# HYBRID MAIZE – A SIMULATION MODEL FOR IMPROVING CORN MANAGEMENT

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**Abstract**

Hybrid-Maize (www.hybridmaize.unl.edu) is a computer program that simulates the growth and yield of a corn crop under non-limiting or water-limited (rainfed or irrigated) conditions. The model can be used to (1) assess the overall site yield potential and its variability based on historical weather data, (2) evaluate changes in attainable yield using different combinations of planting date, hybrid maturity and plant density, (3) analyze yield in relation to silking and maturity in a specific year, (4) assess soil moisture status and explore options for irrigation management, and (5) conduct in-season simulations to evaluate current crop status and predict final yield as a range of yield outcome probabilities based on historical climate data for the remainder of the growing season. The software offers a user-friendly and intuitive graphical interface for both input settings and output analysis. All key model parameters and other default input variables are transparent and modifiable, which makes the model useful in research, teaching, extension education, and practical field management.

## Introduction

We have recently developed a new corn simulation model, Hybrid-Maize (www.hybridmaize.unl.edu). Details of this model and its validation are published elsewhere (Dobermann and Yang, 2004; Yang et al., 2004a; Yang et al., 2004b). Since its release in August 2004, more than 200 copies of the software have been sold through an e-store website (estore.adec.edu), and the model is being used by researchers, extension specialists and educators, crop consultants, industry professionals, and farmers. The objective of this paper is to provide an overview of the Hybrid-Maize software, with emphasis on its capabilities and potential applications based on our own experience and feedback from users.

## Major Features of the Hybrid-Maize Software

The current version of the Hybrid-Maize model simulates potential corn growth and yield under non-limiting or water limited conditions. Specifically, it allows users to: (1) assess the site yield potential and its variability based on historical weather data, (2) evaluate changes in attainable yield using different combinations of planting date, hybrid maturity, and plant density, (3) analyze corn yield in relation to the timing of silking and maturity in specific years, (4) assess soil moisture status and explore options for irrigation management, and (5) conduct in-season simulations to evaluate current crop status and predict final yield at maturity as a range of yield outcome probabilities based on historical climate data for the remainder of the growing season. The current version of the program does not account for nutrient limitations or yield loss from weeds, insects, diseases, lodging, and stresses other than the effects of solar radiation, temperature, and soil-plant water relations.

A flowchart of input settings, operation, and presentation of model outputs is presented in Figure 1. These components are implemented through a multi-page graphical user interface with seven tabs (Fig. 2): (1) 'Input' for input and simulation mode settings, (2) 'Results' for summary of numerical outputs, (3) 'Chart' for display of any of 17 output variables for across-run comparisons, (4) 'Growth' for graphical display of growth dynamics of eight variables, (5) 'Weather' for display of growing season climate data, (6) 'Water' for growing season soil moisture regime and crop water stress index, and (7) 'Yield trend' for displaying trends in in-season yield forecasts.

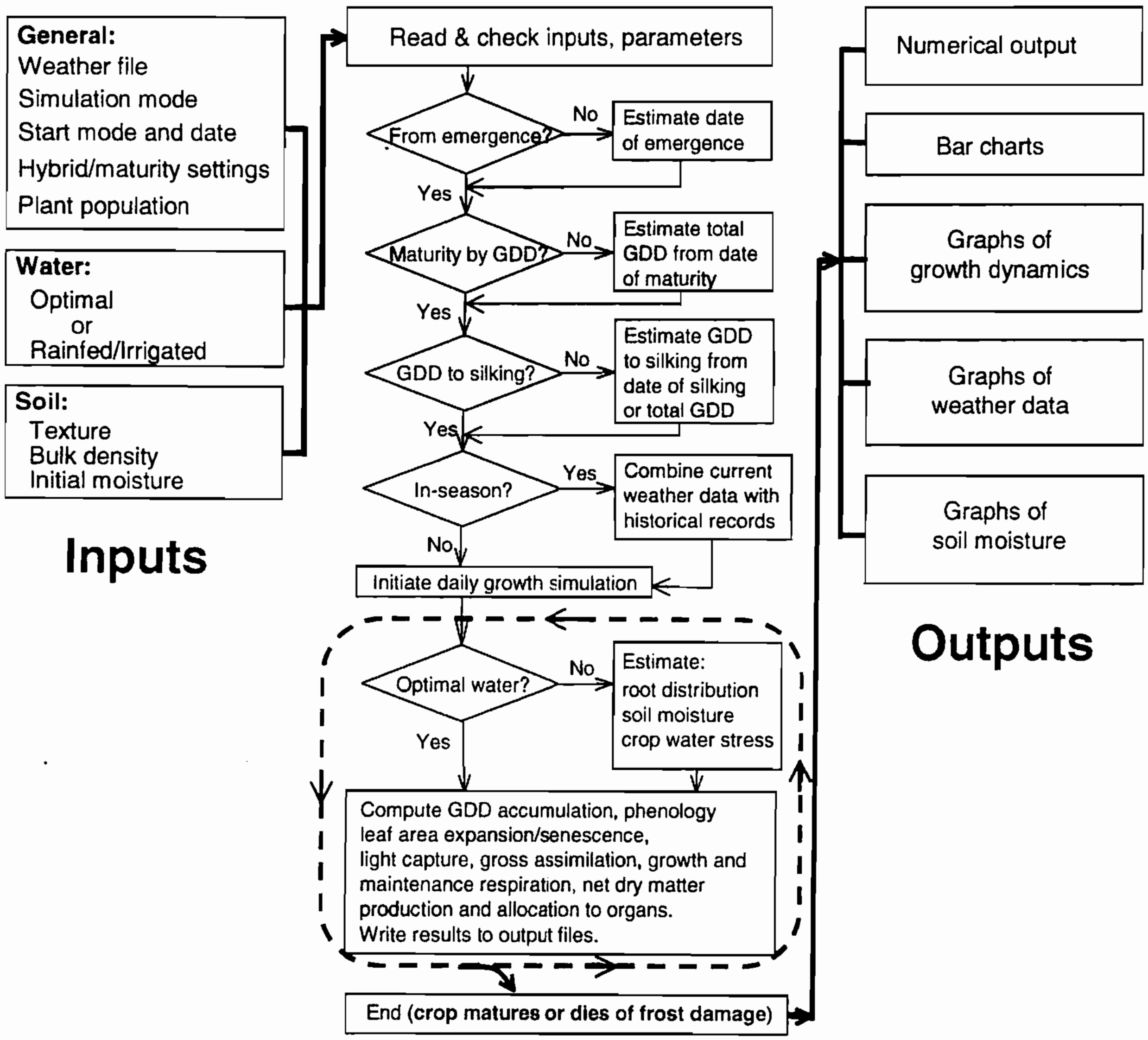


Figure 1. Operational flow of the Hybrid-Maize model.

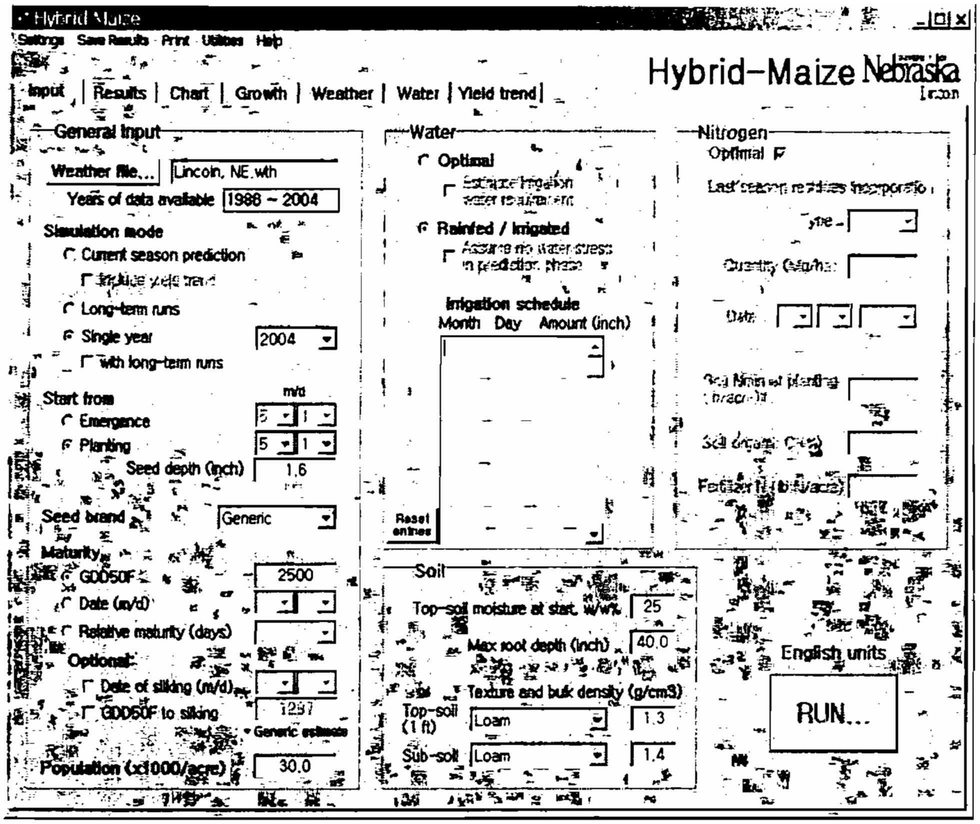


Figure 2. Screenshot of the Hybrid-Maize input page

The software offers the choice of either metric or English units for input and output variables. A unique feature of Hybrid-Maize is that all key internal model parameters are accessible to the user. Each parameter has a text description and some have references to journal papers from which default values were obtained or derived. The user can modify the values for each of these parameters, but there is also an option of restoring all of the original default values with a single mouse click. Simulation settings for a given site can be saved in a working file so that the user can retrieve these settings for future simulation runs. Graphs can also be printed for future reference. The numerical output from the 'Results' screen can be directly edited on-screen, opened in MS Excel or saved as an Excel file. The software includes a context-sensitive help system that can be accessed by pressing F1 on the keyboard or through a pull-down Help menu. Other utilities include easy access to changing the settings for the initial default values for input parameters, folders for working files and weather files, saving and retrieving of input settings from past simulation runs, and saving and printing of simulation results. Window's default text editor and calculator can also be brought up directly within Hybrid-Maize without exiting the software.

## Input Requirements

Hybrid-Maize requires daily weather data in metric units. For simulation under optimal conditions, Hybrid-Maize requires three weather variables: total solar radiation (in MJ $m^{-2}$), minimum air temperature and maximum air temperature (in °C). For water-limited conditions (rainfed or irrigated simulation mode), three additional variables are required: rainfall (in mm), potential evapotranspiration (in mm) and relative air humidity (in %). The weather data must cover the entire growing season from either the date of planting or emergence day to physiological maturity (black layer). For users within the coverage of the High Plains Regional Climate Center (HPRCC, www.hprcc.unl.edu) located in Lincoln, Nebraska, the model contains an automatic conversion utility to convert the weather data downloaded from the HPRCC to the format and units required by the model. Weather data from other sources can also be prepared easily in a spreadsheet program following the instructions in the program's user guide.

Other input settings include start day (either planting or emergence date), crop maturity, plant population, water regime, and soil properties (in case of simulations under water limited conditions). Maturity can be set as either the actual observed date of maturity (e.g., in 'single-run' mode) or as total growing degree-days (GDD) from emergence to physiological maturity (blacklayer) of the hybrid (e.g., in 'long-term runs' and 'current-season prediction' modes). Most commercial seed companies publish GDD values for their hybrids. The base temperature for GDD is 10 °C (metric system) or 50 °F (English system). If information on GDD values to physiological maturity is not available for a hybrid, users can enter a Comparative Relative Maturity (CRM) in days as an alternative. In such cases, the model uses seed brand-specific or generic relationships between GDD and CRM to estimate GDD for reaching maturity. The software offers the option of entering either the observed date of silking (e.g., in 'single run' mode) or GDD from emergence to silking. If neither is known, the program will estimate the date of silking using an internal algorithm based on seed brand-specific or generic relationships between GDD to physiological maturity and GDD to silking.

Optimal or water limited growth simulation can be accomplished by choosing either 'Optimal' or 'Rainfed/Irrigated' modes (Fig. 2). If 'Optimal' is selected, there is no need to enter soil properties, as soil is assumed to provide optimal water supply. However, if the option 'Estimate irrigation water requirement' is selected, soil physical properties must be entered as for rainfed and irrigated crop simulations. Required soil properties include estimated initial gravimetric moisture content of topsoil (i.e., 0 to 30 cm), maximum rooting depth, bulk density and textural class of topsoil and subsoil. When 'Rainfed/Irrigated' is selected, an irrigation schedule can also be specified (dates and amount); if it is left blank the model will assume rainfed conditions. Different irrigation strategies can be explored by changing irrigation times and amounts and evaluating the impact on yield.

## Simulation Modes

Three simulation modes are available: (1) 'Long-term runs' using a selected set or all years of available historical site weather data, (2) 'Single year' simulations with or without a long-term simulation run for comparison, and (3) 'Current season prediction' to the end of the growing season. The 'Long-term runs' mode (1) is used for estimating the long-term site yield potential and its variability under an optimal moisture regime without water stress, or for estimating the attainable water-limited yield potential under rainfed conditions. For both cases, yield potential can be evaluated with respect to different hybrid maturities, planting dates, and plant populations. While the default mode simulates across all years, the user can also select specific periods within historical weather database. All simulations results are ranked by predicted grain yield and a detailed summary of results are reported for five rank years (i.e., the years with the highest, 75th percentile, median, 25th percentile, and worst yield). In addition, predicted mean values and coefficients of variation (CV) are computed for key model outputs. Overall probability of frost damage during grain filling is also reported. For each rank year, detailed outputs are reported for other parameters such as stover yield and harvest index, days to silking and maturity, total duration of vegetative and grain filling periods, total cumulative solar radiation, mean maximum, minimum and average daily temperature during the vegetative and grain filling stages, and total precipitation during the growing season.

Single year without long-term runs mode (2) is primarily used to evaluate the influence of management or climate factors on yield in an individual year, or to estimate the size of the exploitable yield gap by comparing simulated yield potential with actual measured yields. Typically, this type of simulation constitutes a post-hoc analysis of a past growing season. Up to six individual runs can be made sequentially and their results can be compared, both numerically and graphically on the output pages. Single year with long-term runs mode is useful for comparing a given year with the long-term site yield potential as simulated for all other years in the weather database for that site. In this mode, the user can investigate why the yield potential in a given year was above or below average and which climatic factors may have contributed to observed differences across years.

'Current season prediction' mode (3) allows in-season (or real-time) assessment of corn growth up to the current date based on the actual weather data up to that point in time, followed by prediction of growth and final yield thereafter based on historical weather data for the remainder of the growing season (Fig. 3). Similar to the 'Long-term runs' mode, predictions are ranked according to grain yield and results are shown for the scenarios with the highest, 75th percentile, median, 25th percentile, and worst yields.

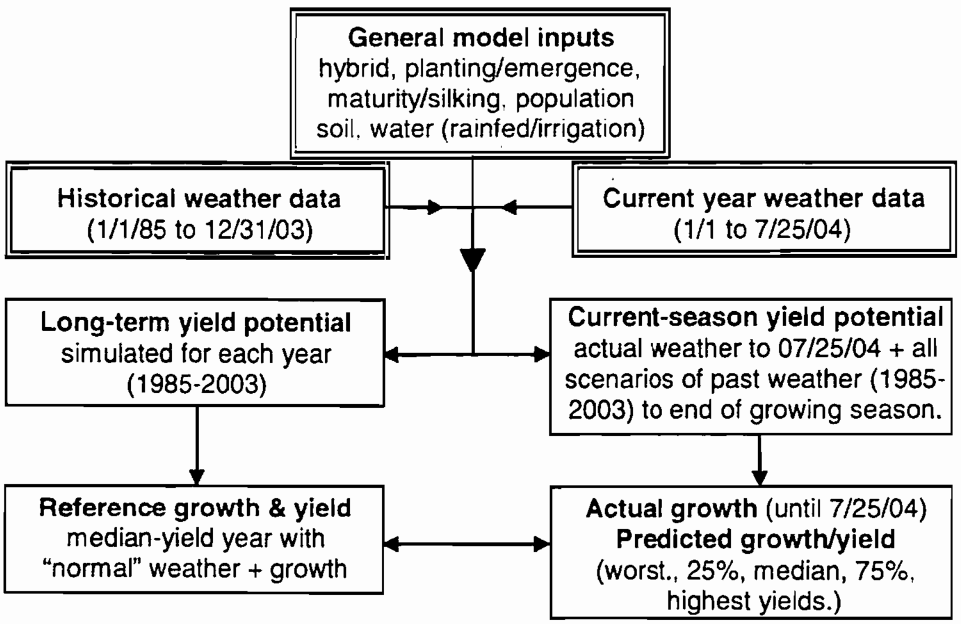


Figure 3. Approach used for in-season (real-time) yield prediction in the Hybrid-Maize model.

In this example. a real-time simulation is conducted for July 25, 2004, using weather data for the period January 1985 to July 25, 2004.

### Example 1: Analyzing Site Yield Potential Under Optimal Conditions

This example illustrates how Hybrid-Maize can be used to explore interactions of planting date and hybrid maturity and their influence on yield potential. This simulation is based on our experience in a research project that seeks to better understand the genetic and environmental determinants of maize yield potential. The research site is located at the University of Nebraska East Campus in Lincoln. Irrigated corn is grown on a deep alluvial soil (Kennebec silt loam) with optimal nutrient supply and pest management. The current recommendation is to plant corn between April 25 and May 5 with 30-inch row spacing and a final population of 32,000 plants/acre. Common hybrids grown in this environment require 2750 GDD50F from planting to maturity (CRM 114 d).

Simulations using long-term historical weather data from 1986 to 2004

| Rank | Year | Gr.Y | Gr.DM | Stover | tDM | HI | vDays | rDays | V+R | tSola | Tmin | Tmax | Tmean | vTmean | rTmean | ETref | tRain | tIrr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Best yield | 1992 | 265.0 | 6.28 | 5.48 | 11.75 | 0.53 | 73 | 69 | 142 | 63583 | 58.1 | 79.8 | 69.0 | 68.4 | 69.6 | 0.19 | 17.4 | 0.0 |
| 75% percentile | 1986 | 239.4 | 5.67 | 5.52 | 11.19 | 0.51 | 61 | 52 | 113 | 59809 | 63.2 | 84.3 | 73.8 | 71.9 | 75.9 | 0.25 | 17.6 | 0.0 |
| Median yield | 2003 | 225.7 | 5.34 | 6.43 | 11.77 | 0.45 | 68 | 50 | 118 | 60283 | 61.2 | 84.4 | 72.8 | 69.8 | 76.8 | 0.23 | 9.9 | 0.0 |
| 25% percentile | 1998 | 216.0 | 5.11 | 5.01 | 10.13 | 0.51 | 64 | 50 | 114 | 51673 | 63.9 | 83.2 | 73.6 | 70.8 | 77.1 | 0.20 | 18.9 | 0.0 |
| Worst yield | 1988 | 188.9 | 4.47 | 7.49 | 11.97 | 0.37 | 54 | 46 | 100 | 58124 | 65.2 | 88.2 | 76.7 | 74.9 | 78.9 | 0.30 | 5.6 | 0.0 |
| Long-term mean | | 227.3 | 5.38 | 5.67 | 11.05 | 0.49 | 63 | 53 | 116 | 56670 | 62.7 | 84.0 | 73.4 | 71.3 | 76.1 | 0.23 | 13.0 | 0.0 |
| Long-term CV, % | | 9 | 9 | 12 | 6 | 9 | 9 | 12 | 8 | 7 | 3 | 3 | 3 | 3 | 4 | 14 | 35 | 0 |

Overall probability of frost occurrence during grain filling (%) : 0

Note:
The ranking is based on GRAIN yield.
Gr.Y is grain yield in bu/acre at 15.5% moisture content. Gr.DM, Stover and tDM are dry matter for grain, stover and total abovegroud biomass in short ton/acre.
The long-term means are the numerical averages of all years.

Abbreviations:
HI : harvest index, i.e., the ratio of grain dry matter to total aboveground dry matter
vDays : days from emergence to silking (i.e., vegetative phase)
rDays : days from silking to maturity (i.e., reproductive phase)
V+R : days from emergence to maturity
tSola : total solar radiation from emergence to maturity (Langley)
tRain : total rainfall from emergence to maturity (inch)
Tmin, Tmax, Tmean and ETref : mean daily Tmin, Tmax, Tmean, and ET-reference, respectively, from emergence to maturity (F)
vTmean, rTmean : mean daily Tmean from emergence to silking (i.e., vegetative phase) and from silking to maturity (i.e., reproductive phase), respectively (F)
tIrr : total irrigation (inch)

User-specified inputs:
Weather file : Lincoln, NE.wth
Start from planting on (m/d) : 5/1 (DOY=122)
Seed brand : Generic
Total GDD50F : 2750
Plant population (*1000/acre) : 32
Seed depth (inch) : 1.5
Water regime : Optimal (fully irrigated)

Note that all GDD values refer to the starting time of planting

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Figure 4. Long-term corn yield potential at Lincoln, 1986-2004: Planting: May 1, 112 d hybrid.

With these settings, the model predicts an average yield potential of about 227 bu/acre, but ranging from 189 to 265 bu/acre during the 19-yr period for which weather data are available (Fig. 4). Risk of frost occurrence is zero because the crop reached full maturity before first frost in each of the 19 years. Note that the average temperature during grain filling (rTmean) is in the 76 to 77 °F range for 50% of all years (25% to 75% percentile range), whereas the lowest yield occurred in 1988, when rTmean was 79 °F. In contrast, the highest yield occurred in 1992, when rTmean averaged only 70 °F, resulting in a long grain filling period (rDays = 69 days) and a total growth duration (V+R) of 142 days.

Upon analysis of these simulated data, the question arises as to whether yield potential in most years could be increased by shifting grain filling later into September when nighttime temperatures begin to cool, but without significantly increasing the risk of frost. This could be accomplished by planting at a later date, choosing a longer maturity hybrid, or a combination of both. Figure 5 shows the results for planting corn on May 10 in combination with a 119 d hybrid (GDD 2860). Planting a 119-d hybrid on May 10 increased the average yield potential to 249 bu/acre and also narrowed the overall range to 213 to 290 bu/acre. Due to the selected changes in planting date and hybrid choice, rTmean decreased to less than 75 F and the average length of the grain filling period increased to 58 days. Risk of frost occurrence before reaching maturity remained small (5%-- one of the 19 years for which data were available).

Simulations using long-term historical weather data from 1986 to 2004

| Rank | Year | Gr.Y | Gr.DM | Stover | tDM | HI | vDays | rDays | V+R | tSola | Tmin | Tmax | Tmean | vTmean | rTmean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Best yield | 1992 | 290.3 | 6.87 | 5.52 | 12.40 | 0.55 | 74 | 82 | 156 | 66853 | 56.2 | 78.5 | 67.3 | 68.8 | 66.1 |
| 75% percentile | 1993 | 273.6 | 6.48 | 4.59 | 11.07 | 0.59 | 68 | 73 | 141 | 57850 | 59.5 | 80.0 | 69.8 | 70.1 | 69.5 |
| Median yield | 1999 | 249.9 | 5.92 | 5.07 | 10.99 | 0.54 | 65 | 54 | 119 | 55071 | 63.5 | 83.5 | 73.5 | 71.3 | 76.1 |
| 25% percentile | 1991 | 228.8 | 5.42 | 5.28 | 10.70 | 0.51 | 54 | 53 | 107 | 49677 | 65.4 | 87.2 | 76.3 | 75.5 | 77.2 |
| Worst yield | 1995 | 212.9 | 5.04 | 5.47 | 10.51 | 0.48 | 66 | 51 | 117 | 54949 | 63.5 | 84.4 | 73.9 | 71.1 | 77.5 |
| Long-term mean | | 248.6 | 5.89 | 5.61 | 11.50 | 0.51 | 62 | 58 | 120 | 57731 | 62.9 | 84.2 | 73.5 | 72.5 | 74.8 |
| Long-term CV, % | | 10 | 10 | 13 | 6 | 10 | 9 | 17 | 12 | 7 | 4 | 3 | 4 | 3 | 5 |

Among the five years above, frost damage during grain filling occurred in:
1992

Overall probability of frost occurrence during grain filling (%) : 5

Figure 5. Long-term corn yield potential at Lincoln, 1986-2004: Planting: May 10, 119 d hybrid.

In summary, simple changes in hybrid selection and planting date resulted in substantial increases in predicted yield potential with greater yield stability and relatively low risk of frost compared to current recommended practices for southeast Nebraska. This modified management regime achieves higher yields through a longer grain filling period as a result of delaying the grain filling period into late September when night temperatures are much cooler than late August and early September. It should be noted, however, that mean temperatures at this site within the City of Lincoln are warmer than in surrounding rural environments and therefore these results may not be widely applicable to the surrounding region. The logistics of harvesting, harvest losses, and cost of grain drying due to delayed maturity must also be considered. Recent field studies at the Lincoln research site have confirmed the predicted improvements in yield potential from later planting with a longer maturity hybrid (Dobermann et al., 2005).

### Example 2: Estimating Water Requirements for Optimal Yields

The southwestern corner of Nebraska is an area with high yield potential (elevation about 1000 m, dry climate with high solar radiation), provided that crops can be fully irrigated, nutrients supplied in adequate quantities in concert with crop demand, and pests controlled to avoid yield loss. Irrigated maize is sometimes grown in strip-till systems. Annual rainfall averages about 20 inches, but is highly variable from year to year. Rainfall during the growing season averages 10 inches. Standard practices on irrigated corn are: planting around May 1 at 30-inch row spacing and a final population of 30,000 plants/acre. Common hybrids grown in this environment require 2670 GDD50F from planting to maturity (CRM 110-112 d). A weather station representing that area is located at Champion, NE, with daily climate data available for the 1982-2004 period. The location of interest is a gently sloping field with a deep, well-drained, fine-loamy soil. Rooting depth is not limited by a hardpan or compacted layer, and general soil quality is good without acidity or salinity.

Average yield potential for the selected planting conditions is 246 bu/acre, but with a very wide range (178 to 316 bu/acre) and a 30% probability of premature frost. The grain filling period is relatively long (average of 67 days) due to cooler average temperatures than at Lincoln, particularly cooler nighttime temperature during grain filling (rTmean averages 69 °F). Thus, there is less potential to extend the growing season because of increased risk of yield loss from frost damage. The key production constraint is water availability for irrigation. Without irrigation, attainable yield averages 141 bu/acre, but may be as little as 69 bu/acre or as much as 270 bu/acre. To overcome the typical water deficit that occurs in this region, irrigation is needed at critical growth stages. We can let the model simulate the water requirement for maintaining adequate water supply (i.e. no water stress) throughout the crop growth period. Assuming that a center-pivot irrigation system is used, we set the maximum amount of water that can be delivered per irrigation event to 1.25 inches. The summary of simulation output is similar to Fig. 4, but an additional column reports the total irrigation water requirement (not shown). On average, 296 mm of additional water (11.7 inches) is required to achieve stress-free growth, but the water requirement varies from about 226 (1999, the best year) to 356 mm (1997, 75% percentile of grain yield). The amount and predicted timing of irrigation for the year of median yield (1991) are shown in Figure 6, along with daily rainfall and soil moisture dynamics in three layers (i.e., 0 to 30, 30 to 60 and < 60 cm). Other years can be selected for display from the dropdown list, and numerical outputs are also available on the 'Results' page.

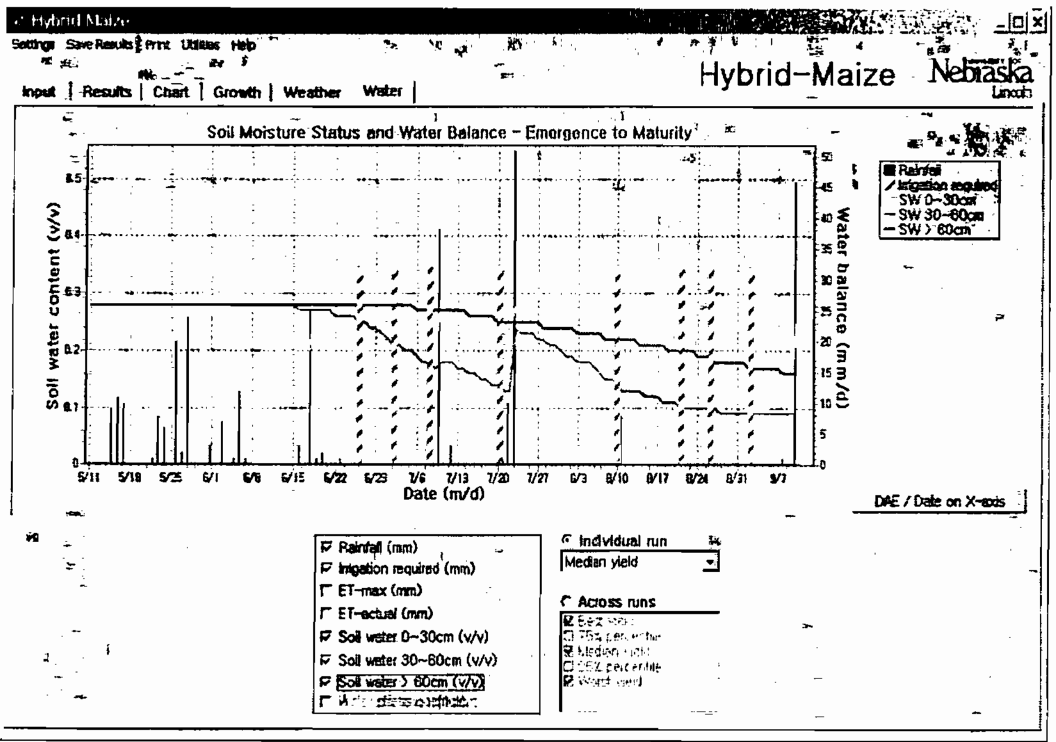


Figure 6. Screenshot of the Hybrid-Maize 'Water' page giving predictions of irrigation water requirement (striped bars) for the year of median yield in the simulation described in the text. The darker bars are rainfall.

Note that the actual amount of irrigation required would also depend on the efficiency of the irrigation system because the Hybrid-Maize assumes that all water that reaches the soil surface enters the soil water pool. It does not account for runoff or evaporation, or non-uniformity of irrigation. The model does account for a small amount of irrigation water loss that is adsorbed on leaf surfaces.

### Example 3: Real-time Crop Growth Simulation and Yield Forecast

Corn yield potential varies considerably from year to year in the same field as a result of the combined effects of variation in solar radiation and temperature in irrigated systems as well as rainfall in rainfed systems. In-season crop model predictions can be used to guide management and marketing decisions, along with other sources of information, common sense, and experience. The 'Current season prediction' mode in Hybrid-Maize allows the user to simulate "real-time" crop growth during a growing season up to the date of the simulation run. Weather files should contain at least ten years of representative historical climate data for the site (or a nearby weather station) in addition to weather data for the current year.

Figure 7 shows an example of in-season yield forecasts made for rainfed corn grown at Mead, Nebraska in 2003. Weather data were downloaded from the High-Plains Regional Climate Center (http://www.hprcc.unl.edu) and yield forecasts were made every 5 days, beginning shortly after planting. At each forecasting date, actual weather data were used in Hybrid-Maize to simulate growth until that date. From that point forward to maturity, the model utilized historical weather records to simulate possible growth scenarios for the remainder of the season. Predicted median yield was close to the long-term median water-limited yield potential early in the season (Fig. 7, upper dashed line), but by silking predicted yields began to fall because of less than normal rainfall. Predicted water-limited yield potential continued to decline throughout the remainder of the growing season because of continued drought. By the end of August the range of predicted outcomes indicated a range in final yield of from 100 to 140 bu/acre, which is 46 to 69% of the long-term median rainfed yield potential at this site. The final measured grain yield of 123 bu/acre confirmed this prediction.

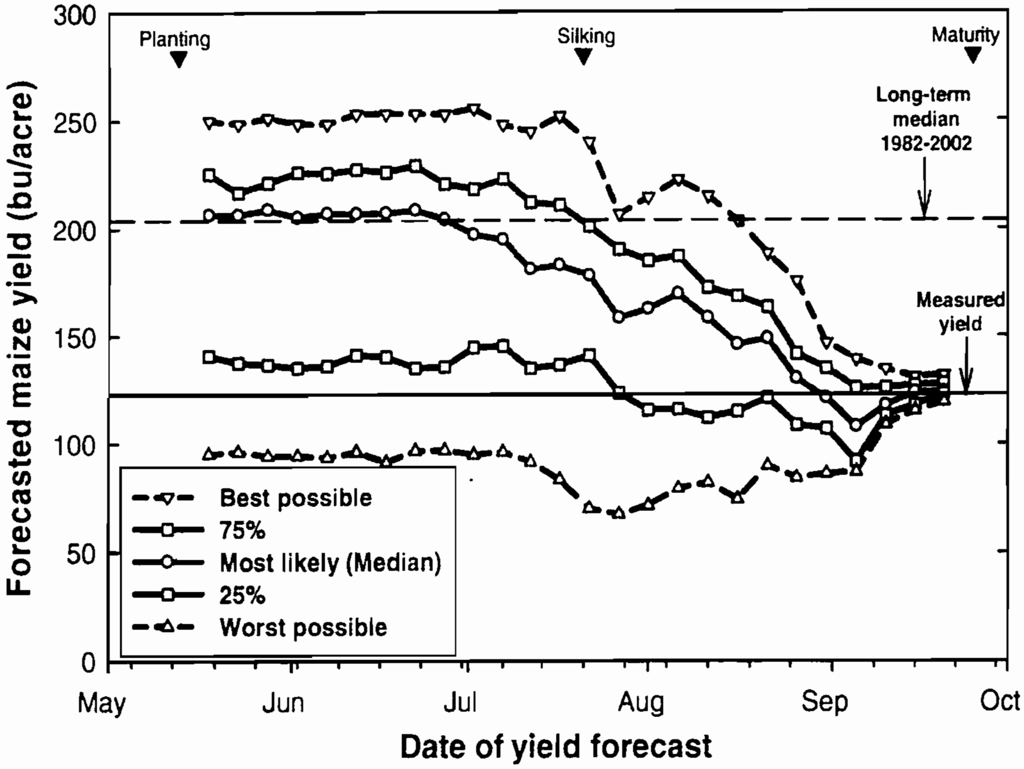


Figure 7. In-season yield forecasting in five-day intervals (points) for rainfed maize grown at Mead, Nebraska in 2003. The long-term median yield potential (under rainfed conditions) and measured final yields are shown as horizontal lines.

Our current experience suggests that, at irrigated sites, the final yield can be accurately predicted by early August. Greater variation in yield predictions may occur at rainfed sites. Relative deviations from normal growth are detectable early in the growing season in both environments, which should allow making adjustments in water and nitrogen management.

## Summary and Outlook

The Hybrid-Maize model was found to be more robust than other existing corn models for simulating growth and yield under optimal growth conditions. Moreover, the Hybrid-Maize software offers an intuitive graphic user interface for input and output settings with features and auxiliary functions that help non-modelers use the Hybrid-Maize model as a tool for crop management, extension education, teaching, and research. Because Hybrid-Maize is based on mechanistic descriptions of corn growth and development, it is expected to perform well in a wide range of environments. As with all simulation models, Hybrid-Maize still represents a simplification of the 'real-world' system and, as such, model simulations may differ from actual outcomes. In exploring site yield potential with the model, it is important to note that yield potential can only be achieved under growth conditions that are 'ideal' with regard to both crop and soil management. Reasonable soil quality is also required. Although it is theoretically possible to overcome shallow soil depth or a hardpan that restricts root growth by employing more precise management of nutrients and irrigation, it is generally not practical or profitable to do so at a production scale. Likewise, some soil constraints, such as salinity or soil acidity, reduce crop growth directly and therefore make it impossible to achieve yield levels that approach the genetic yield potential of a given hybrid even with optimal management of water, nutrients and pests. Therefore, in interpreting investigations of site yield potential, model users must be aware of limitations to crop growth that are not considered in the model. Future work to improve the Hybrid-Maize model will focus on (i) addressing some of the fundamental physiological processes involved, (ii) adding an irrigation decision module, (iii) adding functions for estimating N, P, and K fertilizer requirements, (iv) adding a new module for preparing weather data, and (v) adding a module on predicting grain dry down to harvestable moisture content.

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**PROCEEDINGS OF THE**

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**Potash & Phosphate Institute**
**772 – 22nd Avenue South**
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