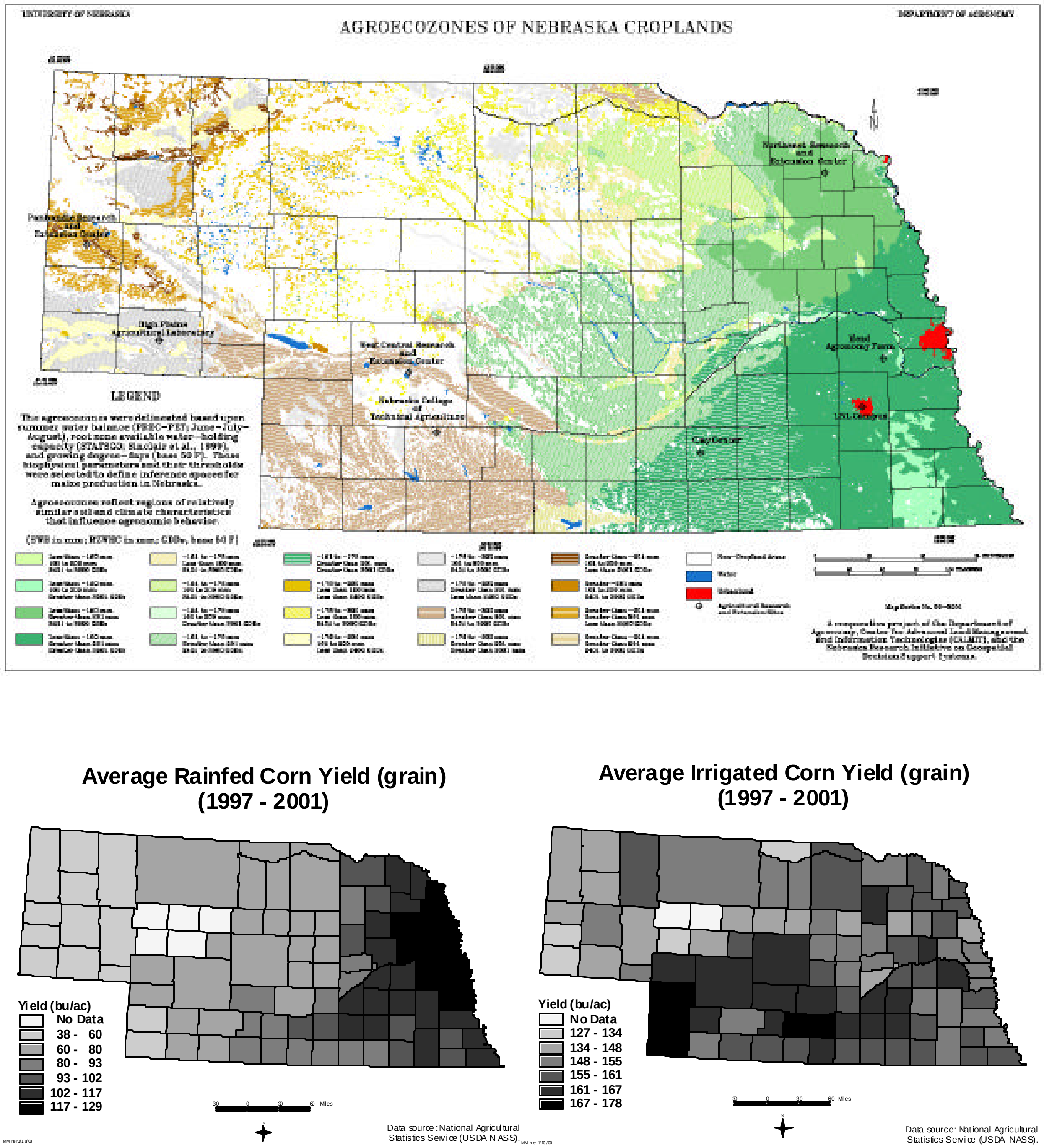



**Fig. 2.** County-level average yields of rainfed and irrigated corn in Nebraska during 1997 to 2001 as compared to agroecological zones, which mainly represent the spatial variation in growing degree days, summer water balance, and root zone available water-holding capacity (Data compiled and mapped by M. Milner, University of Nebraska-Lincoln).

## CROP MODELING FOR UNDERSTANDING AND MANAGING THE SPATIO-TEMPORAL VARIABILITY IN YIELD POTENTIAL

Two approaches dominate simulation modeling of corn growth. In the first approach, generic crop models have been developed based on general processes describing crop growth, which is then followed by adaptation to various crops, including corn. Examples for this are the family of Dutch crop models such as SUCROS, WOFOST and INTERCOM (van Ittersum et al., 2003), the French model STICS (Brisson et al., 2003), or CropSyst (Stöckle et al., 2003). In the second approach, growth simulation models have been developed specifically for corn. Examples for this include CERES-Maize (Jones and Kiniry, 1986) and its implementation in DSSAT (Jones et al., 2003), and the model developed by Muchow et al. (1990).

These two approaches differ in four aspects. First, the generic approach requires fewer crop input parameters than the maize-specific approach, and it also estimates fewer plant parameters such as kernel numbers and cob biomass. Second, maize development in generic models is driven primarily by the availability of assimilate from photosynthesis, while temperature is the primary driving force in the maize-specific models. Third, growth respiration and maintenance respiration are explicitly accounted for in the generic models to determine net dry matter production, while the maize-specific approach derives net dry matter production directly from absorbed solar radiation by means of a fixed value of radiation use efficiency (RUE) that implicitly accounts for respiration costs. Fourth, the generic approach does not consider crop phenology, except the event of anthesis, nor differences in hybrid traits such as sensitivity to daytime length, potential number of kernels and potential grain filling rate. In contrast, the maize-specific approach requires specification or estimation of several phonological events and hybrid parameters.

In earlier work we evaluated several corn models with regard to their requirements for input parameters and their accuracy of predicting maize dry matter accumulation, leaf area development, and final grain and stover yields under near yield potential conditions. Detailed field measurements from a 3-year study at Lincoln, in which maize was grown with minimal possible stress, were used for validation (Dobermann et al., 2002). All models consistently underestimated corn grain and stover yields under near-optimal growth conditions. Such underprediction would result in reduced estimates of C sequestration, especially in high-yield environments where the potential for C sequestration may be large. They may also lead to underprediction of nutrient requirements for fertilizer recommendations that take into account the yield potential. CERES-Maize, in which temperature determines the potential leaf and stem growth, performed better than INTERCOM in which availability of assimilate is the primary driving force. In contrast, the separate routines for photosynthesis and respiration in INTERCOM provided greater sensitivity for crop response to temperature than CERES-Maize, which mostly relies on a fixed value for RUE for determining dry matter accumulation. Whereas INTERCOM requires specification of growing degree days (GDD) to anthesis as an input parameter, CERES-Maize predicts anthesis from the GDD interval from emergence to end of the juvenile phase, whose value, however, is not readily available for most hybrids.

Based on these findings, a new corn simulation model, Hybrid-Maize, was developed by combining the strengths of the two modeling approaches and modification of several functions. Hybrid-Maize features temperature-driven maize phenological development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. It also requires fewer hybrid-specific parameters without sacrificing the prediction accuracy. For example, the linear relationship between GDD to anthesis and GDD to maturity was used to predict anthesis because information about GDD to maturity is available for most commercial hybrids. The model has a Windows-based user interface (Fig. 3), comprehensive graphic presentation of simulation results, climate data, and cross-year comparisons for time-series simulations, and a utility for importing online weather data.

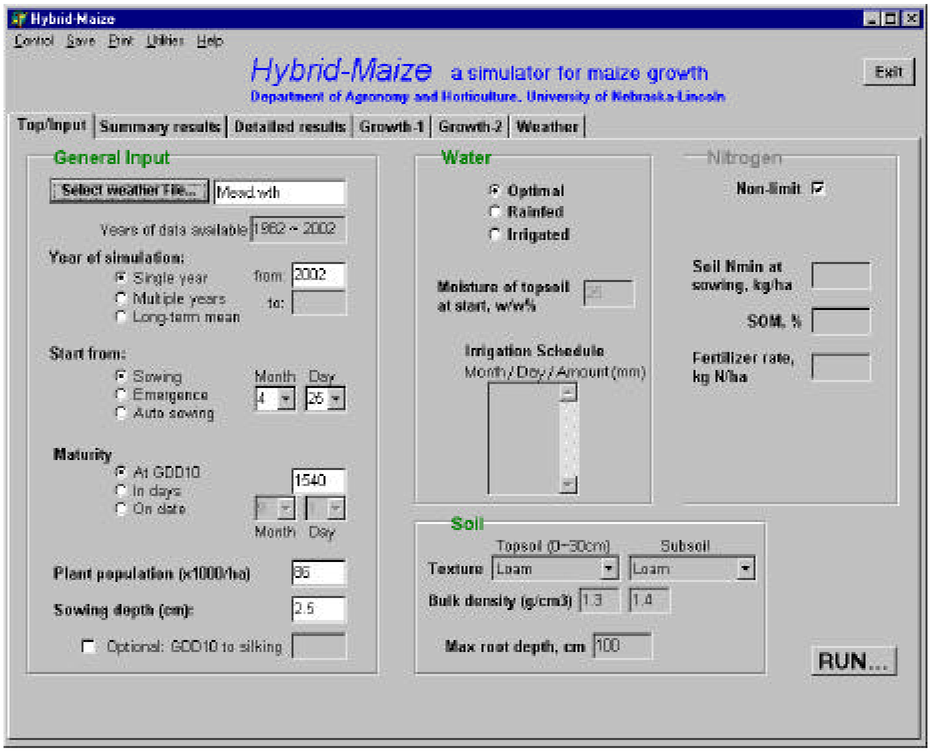



**Fig. 3.** Hybrid-Maize model user interface.

Hybrid-Maize simulated total corn dry matter accumulation, grain yield, harvest index and root biomass more accurately and more consistently in high-yielding environments than INTERCOM, CERES-Maize, or the Muchow-Sinclair-Bennett model (H. Yang et al., unpublished data). Efforts are currently underway to develop a nitrogen management component.

What are the potential uses of a crop simulation model in future agricultural management? Applications can be generally divided into those that are based on long-term, historical climate and site data and those in which climate data for a single growing season are used for making management decisions:

Using historical, long-term climate data:

- Simulate yield potential in relation to other cropping systems for managing land use, enhancing sustainability, decreasing risk and increasing potential profitability
- Simulate long-term yield potential and assess its spatial and temporal variation to set adequate yield goals.
- Simulate yield potential in relation to planting date to determine the optimal planting window.

- Simulate yield potential in relation to maturity group to identify suitable corn hybrids.
- Simulate yield potential in relation to plant density to determine the optimal plant density.
- Simulate water-limited and/or nutrient-limited attainable yields to set adequate yield goals and evaluate economics and risks of various input use scenarios (planting date, plant density, fertilizer).

Using actual climate data for a single growing season:

- Simulate actual yield potential and water-limited attainable yield based on daily records of solar radiation, temperature, rainfall, and irrigation to adjust the yield goal during the season and make subsequent adjustments in fertilizer amounts (sidedress, fertigation); evaluate soil moisture status and make decisions on irrigation.
- Post-harvest analysis: what happened? Evaluate actual plant growth and soil moisture dynamics in comparison with normal years/other years. Make decisions for next year.

As an example, Table 1 shows the simulated corn yield potential at different sites in Nebraska, following the general agroecological gradient shown in Fig. 2. As expected, Ymax is lowest in the western parts of the state (224 to 238 bu/acre) because the length of the growing season is the major yield-limiting factor. Highest mean site yield potentials were simulated for locations in the southwestern and south-central parts of Nebraska (Lexington, Holdredge, Clay center, Central City), reaching average levels in the 283 to 296 bu/acre range. Moving further east (Mead, Beatrice), average Ymax declined slightly, probably due to less solar radiation associated with higher rainfall. At all sites, simulated yield potential fluctuated widely from year to year, with standard deviations of typically about 25 to 30 bu/acre among years.

Three conclusions emerge from this analysis. First, at the locations with the highest corn yield potential in Nebraska, the average Ymax appears to be about 290-300 bu/acre, but it may vary by about ±30 bu/acre from year to year at the same location or by about 70 to 80 bu/acre among different locations in the state. These simulated averages and ranges of Ymax compare well with the trends in contest winner yields observed for irrigated corn in Nebraska, which mainly represent locations that fall within the same zone of highest Ymax in the state. Since the mid 1980s, contest winner yields have fluctuated around 300 bu/acre, with no indication of an increase over time (Duvick and Cassman, 1999). From 1984 to 2002, average yield of the irrigated corn contest winner was 299 bu/acre with a standard deviation of ±39 bu/acre among years. The maximum yield ever reported in this contest for Nebraska was 348 bu/acre in 1986.

Second, the spatial variation in simulated yield potential appears to roughly match the spatial patterns of county-level irrigated corn yields (Fig. 2), although the latter are typically only about 60% of the simulated Ymax. Thus, a considerable yield gap still exists, but exploiting it will require improved crop management technologies. The process of narrowing the yield gap is ongoing, but at a slow pace. Average irrigated and rainfed corn yield in Nebraska continue to increase at an annual rate of about 1.6 bu/acre.

Third, the good agreement between simulated Ymax and yields measured in the annual yield contests provides evidence that the Hybrid-Maize model appears to accurately simulate the present yield potential. We were unable, however, to accurately predict recent record yields of 408 bu/acre (2001) or 442 bu/acre (2002) reported for the site of Francis Childs at Manchester, Iowa; no reasonable modifications to input parameters controlling net primary productivity in currently used corn models could account for the reported yields at Manchester.

**Table 1.** Simulated corn yield potential at different locations in Nebraska. Sites are grouped along a northwest to southeast geographical gradient, which represents the spatial variation in climate (increasing rainfall, temperature, and length of growing season). Using the Hybrid-Maize model, yield potential was simulated using daily historical climate data at each site, based on temperature and solar radiation alone. These simulations represent the climatic-genetic yield potential, assuming no limitation due to abiotic (water, nutrients) or biotic (pests) stresses.

| Site | Years | Planting date [1] | GDD (F)[2] | Yield potential (bu/acre) [4] |
|---|---|---|---|---|
| **Northwest - West** | | | | |
| Gordon | 1984-2002 | 11-May | 2250 | 224 (40) |
| Scottsbluff | 1991-2002 | 11-May | 2250 | 238 (25) |
| Sidney | 1982-2002 | 11-May | 2250 | 237 (31) |
| Arthur | 1982-2002 | 11-May | 2250 | 230 (26) |
| **Southwest - West-central - Northeast** | | | | |
| Champion | 1982-2002 | 5-May | 2500 | 268 (32) |
| North Platte | 1982-2002 | 5-May | 2500 | 262 (31) |
| Ainsworth | 1984-2002 | 5-May | 2500 | 261 (27) |
| Concord | 1982-2002 | 5-May | 2500 | 263 (30) |
| **South-central – East - Southeast** | | | | |
| Lexington | 1986-2002 | 25-Apr | 2750 | 296 (28) |
| Holdredge | 1988-2002 | 25-Apr | 2750 | 283 (22) |
| Clay Center | 1982-2002 | 25-Apr | 2750 | 284 (30) |
| Central City | 1986-2002 | 25-Apr | 2750 | 294 (25) |
| Mead | 1982-2002 | 25-Apr | 2750 | 276 (26) |
| Beatrice | 1990-2002 | 25-Apr | 2750 | 276 (22) |
| Lincoln [5] | 1986-2002 | 25-Apr | 2750 | 249 (23) |

[1] Assumed typical planting date. Plant density in all simulations was 10 plants/$m^2$ (= 40,500 plants/acre).

[2] Assumed average growing degree days for corn hybrids planted in this zone. For a given GDD (or cultivar), crop grow period is longer at cooler temperature and shorter at warmer temperature. This potentially gives an advantage to cooler sites in terms of yield potential for a given GDD, though duration and yield are not linearly correlated.

[3] Simulated length of growth period from emergence to physiological maturity.

[4] Mean simulated corn yield potential and standard deviation among years (in parenthesis).

[5] Location of the UNL Ecological Intensification Experiment. City location with high temperature.

Average yields of 245 to 250 bu/acre have been routinely achieved in the Ecological Intensification experiment at Lincoln from 1999 to 2002, with individual plots yielding up to 280 bu/acre in most years. This compares well to the simulated long-term Ymax of 249 bu/acre for this site (Table 1) and its fluctuations among years (Fig. 4), indicating that crop management reached near optimal growth conditions. Why, however, is Ymax at Lincoln almost 30 bu/acre less than at nearby sites such as Beatrice (40 miles south of Lincoln) or Mead (30 miles northeast of Lincoln, Table 1) and what can be done to increase it?

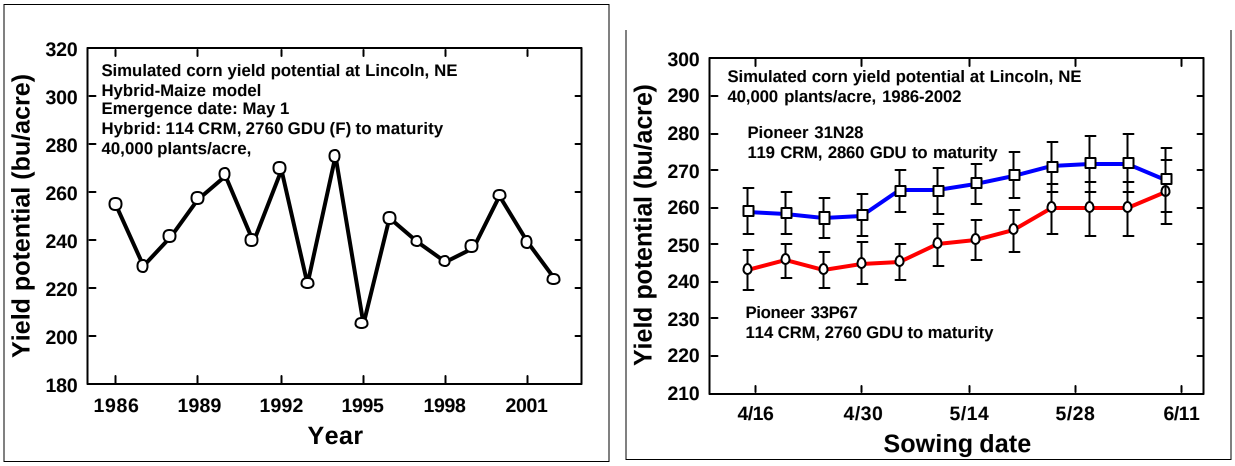



**Fig. 4.** Simulated corn yield potential at Lincoln, NE using the Hybrid Maize model with daily climate data from 1986 to 2002. Left: variation of the annual yield potential for a typical hybrid grown in this environment with a common sowing date of April 25. Right: simulated yield potential for two corn hybrids with different growth duration as affected by sowing date (means and standard deviation among years for each sowing date simulated).

The major reason for the lower Ymax at Lincoln appears to be higher temperature and faster accumulation of growing degree units (see below), which is probably due to the city location of this experimental site and often hastens crop maturity (Dobermann et al., 2002). If so, both changing the planting date and growing a longer-season hybrid may be options for achieving a higher Ymax. Fig. 4 illustrates results of simulating such scenarios. Growing a hybrid with about 100 GDU more than Pioneer® 33P67 could result in about 15 bu/acre higher Ymax at Lincoln, irrespective of the planting date chosen. In addition, delaying planting to about the first week of May would further increase Ymax slightly as compare to planting in late April.

Results of such crop simulations must always be treated with caution until adequate experimental field validation has occurred. Models are not perfect representations of the processes involved because they only represent the current scientific understanding at levels that can be expressed in relatively simple mathematical terms. Therefore, well-validated models mainly allow developing hypotheses and exploring management scenarios, which must then be followed by adequate experimental field validation.

Nevertheless, crop models such as Hybrid-Maize should become more widely used decision aids for researchers as well as agricultural professionals. Such decision-making tools must also account for factors that are not adequately accounted for in a crop model. In the Lincoln case, for example, it is questionable whether delaying planting until end of May/early June would really increase Ymax (Fig. 4) and the actual yield (Y) because delaying planting may cause increases in yield gaps (Fig. 1) due to factors that were not accounted for in the yield potential simulations.

## CORN GROWTH AND YIELD RESPONSE TO NUTRIENTS NEAR THE YIELD POTENTIAL CEILING

In 2002, field experiments were conducted at several sites to (i) collect detailed plant data needed for obtaining better understanding of dry matter production, and nutrient uptake under conditions of very high corn yield, (ii) estimate growth rates and nutrient uptake rates at key growth stages, (iii) quantify light interception and radiation use efficiency, (iv) conduct measurements of soil nutrients, soil microbial biomass, and soil greenhouse gas fluxes, at key growth stages, (v) and refine the Hybrid-maize Model. Below, partial results from four selected sites will be presented.

Major site characteristics are summarized in Table 2. The Lincoln site refers to the *Ecological Intensification Experiment (EI)* conducted since 1999 at the University of Nebraska—Lincoln East Campus for which details were provided elsewhere (Arkebauer et al., 2001; Dobermann et al., 2002). Only data collected in 2002 for treatment CC-P3-M2 (continuous corn – high plant density – intensive nutrient management) are shown here. This treatment emulates practices used by many corn yield contest winners and is an attempt to grow corn at near yield potential levels. The Manchester site is the farm of Francis Childs, winner of the National Corn Growers Association yield contest in recent years. A description of the site and the cropping practices is provided by Murrell and Childs (2000). In 2002, soil, crop, and daily weather data were collected from four sampling plots located within a 40' x 480' strip of the hybrid comparison area ("Visitor plot") managed by Mr. Childs, following the same management program applied in most of his high-yield areas. The sites at Mead and Clay Center are part of the Nebraska Soil Fertility Project conducted at 12 sites in 2002. Mead is located in the eastern part, whereas Clay Center represents the south-central region (Table 1). At both sites, a replicated fertilizer experiment was conducted to evaluate corn response to nutrient supply up to yield levels that approach Ymax. This experiment had 10 treatments, but results shown here refer to selected treatments only, including those in which maximum yield was achieved.

Two sites, Manchester (about 30 years) and Lincoln (4 years) represent continuous corn systems under high-yield production, whereas Mead and Clay Center have mostly been cropped in the past following corn-soybean rotation at average input levels. All Nebraska sites were fully irrigated using different irrigation methods (Table 2). Manchester represents rainfed cropping, but with high and evenly distributed rainfalls throughout most of the growing season. Hybrid-Maize simulations of Ymax based on long-term climate data indicated a decrease in site yield potential in the order Manchester (309 bu/acre) > Clay Center (284) > Mead (276) > Lincoln (249). These site differences were mainly associated with differences in temperature and solar radiation, both also determining the length of the growing season. For example, long-term incident solar radiation at Manchester is about 8% greater than at Lincoln, whereas mean air temperature during the growing season is 73 F at Lincoln as compared to 68 F at Manchester.

The fertilizer program at Manchester included a large amount of N (406 lb/acre), mostly applied in spring, whereas smaller amounts of P, K, and various micronutrients were supplied by starter fertilizers. Phosphorus and K rates in 2002 were small due to previous buildup of these nutrients (see Fig. 5). At Lincoln, 258 lb N/acre were applied, but spread out more evenly during the growing season and combined with a larger pre-plant application of P and K designed to replenish crop removal at very high yield levels. At Mead and Clay Center, N rates in different treatments were 0, 75, 125, 175, or 250 lb N/acre, all receiving 41 lb $P_2O_5$ and 43 lb $K_2O$/acre.

**Table 2.** Site characteristics and cropping practices in field experiments at Manchester (IA), Lincoln (NE), Mead (NE), and Clay Center (NE) in 2002.

| Location | Manchester<br>F. Childs' farm | Lincoln<br>East Campus | Mead<br>ARDC | Clay Center<br>SCREC |
|---|---|---|---|---|
| Simulated site yield potential (bu/acre) [1] | 307 | 249 | 276 | 284 |
| Soil type | Clyde-Floyd L | Kennebec siL | Tomek siCL | Hastings siL |
| Crop rotation | Continuous corn | Continuous corn | Corn-soybean | Corn-soybean |
| Corn hybrid | Pioneer® 33P67 | Pioneer® 33P67 | Pioneer® 33P67 | Pioneer® 33P67 |
| Row spacing (in) | 20 | 30 | 30 | 30 |
| Tillage | Plow | Plow | No-till | Chisel/disk |
| Irrigation | Rainfed | Drip | Sprinkler | Sprinkler |
| Fertilizer rates | | | | |
| lb N/acre | 406 | 258 | 250 [3] | 175 [3] |
| lb $P_2O_5$/acre | 15 | 92 | 41 | 41 |
| lb $K_2O$/acre | 25 | 93 | 43 | 43 |
| N management | | | | |
| (lb N/acre) | 50 | 65 | - | - |
| fall | 356 [2] | 71 | 150 | 105 |
| spring pre-plant | - | 36 | 100 | 70 |
| V6 | - | 36 | - | - |
| V9 | - | 50 | - | - |
| VT | | | | |

[1] Simulated average site yield potential for a corn hybrid with about 2750 GDD and a plant density of 10 plants $m^{-2}$ (40,000 plants/acre). Data for Manchester are based on climate data from Cedar Rapids, located about 35 miles south. Planting dates used were April 25 for Lincoln and May 5 for Manchester. Climate data records ranged from 5 years at Manchester to 17-21 years at the other sites.
[2] Includes 250 lb N/acre pre-plant as anhydrous ammonia + 6 lb N/acre as starter fertilizers + 100 lb N/acre pre-emergence with herbicide as UAN 28%.
[3] N rates at Mead and Clay Center for the treatment with the highest yield.

Soil test levels varied among these sites (Fig. 5). Soil organic matter content was high at Manchester (5.6 % in 0-6" depth and 4.6% in 6-12" depth), as compared to 2.5% at Lincoln or 3.0% at both Mead and Clay Center. This reflects a history of building up organic matter through long-term high-yield cultivation at Manchester, which includes high biomass and crop residue production, use of a mini-moldboard plow for residue incorporation, and application of a small amount of N in fall to stimulate residue decomposition. Soil Bray-1 P levels were high at both Manchester and Lincoln (Fig. 5), but relatively low at Mead (11 ppm) and Clay Center (10 ppm). At all sites, soil test K (1 N $NH_4$-acetate) was in the 300 to 420 ppm range, levels at which limitations to corn growth are unlikely to occur. Measurements in 2002 also showed lower soil nitrate levels at Manchester as compared to Lincoln (Fig. 5), despite much higher amounts of N applied at Manchester (Table 2). At Lincoln, high nitrate levels were probably caused by using a sub-surface drip irrigation system, which failed to provide uniform soil wetting of the upper six inches of soil (see below). Soil pH and soil test levels of sulfur, zinc, iron, manganese, and copper were similar at both Manchester and Lincoln (data not shown).

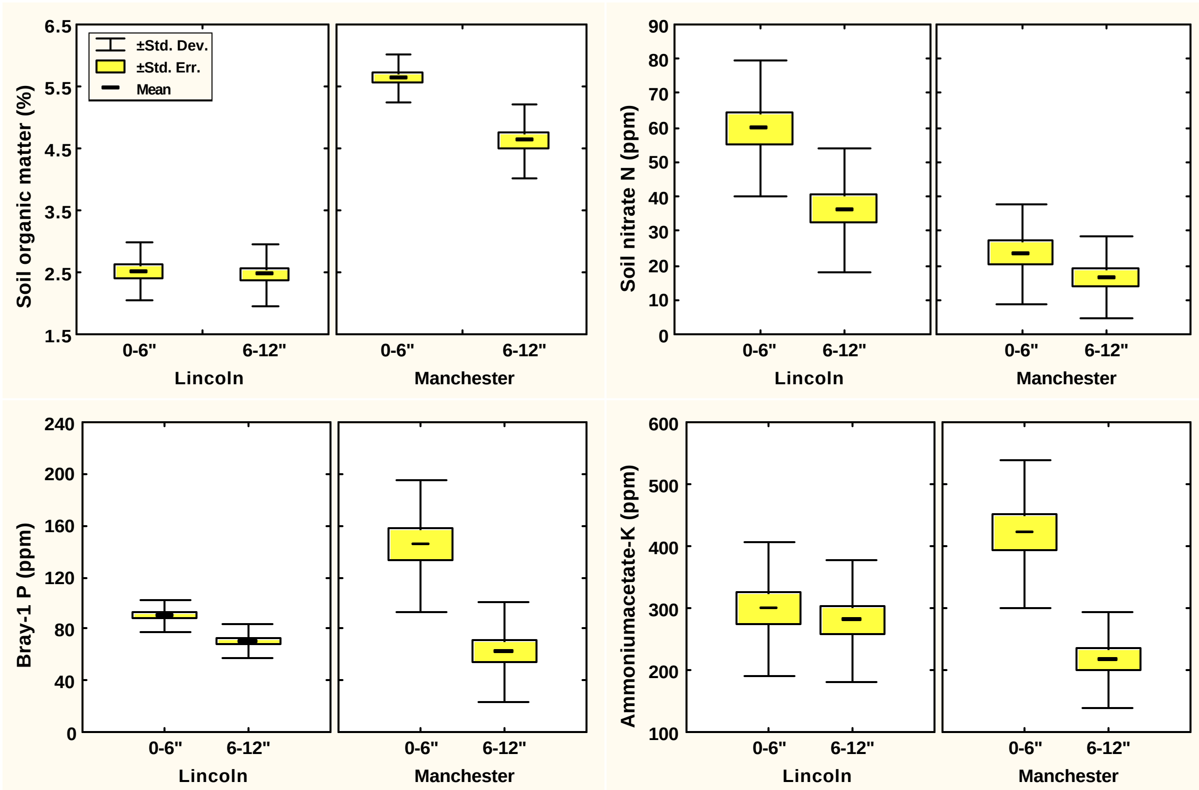



**Fig. 5** Soil test levels in 0-6" and 6-12" depths at the Lincoln (NE) and Manchester (IA) sites. Values shown are means, standard deviations, and standard errors of samples collected at emergence, V6, silking, and physiological maturity stages of corn at each site.

**Table 3.** Crop growth stages and climate during the 2002 growing season at Manchester (IA), Lincoln (NE), Mead (NE), and Clay Center (NE).

| Location | Manchester [1] | Lincoln | Mead | Clay Center |
|---|---|---|---|---|
| Date of sowing | May 8 | May 10 | April 26 | April 25 |
| Date of emergence | May 22 | May 17 | May 10 | May 10 |
| Date of maturity | September 25 | September 12 | September 12 | September 17 |
| Solar radiation ($MJ/m^2$) | 2602 | 2448 | 2675 | 2521 |
| Mean minimum temperature (F) | 58.8 | 65.5 | 60.6 | 59.9 |
| Mean maximum temperature (F) | 82.9 | 88.3 | 85.6 | 85.1 |
| Rainfall (in) | 20.2 | 11.4 | 7.5 | 9.7 |
| Mean daily ET (in) | 0.20 | 0.26 | 0.28 | 0.27 |

[1] On-site weather data have not been processed yet. Values shown for the Manchester site refer to Cedar Rapids, IA.

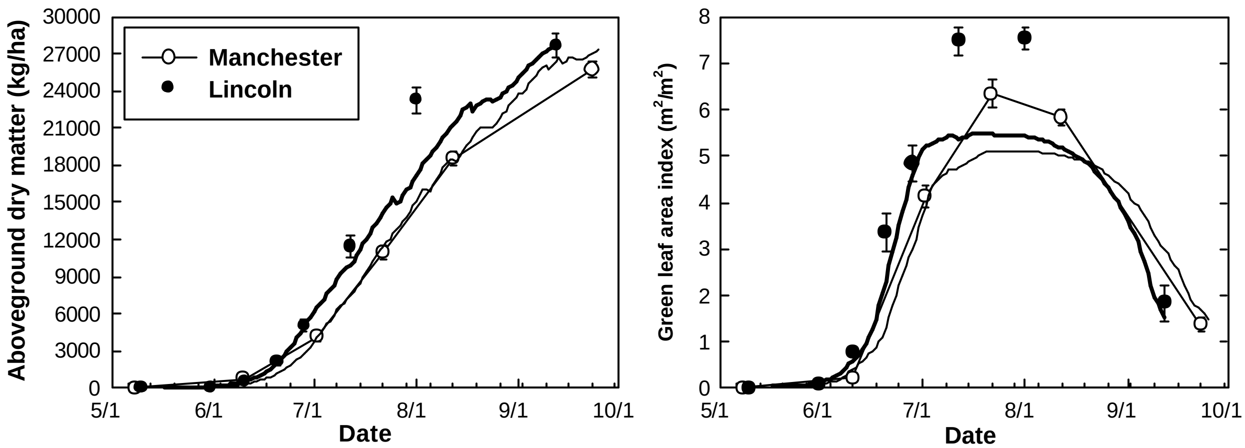



**Fig 6.** Dry matter accumulation and LAI of Pioneer® 33P67 grown at Lincoln (NE) and Manchester (IA) during the 2002 growing season, from planting to physiological maturity. Symbols represent measured values, whereas the lines show growth dynamics simulated by the Hybrid Maize model for optimal growth conditions, based on the actual dates of crop emergence and maturity and the final plant density measured.

At Manchester and Lincoln, Pioneer® 33P67 was planted on May 8 and May 10, respectively, but physiological maturity occurred about two weeks later at Manchester than at Lincoln (Table 3), mainly because cooler temperatures caused a longer growing season at Manchester. A striking feature of the Lincoln site are relatively high minimum (night) temperatures, averaging about 5 to 6 F more than at the other sites.

In general, accumulation of growing degree days proceeded faster at Lincoln than at Manchester, resulting in accelerated crop development, more rapid accumulation of aboveground biomass, faster increase in green leaf area index (Fig. 6), and less cumulative solar radiation during the growing season (Table 3). Despite these site differences, maximum levels of simulated total aboveground biomass and LAI were comparable at Lincoln and Manchester sites. Simulated total dry matter was 27,300 kg/ha at Manchester and 27,700 kg/ha at Lincoln, which compares to measured values of 25,700 kg/ha and 27,700 kg/ha, respectively (Table 4).

Hybrid-Maize predicted biomass accumulation well at both sites, but it underestimated measured peak LAI after tasseling (Fig. 6). Some uncertainties exist about the accuracy of LAI measurements due potential errors associated with representative plant sampling, destructive LAI measurement, and upscaling of the results. Moreover, at Lincoln, the high maximum LAI values of about 7.5 $m^2$ $m^{-2}$ were also caused by strong tillering of Pioneer® 33P67, which may have been due to the high soil nitrate levels observed (Fig. 5). Tillering disproportionally increased LAI as compared to its effect on total biomass. Nevertheless, the potential underestimation of peak LAI by the model requires further study and may indicate scope for improvement.

Final grain yields at all four sites were in the 242 to 259 bu/acre range (Table 4). At Mead and Clay Center, measured yields were near the simulated yield potential for the plant densities used in these experiments, but about 25 to 30 bu/acre less than the simulated long-term site yield potential for corn grown at a density of 40,000 plants/acre (Table 2). In other words, although nutrient and water management at these sites were sufficient to minimize yield gaps 1 and 2 (Fig. 1), the full Ymax may not have been achieved yet. At Clay Center, for example, an additional treatment with a final plant density of 31,000 plants/acre yielded 265 bu/acre (data not shown).

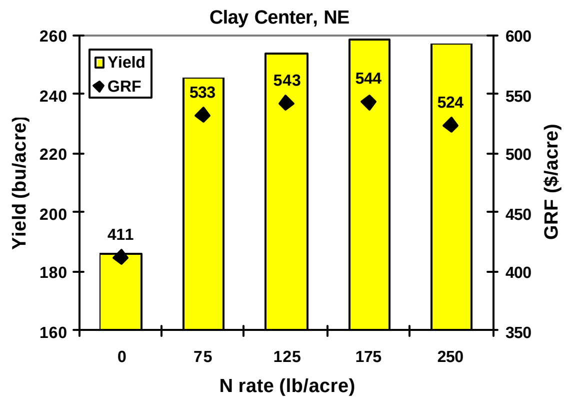
**Table 4.** Plant density, grain yield, harvest index, and total aboveground dry matter of Pioneer® 33P67 grown in high-yielding corn treatments at Manchester (IA), Lincoln (NE), Mead (NE), and Clay Center (NE) in 2002, including both simulated and measured values.

| Location | Manchester | Lincoln | Mead | Clay Center |
|---|---|---|---|---|
| Final plant density (plants/acre) | 34,100 | 37,800 | 27,500 | 28,000 |
| Simulated grain yield (bu/acre) [1] | 282 | 280 | 250 | 259 |
| Simulated harvest index [1] | 0.55 | 0.54 | 0.51 | 0.53 |
| Simulated total dry matter (kg/ha) [1] | 27,300 | 27,700 | 25,800 | 25,900 |
| Measured grain yield (bu/acre) | 248 | 242 | 247 | 259 |
| Measured harvest index | 0.53 | 0.48 | 0.55 | - |
| Measured total dry matter (kg/ha) | 25,700 | 27,700 | 24,800 | - |

[1] Yield potential simulated by Hybrid-Maize for 2002 based on the hybrid grown, the observed dates of emergence and physiological maturity, and the actual plant density at each site. Assumes no limitations by water and nutrients. Simulated yield for Manchester is based on weather data from Cedar Rapids, IA.

Final grain yields were 248 bu/acre at Manchester and 242 bu/acre at Lincoln. Highest yields measured in individual sampling plots were 252 bu/acre at Manchester and 263 bu/acre at Lincoln. The average yields measured at both sites were 34 to 38 bu/acre less than the simulated yield potential for the 2002 growing season at the actual plant densities (Table 4). This may suggest that some yield reductions occurred at both sites due to abiotic stresses because no other yield losses were observed. More data analysis, including on-site daily weather records and measurements of plant nutrient uptake will be conducted to identify possible reasons for this.

For Lincoln, the average corn yield in 2002 was slightly lower than in previous years (Dobermann et al., 2002). The unrealized yield gap was probably due to uneven plant spacing due to soil crusting occurring after planting and extremely dry and hot weather during most of June and July. Although the total amount of rainfall at Lincoln was 11.4 inches for the whole 2002 growing season, it was only 0.9 inches from June 1 to July 25. During the same period, temperatures were above normal, causing high rates of evapotranspiration. The sub-surface drip irrigation system (60” spacing, drip tapes about 10-12” deep) was unable to keep the surface soil moist, particularly in between-row spaces with no underlying drip tape. Even though the total irrigation amount was 24.8” for the whole growing season, signs of water stress were observed for a short period in early July. Moreover, due to non-uniform soil wetting, a significant amount of the nitrogen applied appeared to not have been used efficiently, as indicated by high amounts of soil nitrate during the growing season (Fig. 5).



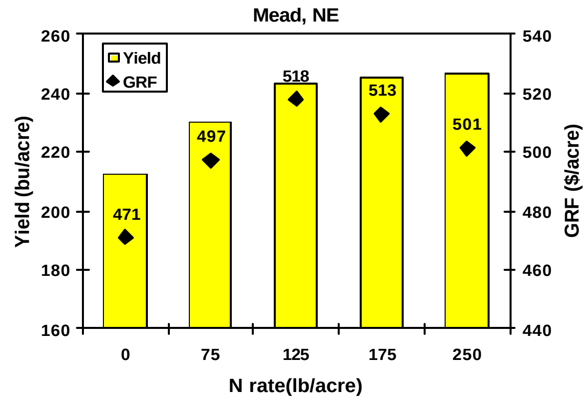




**Fig 7.** Corn yield and gross return after fertilizer cost (GRF = value of corn harvested – total cost of fertilization) at Mead and Clay Center as affected by N rates. At both sites corn was grown after soybean as the previous crop and all treatments received the same amounts of P and K.

Understanding yield potential is likely to lead to improved efficiency of resource management. For practical situations, yields somewhat below Ymax appear to provide the most efficient compromise in terms of food production, profitability, and resource use efficiency. This is illustrated by results from the Clay Center and Mead sites, where yield response of corn grown after soybean was studied at N rates ranging from 0 to 250 lb N/acre (Fig. 7).

Maximum yield at these sites was achieved at N levels of 175 lb N/acre at Clay Center and 250 lb N/acre at Mead. However, beyond 125 lb N/acre yield increases were small and this treatment represented the most profitable one of those tested. Applying 125 lb N at Clay Center resulted in a grain yield of 254 bu/acre (89% of the simulated long-term Ymax, Table 2), a N use efficiency of 2.0 bu grain per lb of N applied (twice the current farm average), and a GRF of $543/acre. Applying 125 lb N at Mead resulted in a grain yield of 243 bu/acre (88% of the simulated long-term Ymax, Table 2), N use efficiency of 2.0 bu grain per lb of N applied, and a GRF of $518/acre.

These results were comparable to what has been observed in a similar treatment of the EI experiment at Lincoln (data not shown). There, in the treatment representing currently recommended Best Management Practices (corn-soybean rotation, about 30,000 plants/acre, UNL fertilizer recommendations), annual N rates strictly followed current management guidelines, including annual spring soil sampling for measuring residual soil nitrate levels in the profile (Shapiro et al., 2001). Over a period of four years, soil nitrate levels varied little and remained low, resulting in little variation of the N rates and an average amount of just 116 lb N/acre applied annually. Average corn yield during 1999 to 2002 was 222 bu/acre (89% of the simulated long-term Ymax, Table 2), resulting in an average N use efficiency of 1.9 bu/lb.

## CONCLUSIONS

Yield potential and yield gaps must be understood in quantitative terms in order to make significant progress in improving crop management, particularly in favorable environments. Crop – ecosystems models play an important role in this process, but their refinement requires high-quality field and on-farm experimentation in diverse environments. A new maize simulation model, Hybrid-Maize, was developed by combining the strengths of two modeling approaches and modification of several other functions. It features temperature-driven maize phenological development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. It also requires fewer hybrid-specific parameters without sacrificing the prediction accuracy.

Present evidence, both in terms of available scientific field research data and understanding of crop physiology embodied in simulation models suggests a corn yield potential of about 300 bu/acre, with an amplitude of perhaps ±30 to 70 bu/acre, depending on location and year. Such ranges of Ymax have been predicted by the Hybrid-Maize model for different environments and available experimental and yield contest data provide further evidence for this. Moreover, our field experiments and the yields achieved by top producers provide evidence that yield levels of 80 to 90% of Ymax are feasible and highly profitable under production conditions. They require, however, that crop management is based on scientific guidelines that aim at achieving high input use efficiency.

Corn contest winning yields of >400 bu/acre have been reported in recent years for the Manchester site in Iowa. So far, such yields have not been achieved at other locations or in research experiments, and currently available crop simulations models cannot predict them accurately. Uncertainties remain about the real yield ceiling and whether available crop growth models can accurately predict the true yield potential. Soil scientists and agronomists should seek to better understand the management factors required to achieve crop yield potential on a consistent basis. Given the importance of trends in crop yield potential for global food security and conservation of natural resources (Waggoner, 1994; Evans, 1998; Cassman, 1999), we believe that accurate measurement and fundamental understanding of yield potential is crucial for meeting human needs in the coming decades.

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