

Hybrid-Maize

A Simulation Model for Corn Growth and Yield

Ver. 2016

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HYBRID-MAIZE IS A PROGRAM (the 'Software'), DEVELOPED AND OFFERED BY THE UNIVERSITY OF NEBRASKA-LINCOLN (UNL), DESIGNED TO PROVIDE INFORMATION THAT CONTRIBUTES TO BETTER UNDERSTANDING OF CORN YIELD POTENTIAL AND THE INTERACTIVE EFFECTS OF CROP MANAGEMENT PRACTICES AND CLIMATE ON CORN YIELDS. ALTHOUGH THE MODEL HAS BEEN VALIDATED UNDER A NUMBER OF ENVIRONMENTS AND CROP MANAGEMENT REGIMES, THE AUTHORS MAKE NO CLAIM THAT THE MODEL PREDICTIONS ARE ACCURATE OR REALISTIC FOR ALL ENVIRONMENTS OR MANAGEMENT REGIMES. THEREFORE, MODEL PREDICTIONS SHOULD BE CONSIDERED AS ONLY ONE SOURCE OF INFORMATION THAT CAN BE USED TO HELP GUIDE DECISIONS ABOUT CROP MANAGEMENT PRACTICES AND GRAIN MARKETING IN COMBINATION WITH OTHER SOURCES OF INFORMATION, COMMON SENSE, AND PAST EXPERIENCE.

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About Hybrid-Maize

Hybrid-Maize is a crop simulation model that uses mathematical formulations to describe the processes of maize (*Zea mays* L.) growth and development in relation to weather, soil properties, and management factors. As with all simulation models, it represents a simplification of the ‘real-world’ system and, as such, model predictions may differ from actual outcomes. Therefore, the results of model simulations should be considered approximations and not taken as fact. The purpose of this simulation model is to allow maize producers, crop consultants, and researchers to hypothetically explore the impact of weather and management factors on crop performance with the goal of better understanding site yield potential, year-to-year variation in yield potential, and potential management options that affect yield and yield stability. Neither the University of Nebraska at Lincoln, nor the authors of the Hybrid-Maize model accept any liability for errors in model predictions, outcomes that result from use of model predictions, or any problems associated with installation of the program.

Hybrid-Maize simulates the growth of a maize crop under non-limiting or water-limited (rainfed or irrigated) conditions based on daily weather data. It allows the user to (i) assess the overall site yield potential and its variability, (ii) evaluate changes in attainable yield using different choices of planting date, maize hybrid, and plant density, (iii) analyze maize growth in specific years, (iv) explore options for irrigation water management, and (v) conduct in-season simulations to evaluate actual growth and forecast final yield starting at different growth stages. Hybrid-Maize does not allow assessment of different options for nutrient management nor does it account for yield losses due to weeds, insects, diseases, lodging, and other stresses. However, for weed management decisions, we recommend the WeedSoft - A Weed Management Decision Support Tool from the University of Nebraska–Lincoln (visit: <http://weedsoft.unl.edu> for more information). Hybrid-Maize has been evaluated primarily in rainfed and irrigated maize systems of North America. Caution should be exercised when applying this model to other environments as this may require changes in some of the default model parameters.

For more information, FAQ and update of the model, please visit: www.hybridmaize.unl.edu

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Plains Regional Climate Center of the University of Nebraska for providing the historical weather data included with the Hybrid-Maize model (<http://www.hprcc.unl.edu/>).

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New features in version 2016 of Hybrid-Maize compared with version 2006

Note that the new features are illustrated with screenshots on the following pages and associated text in the designated sections. Motivation for updating the Hybrid-Maize model was to improve its capability to simulate maize yields under water-limited conditions, and the availability of good data to validate performance of these modifications from field studies that experienced severe drought, especially during the U.S. Corn Belt drought of 2012.

1. Inclusion of crop stages in output (Fig. 1, Section 4.1.4)
2. Improved simulation of the impact from water stress on leaf area expansion and senescence (Fig. 1, Section 4.1.5)
3. Improved simulation of soil water balance:
 - a. Inclusion of field runoff estimation based on field slope, soil hydraulic properties that govern drainage, and degree of surface coverage by crop residues (Fig. 2, Section 4.2.5).
 - b. Inclusion of effect of crop residues cover on soil evaporation (Fig. 2).
 - c. Option of estimating soil moisture at planting by tracking soil water balance during pre-planting fallow period (Fig. 3, Section 4.2.6)
 - d. Simplified simulation of soil evaporation (Section 4.2.3)
4. Improved simulation of kernel setting (Section 4.1.9)
5. Improved simulation of root depth penetration rate (Section 4.1.7)
6. Option of using alfalfa- or grass-referenced ET in weather data (Section 2.3.2.1)
7. Simulations using input settings in Excel spreadsheet (Fig. 5, Section 3.5)
8. Compatible with Windows 7 and earlier Windows operation systems
9. Upgraded utility program, the **WeatherAid**, which is fully compatible with Windows 10 and earlier Windows operation systems.

Overall, the new version offers a more user-friendly interface and functionalities, and more importantly, produces more robust simulation results under water stress conditions.

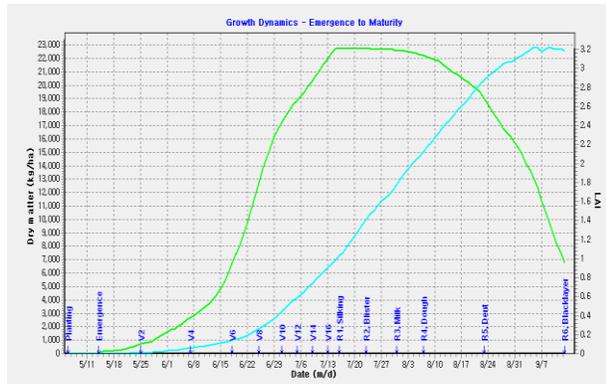


Fig. 1. Crop stages (vertical text in blue) in output.

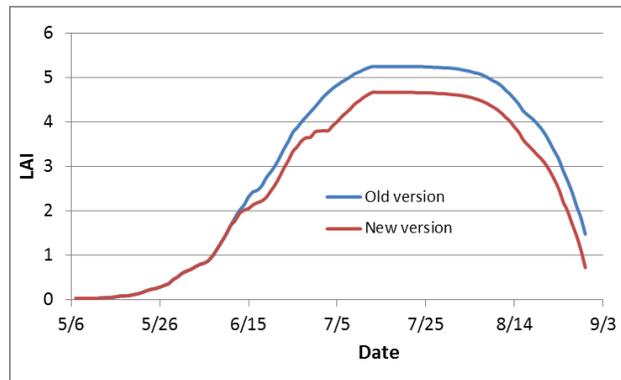


Fig. 2. New version vs old version of simulated leaf area index under water stress

Figure 3 shows the "Soil & field" input settings. The "Maximum rooting depth" is set to 120 cm. The "Top-soil (30 cm)" texture is "Silt loam" and the "Sub-soil" texture is "Silt loam". The "Bulk density" is 1.3 g/cm³. The "Soil moisture" is set to "wet (75% AW)". The "at start of fallow" option is selected, and the "months before planting" is set to 6. A note states: "*only for sites without snow during fallow".

Fig. 3. User input settings for estimating soil moisture status at planting by tracking soil water balance in the pre-planting fallow period.

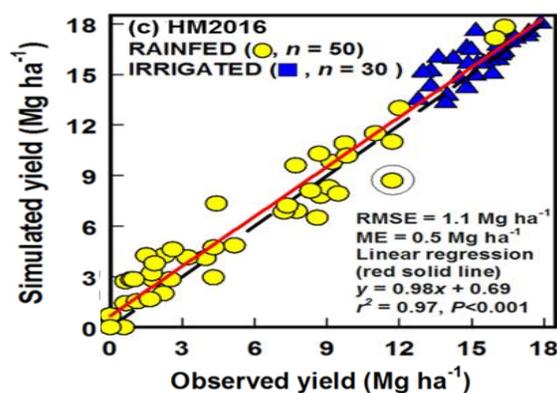


Fig. 4. Simulated vs. measured corn yield under irrigated as well as rainfed conditions in the US Corn Belt.

Figure 5 shows the HM simulation software interface. On the left is the "HM simulation using row input settings from Excel file" dialog box, which includes an "Excel-format simulation input setting file" field, a "Run..." button, an "Abort" button, a "View results" button, and a "Close" button. Below the dialog box is a note: "A template file for simulation input settings, 'Template for row input setting.xls' is available in the folder where Hybrid-Maize is installed. Copy that file to a new place and set up simulations using the instructions in column comments". On the right is a screenshot of an Excel spreadsheet titled "Meed1_Output_34.xls (Compatibility Mode)". The spreadsheet contains simulation input settings for various years and dates of planting, including columns for "Simulation year", "Date of planting", "Weather file", "From", "To", "Month", "Day", "Total GDD", "Plant population, thousand/ha", and "Irrigated".

Fig. 5. Simulations using input settings from Excel file

Contents

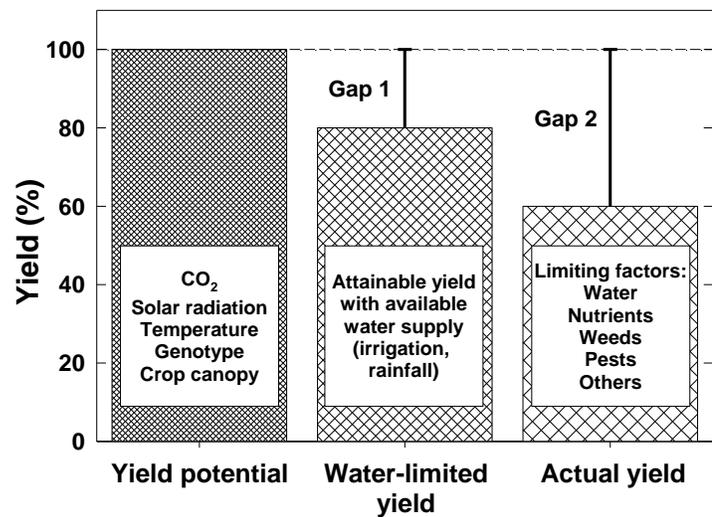
1. Yield Potential and Yield Gaps	1
2. Using the Hybrid-Maize Model	3
2.1. Installation	3
2.2. A Quick Simulation Run	3
2.3. Model Inputs	8
2.3.1. General Options and Parameter Settings.....	9
2.3.2. Weather Data.....	14
2.3.3. Simulation Modes	19
2.3.4. Crop Management Details.....	22
2.3.5. Water	25
2.3.6. Soil & field	26
2.4.1. Results	27
2.4.2. Chart	30
2.4.3. Growth.....	31
2.4.4. Weather	32
2.4.5. Water	33
2.4.6. Yield trend.....	33
2.4.7. Saving and Printing Results	34
3. Model Applications.....	35
3.1. Analyzing Site Yield Potential Under Optimal Conditions	35
3.2. Analyzing Water Requirements for Achieving the Site Yield Potential.....	39
3.3. Analysis of Yield Determinants in Past Cropping Seasons and Cropping Systems	43
3.4. Current Season Simulation of Maize Growth and Yield Forecasting	47
3.5. Simulation using input settings in Excel file.....	53
4. Detailed Information about the Hybrid-Maize Model	53
4.1. Crop Growth and Development Processes.....	54
4.1.1. Daily GDD Computation	54
4.1.2. Daily CO ₂ Assimilation.....	56
4.1.3. Maintenance Respiration and Net Carbohydrate Production	58
4.1.4. Growth Stages	59
4.1.5. Leaf Growth and Senescence	60
4.1.6. Stem and Cob Growth.....	63
4.1.7. Root Extension and Biomass Growth	63
4.1.8. Adjustment of Growth Rates for Leaf, Stem, Cob and Roots.....	64
4.1.9. Grain Filling	64
4.1.10. Initiation of a Simulation Run.....	66
4.2. Water Balance and Soil Water Dynamics	66
4.2.1. Rooting Depth and Water Uptake Weighing Factor	66
4.2.2. ET ₀ adjustment, Maximum Transpiration and Maximum Soil Evaporation.....	67
4.2.3. Actual Soil Evaporation	68
4.2.4. Actual Transpiration and Water Stress Index	68
4.2.5. Water losses through canopy interception and surface runoff.....	70
4.2.6. Estimation of soil moisture at planting through fallow period soil water balance.....	70
4.3. Correlations of total GDD to RM and GDD-to-silking to total GDD.....	71
4.4. Sensitivity Analysis and Model Validation.....	73

4.4.1. Sensitivity to Selected Model Parameters	73
4.4.2. Prediction of LAI and Aboveground Biomass Dynamics.....	75
4.4.3. Prediction of Grain Yield	77
4.5. Uncertainties and Future Improvements	80
5. References.....	83
6. Appendix	88
6.1. User-modifiable Parameters Describing Crop Growth and Development.....	88
6.2. Default Soil Physical Properties for Different Soil Texture Classes	900
6.3. Guideline for estimating ground coverage of corn and soybean residues.....	91
6.4a. Default Curve Numbers (CN) for different field slopes and drainage classes.....	93
6.4b. Simulation of Major Growth and Development Processes in Different Models	93
6.5. Simulation of Major Processes in Different Models.....	93

1. Yield Potential and Yield Gaps

Yield potential is defined as the yield of a crop cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting, and pests and diseases effectively controlled (Evans, 1993). Hence, for a given crop variety or hybrid in a specific growth environment, yield potential is determined by the amount of incident solar radiation, temperature, and plant density—the latter determining the rate at which the leaf canopy develops under a given solar radiation and temperature regime. The difference between yield potential and the actual yield represents the exploitable yield gap (Fig. 1.1). Hence, genotype, solar radiation, temperature, plant population, and degree of water deficit determine water-limited yield potential. In addition to yield reduction from limited water supply, actual farm yields are determined by the magnitude of yield reduction or loss from other factors such as nutrient deficiencies or imbalances, poor soil quality, root and/or shoot diseases, insect pests, weed competition, water logging, and lodging.

Figure 1.1. Conceptual framework of yield potential, water-limited yield potential, and actual farm yields as constrained by a number of production factors (Cassman et al., 2003; van Ittersum et al., 2013).



Management decisions such as hybrid selection, planting date, and plant density can affect the yield potential at a given site by influencing the utilization of available solar radiation and soil moisture reserves during the growing season. Yield potential also fluctuates somewhat from year to year (typically $\pm 10-15\%$) because of normal variation in solar radiation and temperature regime. To achieve yield potential, the crop must be optimally supplied with water and nutrients and completely protected against weeds, pests, diseases, and other factors that may reduce growth. Such conditions are rarely achieved under field conditions, nor is it likely to be cost-effective for farmers to strive for such perfection in management. Instead, understanding site yield potential and its normal year-to-year variation can help identify management options and input requirements that combine to reduce the size of the exploitable yield gap while maintaining profitable and highly efficient production practices.

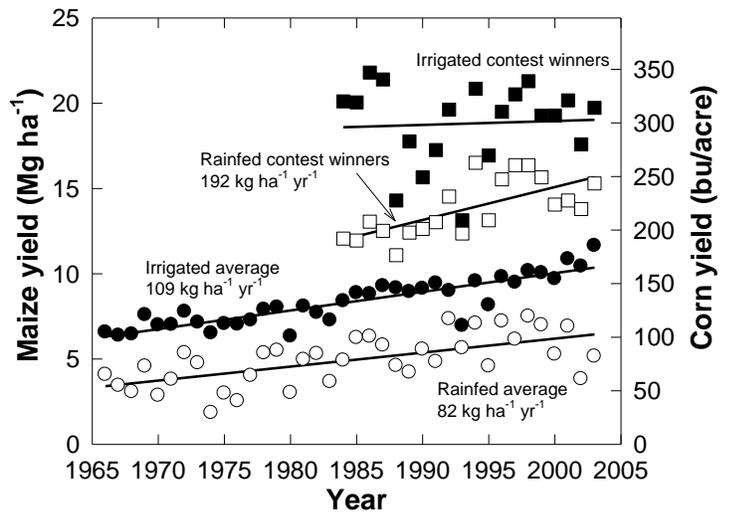
For much of the U.S. Corn Belt, available moisture is the most important growth-limiting factor. The water deficit is determined by factors such as soil water holding capacity, rainfall, irrigation, and reference evapotranspiration, which vary from site to site and year to year. Because irrigation can help ensure adequate water supply in the face of suboptimal rainfall, differences between yield potential and water-limited yield (yield gap 1 in Fig. 1.1.) are smaller and less variable in irrigated systems compared to rainfed maize systems.

In well-managed irrigated maize, the attainable water-limited yield is close to the yield potential ceiling and relatively stable from year to year because irrigation is provided during key growth stages to make up for water deficits (Grassini et al., 2011a, b). Management can therefore focus on providing sufficient nutrients to fully exploit attainable yield and on minimizing yield-reducing

factors that determine yield gap 2 shown in Fig. 1.1. In rainfed maize, the attainable water-limited yield is typically less than that for irrigated maize, but fluctuates widely, depending on the initial soil moisture status, soil water holding capacity, planting date, plant density, evapotranspiration, and rainfall during the growing season. Therefore, setting a realistic yield goal is more difficult in rainfed (also called dryland agriculture) than under irrigated conditions because both yield gaps 1 and 2 can vary greatly from site to site or year to year.

Maximum yields obtained in yield contests or in well-managed research experiments provide the best estimates of yield potential because maize is grown at high plant density with optimal water and nutrient supply, and effective control of weeds, diseases, and insect pests. For example, in the past 20 years yield levels achieved by winners of the irrigated maize contest in Nebraska have averaged 300 bu/acre (18.8 Mg/ha), with a standard deviation of ± 38 bu/acre among years (13%), which indicates the effect of growing season weather on the yield potential (Fig. 1.2).

Figure 1.2. Yield trends of irrigated and rainfed maize in Nebraska, comparing statewide average yields with yields obtained by the winners of the annual corn yield contest organized by the National Corn Growers Association (NCGA) (Duvick and Cassman, 1999).



The extremes in yield potential are represented by low-yield years of 1993 (210 bu/acre, wet and cold) and 1988 (228 bu/acre, dry and hot) versus highest yields in 1986 (348 bu/acre) and 1998 (338 bu/acre) when temperatures and solar radiation supported high yield potential. During the same period, yields achieved by the winners of the rainfed maize contest in Nebraska have averaged 220 bu/acre (13.8 Mg/ha) but are steadily increasing such that maximum rainfed yields are now reaching 250 bu/acre in years with favorable weather. These numbers illustrate the typical upper limits of yield potential and water-limited rainfed maize yield in Nebraska.

The Hybrid-Maize model simulates maize growth on a daily basis from sowing to physiological maturity. This version of the program simulates maize yield potential and/or water limited yield, both assuming optimal nutrient supply and no yield losses from other factors (Fig. 1.1). For simulation of yield potential, the model requires *daily* weather data for solar radiation and maximum and minimum temperatures. For simulation of the water-limited rainfed or irrigated yield at a given site with optimal nutrient supply, the model requires *daily* weather data for solar radiation, maximum and minimum temperature, rainfall, and reference evapotranspiration, as well as basic soil information influencing available water status such as soil textural class and bulk density.

2. Using the Hybrid-Maize Model

2.1. Installation

System requirements: Microsoft Windows XP or later operation system

Installation steps:

The following instructions refer to installation using download package of the Hybrid-Maize version 2016. For users who upgrade from earlier versions, first uninstall the old version remove all remaining files in the program folder before installing the new version.

To install the new version, run the file **HM2016_Setup.exe** and follow the on-screen installation instructions.

***No questions asked installation:** Hybrid-Maize will be installed in the default directory designated by the Windows Operation system. If a previous version of the Hybrid-Maize program is currently installed, the new version will replace the old version. If the user wants to keep the old version, choose the **Advanced Options Installation** described below and select a different folder.*

***Advanced Options Installation:** Hybrid-Maize will be installed in the directory chosen by the user, including subfolders containing weather data. When a previous version of the Hybrid-Maize program is currently installed, using this option will enable keeping the old version while installing the new version.*

The installation procedure will automatically set up a shortcut for launching the model on both the desktop and in the Programs list in the Windows Start menu on the lower left corner of the screen.

2.2. A Quick Simulation Run (“It’s so easy”)

The following example provides an initial trial run with the Hybrid-Maize model with instructions about how to select appropriate input values and how to review the results. We use the default English measurement units in this example. The scenario for this simulation trial run is to simulate maize growth and yield potential (i.e., the yield with optimal irrigation and nutrient supply and without yield losses caused by diseases, pests and insects) in the year 2004 at Clay Center, south-central Nebraska and compare it with the long-term yield potential at this site based on 24 years of weather data. The soil is deep loess with no significant constraints to growth. Full irrigation is provided throughout crop growth whenever rainfall does not meet crop water requirements. The maize hybrid grown requires 2650 growing degree days (GDD, Fahrenheit based) from emergence to physiological maturity (blacklayer), which represents a comparative relative maturity (CRM) of about 110 day. Maize is typically planted on May 1, and the final plant population is 30,000/acre.

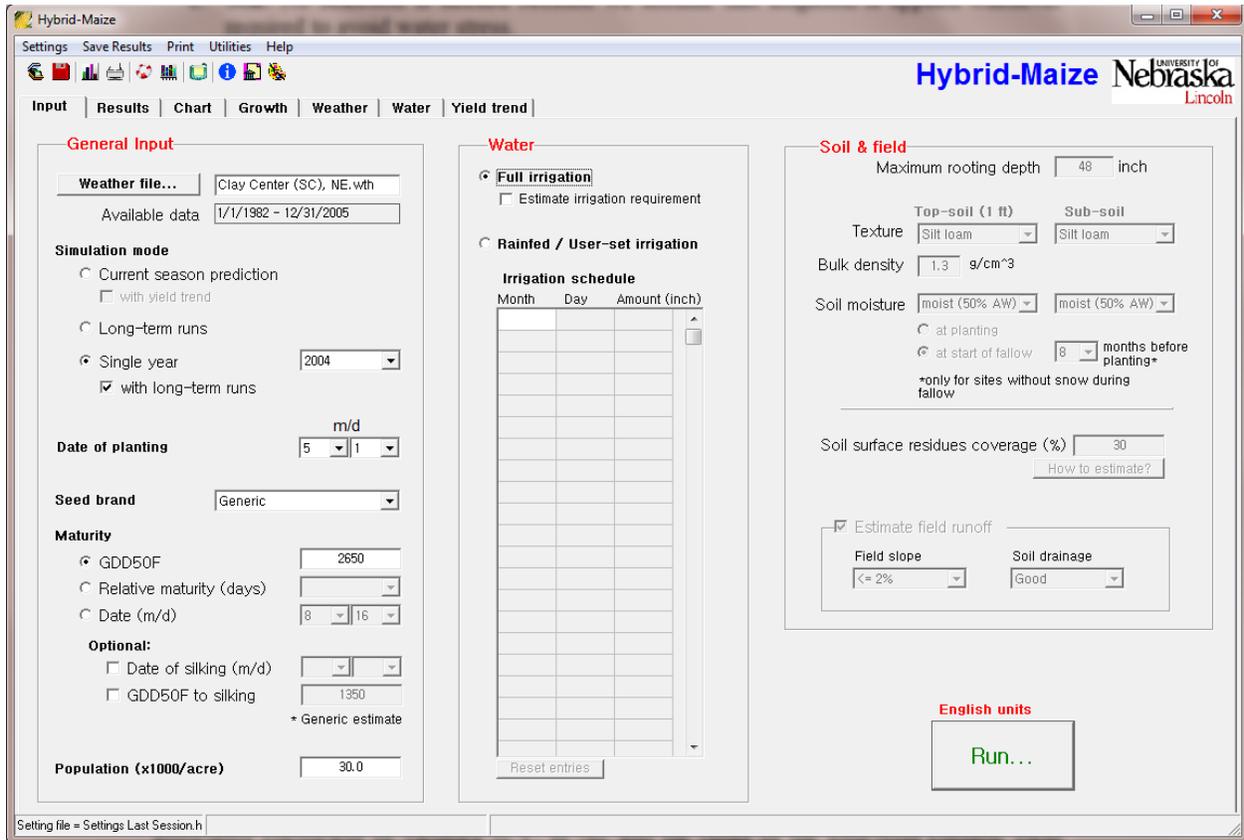
1. Launch the Hybrid-Maize program by clicking on the desktop icon or select from the Start menu. Enter all model inputs based on the description below. If the lower right corner of the front page indicates **Metric units**, then change it to English units by clicking **Settings** on the menu bar, select **General Options** and choose **English units** under the entry Measurements units.

a. **General Input:** Select the weather file for this site by clicking on the button **Weather file**. Browse and choose the file for **Clay Center (SC), NE.wth**. Select **Single year** as simulation mode and choose the year **2004** from the drop-down list of available years. Also check the option **with long-term runs**. For **Start from**, select **5** as month and **1** as day for a May 1 planting date. For **Seed brand**, use the default **Generic**. For **Maturity**, select **GDD50F** and change the default to **2650**, which is the GDD for

the hybrid to be grown. For final **Plant population**, change the default value to **30** (=30,000 plants/acre).

b. **Water:** Select **Full irrigation** because the goal is to simulate yield potential.

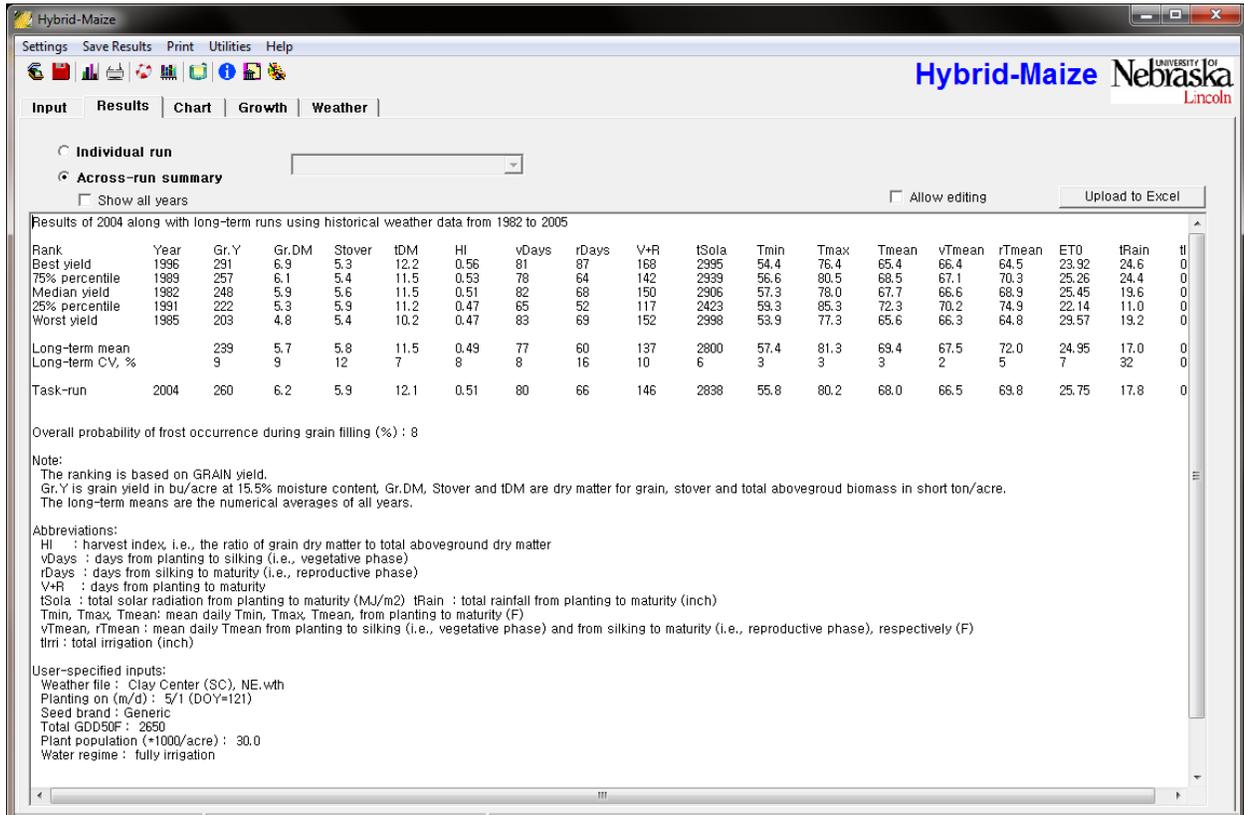
c. **Soil:** No selection is needed because we assume that irrigation is applied whenever required to avoid water stress.



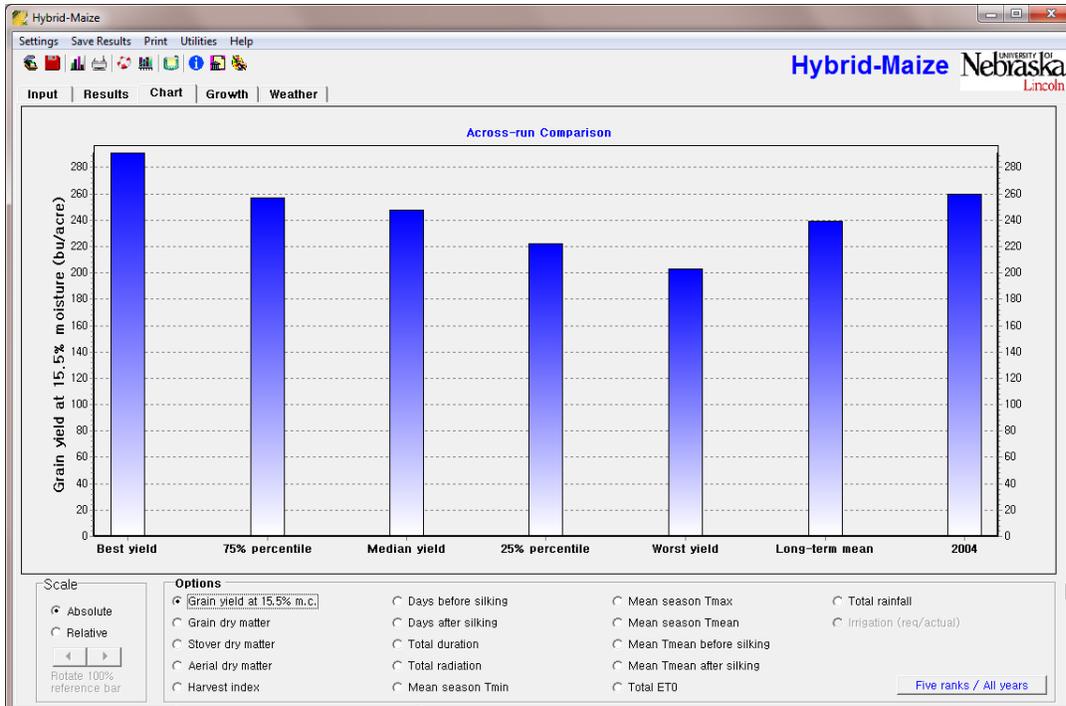
2. Verify all entries. Click on the button **Run...** on the lower right. A beep will sound when the simulation is completed.

3. The first simulation output is a summary table comparing the simulated yield potential in 2004 with the median, 25% and 75% percentiles, the range, the long-term mean and associated coefficient of variance (CV, in %), and the range of the long-term climatic yield potentials simulated using all available weather data from 1982 to 2005 when the same hybrid was planted on May 1 in each of these years. The table provides values for simulated grain yield at standard moisture content (15.5%, in bu/acre), and dry matter yield (in short tons per acre at zero moisture) for grain, stover, and total aboveground biomass. If simulated grain yield is < 2 Mg/ha, the following message appears: "WARNING: simulation results are doubtful due to extremely low yield". The reason for this warning is because Hybrid-Maize has not been rigorously validated against good quality field data under conditions of highly severe drought that would result in such low water-limited yield potential. Other data in the table include harvest index (i.e., the ratio of dry matter grain yield to total aboveground biomass yield), the length of vegetative and reproductive growth periods (**vDays** and **rDays**, respectively, and **V+R**, which gives total days from planting to maturity), and mean values for climatic variables during the growing season. In this example, simulated yield potential in 2004 (260 bu/acre = 16.3 Mg/ha) was 31 bu/acre (=1.9 Mg/ha) below

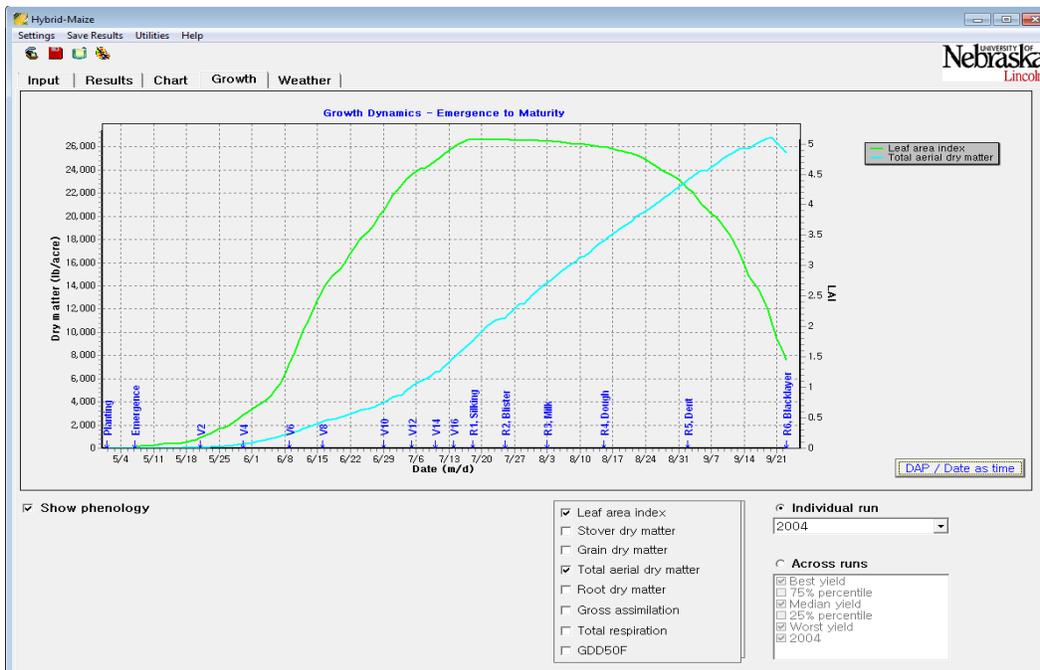
the maximum yield of 291 bu/acre (=18.2 Mg/ha) predicted for this site in 1996, but 21 bu/acre (1.3 Mg/ha) above the long-term mean yield. The reasons for the high yield potential in 2004 was a relatively long grain filling period, which resulted from cool mean temperature during grain filling (**rTmean**) that led to increased cumulative intercepted solar radiation (**tSola**) compared to long-term mean values.



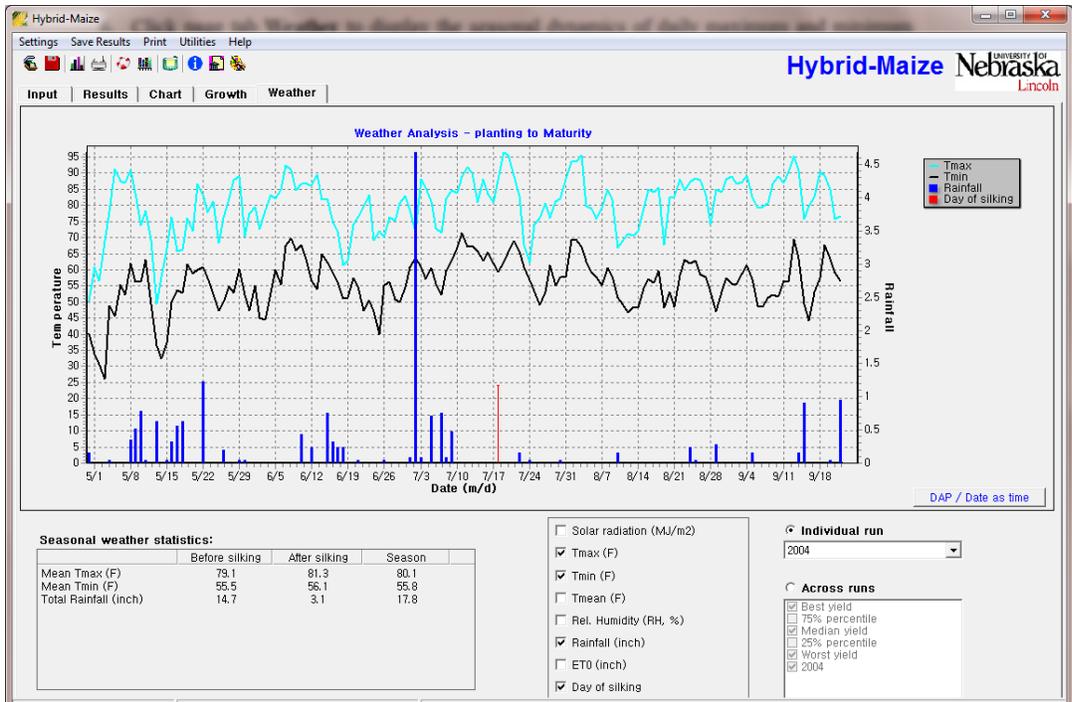
4. Graphic presentation of outputs, including growth dynamics and weather data can also be viewed for individual model runs or to compare up to five different model runs at one time. At top of the page, click on the tab **Chart** to view a bar graph of grain yield or other simulated variables, thus allowing visual comparison with the simulated outcomes from other years or the long-term mean value for all years included in the weather database. For long-term runs or single runs with inclusion of long-term runs, click **Five ranks/All years** will toggle between results of ranked years and results of all years.



5. Click page tab **Growth**. The growth curves from emergence to maturity for leaf area index (LAI, on the right axis) and total aboveground biomass (total aerial dry matter, on the left axis) are shown for 2004. Crop stages (the vertical text in blue) are shown along the X-axis. Select **Stover dry matter**, **Grain dry matter**, and **Root dry matter** in the variable list to add those variables to the graphic display. Click the button **DAP / Date as time** to toggle the time scale on the x-axis between days after planting (DAP) and the corresponding calendar date. Day of silking is indicated by a short red bar, and can be removed by deselecting it in the variable selection list



6. Click page tab **Weather** to display the seasonal dynamics of daily maximum and minimum temperatures for 2004 as well as seasonal weather statistics. Select **Rainfall** and **ET-reference** (reference evapotranspiration) to add these variables to the graph (right y-axis is for rainfall and ET units). As on the page **Growth**, day of silking is indicated by a short red bar.



7. To quit the program, either click the **X** on the upper right corner of the window, or go to **Settings** on the menu bar, then click **Quit**, or using the short-cut of **Ctrl-Q**.

*Note that simulation settings of the last run before closing the program are saved automatically when closing **Hybrid-Maize**. Next time, the settings will be retrieved automatically as default.*

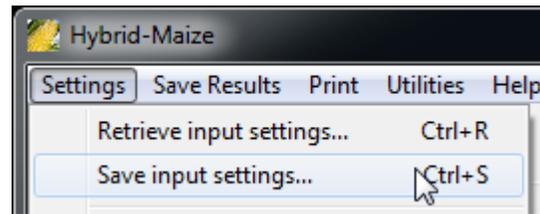
2.3.1. General Options and Parameter Settings

Settings – Retrieve / Save Input Settings

All input settings specified on the front page can be saved to a file and re-used later. This not only saves time, but more importantly, avoids creating unintended differences in future runs if the user wants to use the same settings when repeating or modifying simulations.

Click ‘**Settings**’ on the menu bar, select **Save input settings**, (shortcut is **Ctrl-S**), or click the icon  on the toolbar. Then specify a name for the file and directory. Settings files have the default file extension **.stg**. To retrieve input settings saved in a file, click ‘**Settings**’ on the menu bar, select **Retrieve input settings** (shortcut is **Ctrl-R**), or click the icon  on the toolbar. Then select the desired file.

NOTE: The weather file name retrieved from a settings file contains full file path. It may be necessary to verify the existence of the weather file if the settings are retrieved from a settings file that was saved in another computer or if the weather file has been moved to a different location.



Settings -- General Options

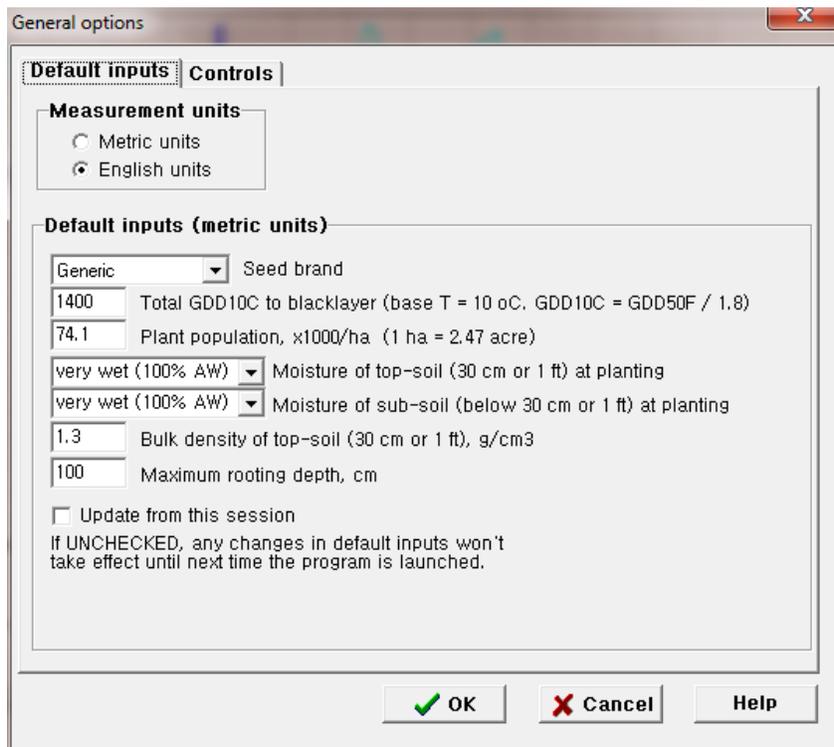
General options are grouped on two pages: Default inputs and Controls.

Default inputs

Measurement units: Select **Metric** (e.g., final yield and dry matter in Mg/ha, daily dry matter gain in kg/ha, rainfall or ET in mm, temperature in Celsius) or **English** (e.g., final yield in bu/acre, dry matter in short ton/acre, daily dry matter gain in lb/acre, rainfall or ET in inches, temperature in Fahrenheit) as measurement units for your simulations.

Default inputs: The default input values are provided for seed brand, hybrid maturity rating (growing degree days [or GDD] from emergence to

physiological maturity), plant density, planting depth, soil moisture status in the top 30 cm and subsoil at planting, topsoil bulk density, and maximum rooting depth. These values are used when Hybrid-Maize is launched and all are expressed in metric units. Instead of changing these default



values, users can also save/retrieve their own input settings for specific simulations they perform (see below).

Controls

Default time scale for graphs: Select either **Date** or **Days after planting** (DAP) as the X-axis time scale for plotting graphs. The two scales can be toggled instantly in any of the graphs.

Interval for yield trend prediction: When running a real-time simulation for **Current season prediction** with the option of **Include yield trend**, either the total number of prediction intervals or the duration of each interval (in days) can be set.

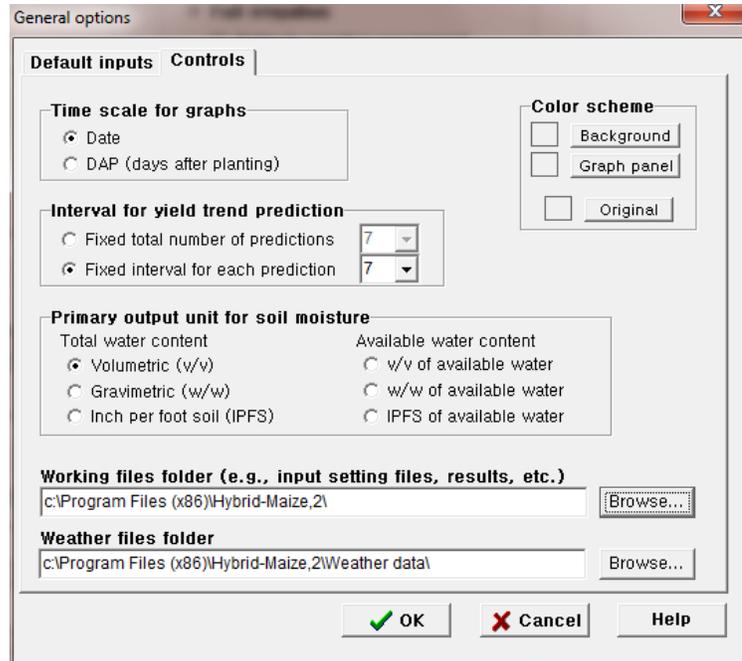
Primary out unit for soil moisture: Select one of the six (in English unit system) or four (in Metric unit system) units for soil moisture content. The units for soil moisture in

inch-per-foot-soil are not available in the Metric unit system. The selected unit is used for numerical results and the default unit for plotting graphs of seasonal soil water dynamics on **Water** page. Users can choose one of the available units for plotting soil water content on the **Water** page: total volumetric, total gravimetric and total inch-per-foot-soil, and the same units but for available water (i.e., the total minus that at permanent wilting point). The unit is selected by clicking the up-down buttons of the page. For numerical output on the **Results** page, only one unit is used, which is user-selected on the **General options** page

Directory of working files: This box allows the user to change the default folder for storing input settings files (*.stg) and simulation results.

Directory of weather files: This box allows the user to change the default folder for the weather data used in the simulations.

Color scheme: Users can set colors for the main frame background and for the graph panels. Note that the color for individual graph panels can be set independently by clicking **Settings, Set graph panel color** on the main menu, or by clicking the icon  on the toolbar. Color of the main window and the graph panel can be set independently, and the changes are maintained in the future sessions. During a session, the graph panel color on each graph can also be changed instantly through a toolbar button or the main menu. Those changes apply to the current session only.



Settings --- Parameter Settings

A unique feature of the Hybrid-Maize model is that all important internal model parameters are transparent and accessible to users. However, model parameters should not be modified unless the user understands the scientific basis of these parameters and their function in the model. For most of the internal model parameters, their functions are described in Yang et al. (2004) and in section 4 of this documentation; for the rest, the user should refer to the references given in the program. One reason for modifying model parameters might be for testing the sensitivity of the model to changes in key parameters. Modifying some parameters may also be necessary under special circumstances, e.g., when new experimental data become available or if the model is being used in situations for which it has not been developed or validated. An example of the latter would be simulations with maize hybrids that differ significantly in canopy architecture from the commonly used commercial maize hybrids, for which Hybrid-Maize was developed and validated against.

To access the internal model parameters, click **Settings**, then **Parameter settings** on the main menu bar. The parameters are shown in five groups (tabs): **Management**, **Crop growth**, **Resp & Photosyn** (respiration and photosynthesis), **Hybrid-specific**, and **Soil&field**. Each parameter has a brief explanation, and most of them also have default values. To change parameter values, check the option **Modification allowed** at the bottom of the page, which allows the user to modify specific parameter values. When saving the new parameters, the old ones are also saved automatically into the file **Parameter, old.hmf** and **Parameter-2, old.hmf** in the program folder (note that only one version of the old parameter files are kept at any time). If the user wants to restore all the parameters to their original default values, click the button **Retrieve defaults** (if the button is still grayed, make sure the option **Modification allowed** is checked).

Management: These parameters provide various constraints to the simulations in order to avoid unrealistic results or to limit the range of model applications to those situations for which

Parameter Settings

Management | Crop growth | Resp & Photosyn | Hybrid-specific | Soil & field

970 Minimum total GDD10C for maturity allowed: default=970

1730 Maximum total GDD10C for maturity allowed: default=1730

200 Maximum days of growth allowed: default=200

30 (x1000/ha) Lower-limit of plant population allowed

125 (x1000/ha) Upper-limit of plant population allowed

1.5 Interception of incoming water by plants at full canopy (mm)

32 Maximum amount of water that can be applied in each irrigation event (mm); default=32 mm (1.25 in) for center-pivot systems

95 Irrigation target soil water content (as % of field capacity) in top 30 cm (or 1 ft)

4 Sowing depth (cm, default = 4)

NOTE:
The parameters on this page and the following three pages are internal parameters that the model uses. Their modifications can have drastic effects on simulation. As a result, cautions are required when doing so. It is strongly recommended that the user contact the authors of the model or refer to relevant scientific literature for reference of those parameters.

Retrieve defaults Modification allowed

experimental validation has been conducted.

Crop growth, respiration & photosynthesis: These parameters provide general physiological coefficients used in functions describing crop growth and development. See Appendix 6.1 for a complete list and section 4.1 for a more detailed description of these parameters.

Parameter Settings

Management | **Crop growth** | **Resp & Photosyn** | Hybrid-specific | Soil & field

Respiration and photosynthesis

0.470	Growth respiration coefficient of leaf (gCH ₂ O/gDM); default=0.47 from Kropff and van Laar (1992)
0.520	Growth respiration coefficient of stem (gCH ₂ O/gDM); default=0.52 from Kropff and van Laar (1992)
0.450	Growth respiration coefficient of root (gCH ₂ O/gDM); default=0.45 from Kropff and van Laar (1992)
0.490	Growth respiration coefficient of grain (gCH ₂ O/gDM); default=0.49 from Kropff and van Laar (1992)
0.0100	Maintenance respiration coefficient for leaf (g CH ₂ O/(g DM)/d); default=0.01
0.0060	Maintenance respiration coefficient for stem (g CH ₂ O/(g DM)/d); default=0.006
0.0050	Maintenance respiration coefficient for root (g CH ₂ O/(g DM)/d); default=0.005
0.0050	Maintenance respiration coefficient for grain (g CH ₂ O/(g DM)/d); default=0.005
7.0	Maximum photosynthetic rate (g CO ₂ /(m ² leaf area, hr)); default=7.0 as converted from 70 kg CO ₂ /(ha leaf area, hr) of Kropff and van Laar (1993)
8	Lower temperature threshold (degree C) at which assimilation stops; default=8 from Kropff and van Laar (1993)
18	Lower threshold (degree C) of the optimal temperature range for maximum photosynthesis; default=18 from Kropff and van Laar (1993)
30	Upper threshold (degree C) of the optimal temperature range for maximum photosynthesis; default=30 from Kropff and van Laar (1993)
12.5	Initial light use efficiency (quantum efficiency) (g CO ₂ /MJ PAR); default=12.5 as converted from 0.45 kg CO ₂ /(ha leaf, hr)/(J/(m ² leaf, s)) of Kropff and van Laar (1993)
30	Upper-cutoff of Tmax (degree C) for computing reference T for maintenance respiration; default=30 from Driessen and Koniijn (1992)
30	Upper-cutoff of Tmax (degree C) for maintenance respiration; default=30 from Kropff and van Laar (1993)
10	Number of consecutive days for computing reference temperature for maintenance respiration; default=10 from Driessen and Koniijn (1992)

Retrieve defaults Modification allowed **Cancel** **Save** **Help**

Hybrid-specific: These are brand-specific hybrid parameters. They describe the starting time for growing degree days (GDD) computation (i.e., either from planting or emergence), the minimum and maximum of relative maturity ratings (RM, in days), and coefficients of linear regression of total GDD (Y) to GDD-to-silking (X) in the form of $Y = aX^2 + bX + c$, and the coefficients of linear regression of GDD-to-silking (Y) to total GDD (X) in the form of $Y = aX + c$. Note that only the brands that have GDD-to-silking data along with total GDD data have the coefficients for the regression of GDD-to-silking to total GDD. When one of those brands is selected, the brand-specific function will be used to estimate GDD-to-silking from total GDD when the former is not provided. For other brands that don't have GDD-to-silking data and thus have no regression of GDD-to-silking to total GDD (shown as 'N/A'), GDD-to-silking will be estimated using the coefficients for Generic brand, which are based on the pooled data of all available data. Details about the regression functions are discussed in section 4.3.

Soil & field: These parameters provide generic default values of soil physical properties for major soil texture classes and field conditions that govern the plant-available water supply. See Appendix 6.2 and 6.3 for a complete list and Section 4.2 for more detailed descriptions of these parameters.

Parameter Settings

Management | Crop growth | Resp & Photosyn | Hybrid-specific | Soil & field

GDD starting time, range of relative maturity (RM), and regression coefficients of GDD-total to RM and GDD-silking to GDD-total
 Values of the parameters are based on data compiled from seed company catalogs (print or on-line sources) as of January 2005. Temperature is in oC. Parameter values of the Generic brand are based on pooled data of all other brands.

Coefficients of linear regressions

Brand	Start of GDD	RM range, days		GDD-total (Y) to RM (X)			GDD-silking (Y) to GDD-total (X)	
		Min	Max	a	b	c	a	c
Generic	Planting	75	124	0	11.564	196.5	0.4104	145.4
Asgrow	Planting	102	124	0	12.764	119.6	0.514	-30.4
Croplan	Planting	75	120	0	11.576	222.5	N/A	N/A
Dekalb	Planting	85	119	0.0801	-4.334	1025.5	0.3081	273.3
Garst	Emergence	75	120	0	11.28	176.9	N/A	N/A
Hoegemeyer	Emergence	101	115	0.3991	-77.002	5057.5	N/A	N/A
Kruger	Planting	84	117	0	8.729	505.2	N/A	N/A
Lewis	Emergence	105	118	0	11.704	206.2	N/A	N/A
NC+	Planting	92	120	0.1792	-25.807	2147.5	0.5198	-2.3
Ottillie	Planting	96	114	0	14.037	-77.6	N/A	N/A
Pioneer	Planting	84	119	0	13.419	-5.9	0.4529	97.1
Stine	Planting	88	115	0	9.546	353.1	N/A	N/A
Triumph	Planting	105	115	0	15.1	-265.8	N/A	N/A

$Y = aX^2 + bX + c$ $Y = aX + c$

Retrieve defaults Modification allowed

Parameter Settings

Management | Crop growth | Resp & Photosyn | Hybrid-specific | Soil & field

16000 Soil matric potential at permanent wilting point (i.e., pF=4.2, or 1600 kPa, or 16 bar)
 0.70 Start of stage-2 soil evaporation as a fraction of total evaporable water (TEW). Default = 0.7 based on Fig 38 of FAO Report 56

Texture-specific parameters

Porosity	GAM	PSImax	Ksat	Alfa	AK	
0.4400	0.0330	200	26.50	0.0398	16.40	Loamy sand
0.4800	0.0258	250	16.50	0.0300	31.85	Sandy loam
0.5100	0.0185	300	6.50	0.0200	47.30	Silt loam
0.5000	0.0180	300	5.00	0.0231	14.40	Loam
0.4300	0.0096	200	23.50	0.0353	33.60	Sandy clay loam
0.4500	0.0105	300	1.50	0.0237	36.00	Silt clay loam
0.4500	0.0058	300	0.98	0.0248	1.69	Clay loam
0.5400	0.0042	80	0.22	0.0380	4.86	Clay
0.5100	0.0065	50	1.30	0.0480	28.20	Silty clay

Porosity (in fraction) is used to estimate bulkdensity of sub-soil (below 30 cm)
 GAM : texture-specific constant, cm⁻².
 PSImax : texture-specific suction boundry, cm.
 Ksat : saturated hydraulic conductivity, cm/d.
 Alfa : texture-specific geometry constant, cm⁻¹.
 AK : texture-specific empirical constant, cm^{-2.4} d⁻¹.

Refer to User's Manual for more information about the parameters on this page.

The default values are primarily for temperate soil. Caution should be taken for tropical soils, including Histosols, Andosols, Vertisols, Oxisols.

Quantification of initial soil moisture on input page
 As % of crop available water (AW)

100	very wet
75	wet
50	moist
25	dry

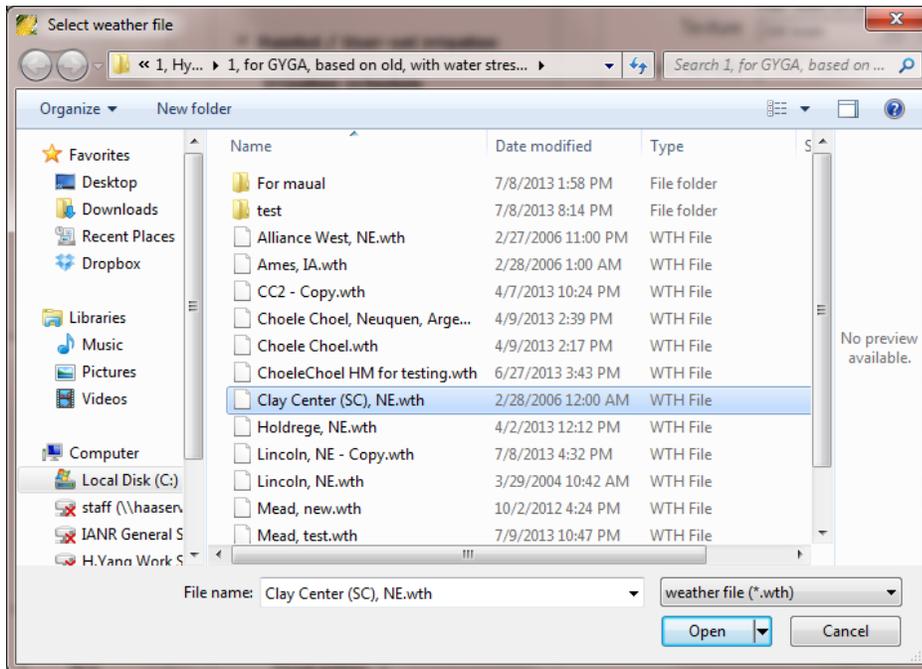
CN value for runoff estimation

Field slope	Drainage		
	Excellent	Good	Poor
<2%	61	73	84
2-5%	64	76	87
5-10%	68	80	91
>10%	71	83	94

Retrieve defaults Modification allowed

2.3.2. Weather Data

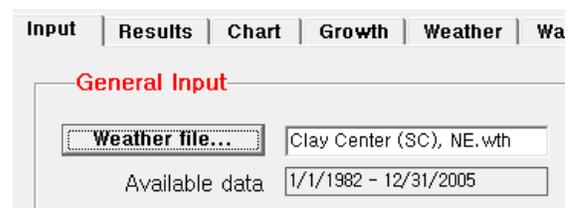
For each simulation run, a weather data file must be selected that best represents the site for which the simulation is intended. Clicking the button **Weather file...** in the panel **General Input** on the front page displays the file selection sub-window, and a file can be selected by browsing to the appropriate directory and file name.



The default directory (or folder) can be changed if necessary (go to **Settings** → **General options** or press **CTRL-O**). By default, only files with extension **.wth** will be displayed in the file list because **.wth** is the default extension for weather files. In case a weather file uses a different extension, select **all file** in the **List files of type** window in order to display the file. Clicking **Open** will select a file and close the sub-window. Then the selected weather file will be displayed in the box next to the weather file selection button, and the box below shows the start and end dates of the which data.

2.3.2.1. Creating a Weather Data File

When simulating yield potential (i.e. under full irrigation) but without the need to estimate irrigation water requirements, the Hybrid-Maize model requires three daily weather variables to run: solar radiation, maximum temperature (**T-high**), and minimum temperature (**T-low**). When simulating growth under rainfed or user-set irrigation, or full-irrigation management with estimated irrigation water requirements, three additional daily weather variables are required: relative humidity, rainfall, and reference evapotranspiration (**ET**). All internal computations are based ET that is grass referenced. If the ET in the weather file is alfalfa-referenced, a conversion ratio to grass-referenced ET, 1.3 by default, must be set on **Crop growth** page of the Parameter settings.



All weather data must be in a plain text file format (so-called ASCII file) with the extension **.wth**. Below is an example of such a file for a site with daily weather data from January 1, 1990 to December 31, 2003:

BEATRICE NE Lat.(deg)= 40.30 Long.(deg)= 96.93 Elev.(m)= 376.
40.30 (Lat.)

Year	day	Solar MJ/m2	T-High °C	T-Low °C	RelHum %	Precip mm	ET-NE Mm	SoilT °C	WndSpd km/hr
1990	1	8.829	5.5	-9.8	68	0.0	1.7	-1.7	11.8
1990	2	8.797	10.5	-1.6	63	0.0	2.5	-1.0	13.7
1990	3	7.373	7.1	-8.0	82	3.1	1.2	-0.3	12.5
1990	4	9.143	4.0	-10.6	71	0.0	1.4	-0.2	10.6
1990	5	8.799	3.9	-11.0	67	0.0	1.4	-0.8	9.8
.....									
.....									
2003	360	1.212	11.2	0.7	84	0.0	1.3	0.9	21.0
2003	361	9.021	13.8	-0.5	57	0.0	3.9	5.0	20.8
2003	362	7.564	6.5	-4.9	62	0.0	2.1	1.9	13.6
2003	363	9.326	5.5	-4.4	63	0.0	2.1	1.2	14.1
2003	364	7.829	9.8	-4.5	53	0.0	3.1	0.7	15.1
2003	365	8.509	4.7	-7.1	60	0.0	1.7	0.6	11.2

Note that all data are in metric units, and are placed in a row in the order as shown above. Detailed specifications for the weather file format are:

Row 1: Site information (location, latitude, longitude, elevation). All info in this row is not used in simulation itself but will be copied as ‘site info’ to the output file of a simulation run.

Row 2: Latitude of the site in decimal degrees. If the program can’t find a value at the beginning of the second row, a warning message will pop up and the simulation will abort. For the southern hemisphere, this value must be negative. Any other text in this row must be separated by one or more spaces or a tab, and will be ignored when the program runs.

Row 3: Names of variables. Variables should be in the exact order shown above. From left to right the variables are: year, day (ordinal day of the year, 1-365 or 366 for leap year), solar radiation, T-high (maximum temperature), T-low (minimum temperature), RelHum (humidity), and precip (rainfall). The example above shows two additional variables that are often available--soil temperature and wind speed--but they are not used in the current version of Hybrid-Maize and will thus be ignored by the program.

Row 4: Measurement unit (metric) for each variable. Solar radiation = MJ/m², temperature = °C, relative humidity = %, rainfall and ET = mm. If raw data obtained are in other units, they must be converted to the appropriate metric units. If the data are in English units, daily solar radiation is often expressed in Langley (1 Langley=41.868 KJ m⁻²), temperature in °F (1 °F=(1 – 32)/1.8 °C), and rainfall and ET in inch (1 inch = 25.4 mm).

Row 5 to end: One row represents one day. Within a row, values must be separated from each other either by space (one or more) or tab (one or more). Alignment is not important, and there is no limit to the number of decimals. If humidity, rainfall and ET are not available, the three variables

must be entered as 0 (zero) and the model can only be used for simulating yield potential, not water-limited yield.

2.3.2.2. Sources of Weather Data

The Hybrid-Maize program package contains historical daily weather data obtained from the High Plains Regional Climate Center (HPRCC) for 21 selected locations in the western Corn Belt. (see the map and table below; data are provided until 12/31/2005).

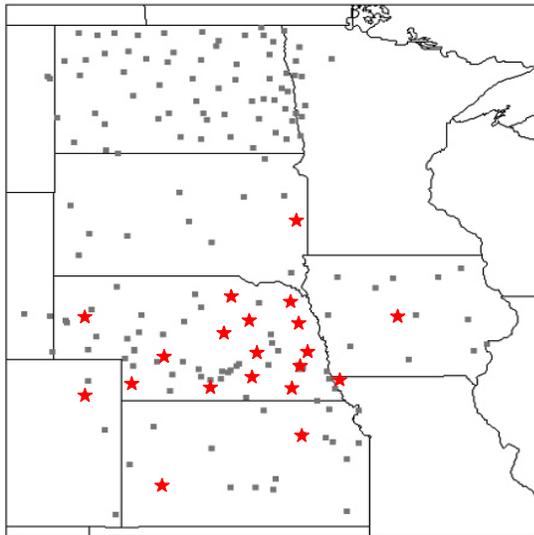


Figure 2.1. Sites of daily weather data included in the program package. The sites are part of the Automated Weather Data Network (AWDN) of the High Plains Regional Climate Center (HPRCC) of the University of Nebraska - Lincoln. The stars on the map show the locations of the sites included with your version of Hybrid-Maize; the gray squares show other weather stations in the AWDN database. We recommend that users who wish to actively use Hybrid-Maize to explore crop management options should purchase the expanded AWDN database on CD-ROM from the HPRCC or subscribe for specific sites to obtain up-to-date weather data for locations in closest proximity to the sites for which simulations are desired.

Site	County	State	Latitude	Longitude	Elevation (m)	Database period
Alliance West	Box Butte	NE	42°01'	103°08'	1213	5/88-12/05
Beatrice	Gage	NE	40°18'	96°56'	376	1/90-12/05
Central City	Merrick	NE	41°09'	97°58'	517	9/86-12/05
Champion	Chase	NE	40°40'	101°72'	1029	1/82-12/05
Clay Center	Clay	NE	40°34'	98°08'	552	7/82-12/05
Concord	Dixon	NE	42°23'	96°57'	445	7/82-12/05
Elgin	Antelope	NE	41°56'	98°11'	619	1/88-12/05
Holdrege	Phelps	NE	40°20'	99°22'	707	5/88-12/05
Lincoln (IANR)	Lancaster	NE	40°82'	96°65'	357	1/86-12/05
Mead	Saunders	NE	41°09'	96°24'	366	5/81-12/05
North Platte	Lincoln	NE	41°05'	100°46'	861	9/82-12/05
O'Neill	Holt	NE	42°28'	98°45'	625	7/85-12/05
Ord	Valley	NE	41°37'	98°56'	625	7/83-12/05
Shelton	Buffalo	NE	40°44'	98°45'	614	1/91-12/05
West Point	Cuming	NE	41°51'	96°44'	442	5/82-12/05
Akron	Washington	CO	40°09'	103°09'	1384	10/83-12/05
Ames	Story	IA	42°01'	93°45'	309	7/86-12/05
Brookings	Brookings	SD	44°19'	96°46'	500	7/83-12/05
Garden City	Finney	KS	37°59'	100°49'	866	3/85-12/05
Manhattan	Riley	KS	39°12'	96°35'	320	6/84-12/05
Rock Port	Atchison	MO	40°28'	95°29'	268	1/91-12/05

For more precise location-specific simulations, and particularly for real-time simulations in the current growing season (see sections 3.1. to 3.4.), users must acquire weather data directly from available public or commercial sources through free or fee-based subscription. Many weather

station networks in the USA provide online access to weather databases, including daily historical records as well as daily records of the current growing seasons. Examples of such weather data sources include:

Center	Website	U.S. States
National Climatic Data Center (NCDC)	http://www.ncdc.noaa.gov	All
High Plains Regional Climate Center (HPRCC)	http://www.hprcc.unl.edu	NE, KS, IA, ND, SD, selected stations in other states
Midwest Regional Climate Center (MRCC)	http://mcc.sws.uiuc.edu	MO, IA, MN, IL, WI, KY, IN, OH, MI
Southeast Regional Climate Center (SERCC)	http://water.dnr.state.sc.us/water/climate/sercc	FL, SC, NC, GA, AL, MS, TN, VA, WV, MD, DE, KY
Northeast Regional Climate Center (NRCC)	http://www.nrcc.cornell.edu	CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, WV
Western Regional Climate Center (WRCC)	http://www.wrcc.sage.dri.edu	AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, UT, WA, WY
Southern Regional Climate Center (SRCC)	http://www.srcc.lsu.edu	AR, LA, OK, MS, TN, TX
Illinois Climate Network	http://www.sws.uiuc.edu/warm/datatype.asp	IL
National Aeronautics and Space Administration (NASA)	http://earth-www.larc.nasa.gov/power/	Global

It is important to note that not all weather stations have complete weather data observations for long-term historical time periods and that spatial coverage varies. In particular, solar radiation data are often unavailable, except for more recent years and in the relatively new networks such as the AWDN at the HPRCC. Before subscribing or downloading data, check what data are available for a station located as close as possible to the location you wish to simulate and make sure that solar radiation is included. For simulating long-term yield potential using Hybrid-Maize, users should have at least 10 or more years of historical weather data. Also check the format and measurement units of the daily data that are available and how the data can be converted into the format shown above in section 2.3.2.1.

There will be cases when some of the essential weather data are incomplete. Hybrid-Maize will malfunction if a weather file contains missing data. In many cases, individual missing cells can be filled by extrapolating a value from surrounding dates. In some cases, long stretches of missing data in historical weather files might be filled in by averaging the same time period from years with complete data. For locations where no weather station with complete records is available nearby, various data sources could be combined to generate a more location-specific data set. Except for mountainous and coastal areas, solar radiation and temperature vary less than rainfall over short distances. Therefore, obtaining solar radiation and temperature from a weather station located within about 20-100 miles of your location is often sufficient for reasonable yield potential simulations. More precise rainfall and temperature data can be measured directly on-site by using relatively inexpensive rain gauges and a max/min thermometer although both must be placed in an appropriate location.

2.3.2.3. Converting, Organizing, Updating, and Checking Weather Data

1. **WeatherAid** is included as a utility to capture and convert weather data (Fig. 2.1). It can be invoked from the toolbar  or **Utilities** on the main menu. **WeatherAid** has the following functions:

- Convert and reformat raw weather data for **Hybrid-Maize** use
- Add new data to existing weather data files
- Estimate solar radiation from sunshine hours or temperature
- Estimate potential ET from pan evaporation or using the Penman-Monteith method
- Check for erroneous data entries, including missing data
- Utilize data templates to streamline import and conversion of raw weather data. Users can build templates and save them for repeated use.
- A built-in internet explorer, **WeatherAid Explorer**, for downloading weather data from online sources (Fig. 2.2). After accessing online data, clicking **Capture** on the toolbar of **WeatherAid Explorer** will transfer the data directly to **WeatherAid** input data panel. Web links to online weather data sources are provided, and frequently used data sources can trigger the automatic selection of data templates.

Refer to **Instructions** in **WeatherAid** for detailed guide and help.

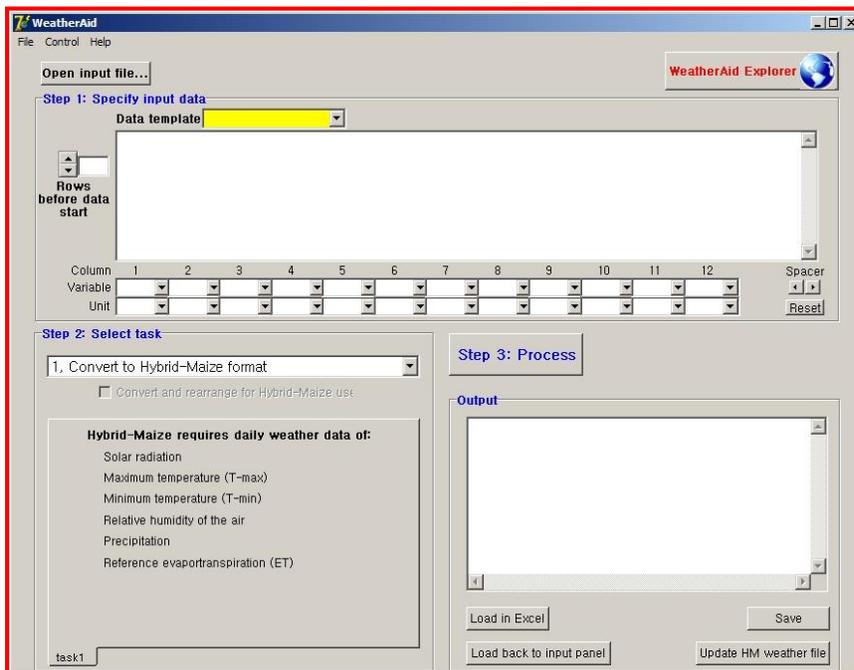


Fig. 2.1



Fig. 2.2

Alternatively, users can convert and format raw weather data manually according to the specifications in section 2.3.2.1. This can be done most efficiently in Excel spreadsheet. Once the units of the data are correctly entered and the data have been placed in the right columns with four rows of text on top, the file can then be saved as a tab-delimited **text** file. After this, the extension of the weather file needs to be changed from **.txt** to **.wth**. Updating a weather file can also be done in a Excel by opening the previously created **.wth** file and appending new data, then saving the file under the same name. Alternatively, **.wth** files can also be edited in any text editor. Hybrid-Maize includes the Notepad text editor for this purpose, which can be launched by clicking on **Utilities** → **Text editor** from the main menu of the program. New data, which must have correct units and order of variables, can then be appended as unformatted text to the end of the existing file.

*NOTE: In text editors such as MS Wordpad, one has to use **Paste special...** through the menu bar to select the unformatted text option for pasting when transferring text from MS Excel to a text file.*

For example, a raw data file downloaded from a network such as AWDN may look like this:

```
BEATRICE, NE Lat.(deg)= 40.30 Long.(deg)= 96.93 Elev.(m)= 376.
a250629 T-High T-Low Rel Hum Soil Tmp WindSpd Solar Precip ET-NE
date/time F F % F@4 in. mi/hr langleys inches inches
1 1 1990 2400 41.914 14.277 68.244 28.859 7.310 210.873 0.000 0.065
1 2 1990 2400 50.868 29.190 62.523 30.240 8.503 210.116 0.000 0.097
1 3 1990 2400 44.844 17.518 82.046 31.481 7.741 176.111 0.121 0.049
1 4 1990 2400 39.234 12.955 70.573 31.680 6.586 218.365 0.000 0.055
```

Manual data preparation includes the following steps:

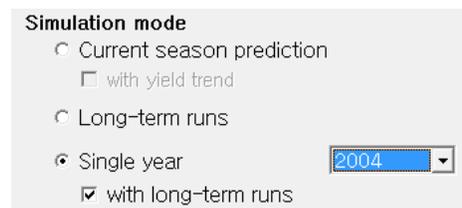
1. Conversion of all English units to metric (S.I.) units (solar radiation MJ/m² = Langley/23.885; Temperature °C = 0.5556 x (°F - 32); rainfall and ET in mm = inch x 25.4; Wind speed in km/hr = miles/hr x 1.609),
2. Conversion of month-day format (first two columns) into running day format (day 1 = January 1 in each year, day 365 = December 31 in each year or 366 in a leap year),
3. Re-arrangement of data columns to arrive at the appropriate finale file format:

```
BEATRICE, NE Lat.(deg)= 40.30 Long.(deg)= 96.93 Elev.(m)= 376.
40.30 (Lat.)
year day Solar T-High T-Low RelHum Precip ET-NE SoilT WndSpd
MJ/m2 oC oC % mm mm oC km/hr
1990 1 8.829 5.5 -9.8 68 0.0 1.7 -1.7 11.8
1990 2 8.797 10.5 -1.6 63 0.0 2.5 -1.0 13.7
1990 3 7.373 7.1 -8.0 82 3.1 1.2 -0.3 12.5
1990 4 9.143 4.0 -10.6 71 0.0 1.4 -0.2 10.6
```

4. Save the file as a tab delimited text file or MS-DOS text file (but not Unicode text file) with the extension **.wth**

2.3.3. Simulation Modes

Single year: Simulation of growth in a single year (cropping season) is the default simulation mode. This mode is primarily used for analysis of past cropping seasons (see section 3.3.) to gain understanding of factors that may have caused yield loss or to estimate the size of the exploitable yield gap by comparing simulated yield



potential with actual measured yields. The year of simulation is selected from the drop-down box on the right, which lists all available years in the weather file. Up to six individual single year runs can be made sequentially and their results can be compared, both numerically and graphically on the output pages. If more individual runs are attempted, the program will ask for permission to erase the results from previous runs before conducting a new run. Previous results can also be erased manually by clicking **Settings** on the menu bar and selecting **Erase current results**.

Single year with long-term runs: Single year simulation can be run in combination with long-term runs utilizing all available years of weather data. If this option is checked, a simulation will be run for every year in the weather file in addition to the selected year. This mode is useful for comparing a known year with the long-term site yield potential and understanding why yields in certain years were above or below normal and what climatic factors may have contributed to the observed results.

Results shown include the single year selected as well as the long-term simulation results. The latter are ranked based on grain yield. By default, simulated values are shown for the years with the maximum (best), 75% percentile (three out of four years have lower yields than this yield level), median (50% percentile), 25% percentile (three out of four years have higher yields than this yield level), and the minimum (worst) yield. The summary results table also displays the (long-term) mean and the coefficient of variance (CV, in %) calculated from simulations of all years. For result summary and bar chart plot, users can also choose to show all years of results by checking the option **Show all years** on the **Results** page or click the toggle **Five ranks / All years** on the Chart page. Whenever **with long-term runs** is selected, all previous run results, from single year mode or other modes, will be erased, and comparisons can only be made among years of the current long-term run.

Long-term runs: This simulation mode is used for estimating the long-term yield potential or attainable water-limited yield at a given site, as affected by different choices of maize hybrid, planting date, and/or plant population. In other words, this mode can be used to explore how to exploit the available yield potential through management (see section 3.1.). When this mode is checked, a new box will appear on the right for the starting year. The start and end years for long-term runs must be specified, but a minimum of five years must be included to perform long-term simulations. By default, the first year and the last year of the weather file appear in the respective start/end boxes, and we recommend that as many years as possible be used for such analyses to ensure that the widest possible range of weather conditions are used in the simulation.

In this mode the model simulates maize growth in each year of the range selected. All runs (=years) are ranked based on grain yield. By default, simulated values are only shown for the years with the maximum (best), 75% percentile, median (50% percentile), 25% percentile, and the minimum (worst) yield. The summary results table also displays the numerical mean calculated from all simulations of all years, which is referred to as the long-term mean. For result summary and bar chart plot, users can also choose to show all years of results by checking the option **Show all years** on the **Results** page or click the toggle **Five ranks/All years** on the Chart page. It is important to remember that all runs (years) in this mode

Simulation mode

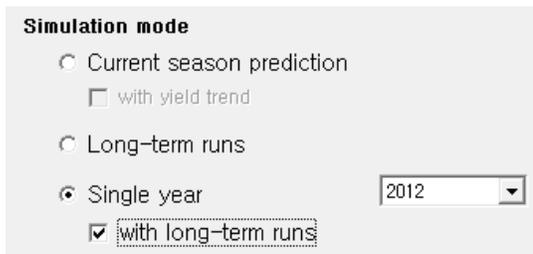
- Current season prediction
 - with yield trend
- Long-term runs
 - from: 1982
 - to: 2004
 - with long-term runs
- Single year

will display grain yields and other simulated data with respect to the same set of input data (e.g. planting date, GDD, etc).

Note: Comparison of specific years where these input data vary from one year to the next is best carried out by multiple runs in the 'Single year' mode.

Current season prediction: This mode is used for in-season (or real-time) simulation of maize growth and forecasting the final yield before the crop matures (see section 3.4). Predictions are based on the up-to-date weather data for the current growing season, supplemented by the historical weather data for the rest of the season at the simulation location. To use this mode, the weather data file must contain at least ten years of reliable weather data for the site, in addition to updated real-time weather data for the current growing season.

When this mode is selected, the year selection box will be grayed out and the last year (i.e. the current year) of the weather file will be selected automatically as the year for which a prediction is to be made. For locations at which a growing season crosses into another year (such as in the southern hemisphere where crops are planted in September/October and harvested in the following year), the year when the current season starts will automatically be selected. Note that this mode will not run if the weather data for the current season are already available for the entire growing season. In this case, a message will pop up recommending the user to select the **Single year** mode.



The screenshot shows a 'Simulation mode' panel with the following options:

- Current season prediction
 - with yield trend
- Long-term runs
- Single year (selected)
 - Year selection: 2012 (dropdown menu)
 - with long-term runs

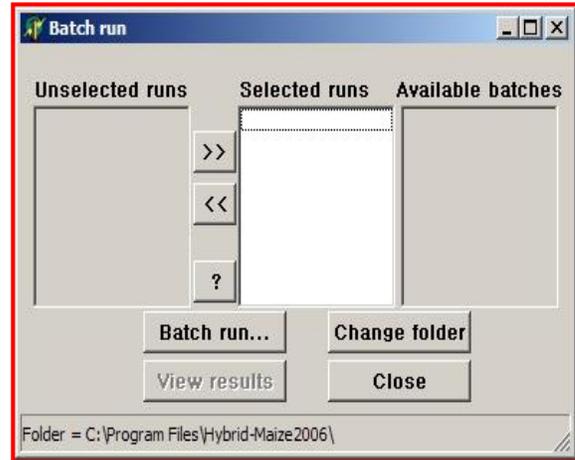
In the current-season prediction mode, the model first uses the current year's weather data to simulate actual growth up to the current date, and then utilizes the climate data for each subsequent day based on the historical weather data from all previous years to simulate all possible growth scenarios until crop maturity. As with long-term runs, predictions are ranked according to grain yields and results are shown for the scenarios with the best, 75% percentile, median (i.e. 50% percentile), 25% percentile, and the worst yields.

In addition, for the current season prediction mode, the model also performs a complete long-term run using the same settings for GDD, date of planting, etc as specified for the current season. Results for the year representing the median grain yield from the long-term run are added to the overall model outputs displayed in the current-season prediction mode, along with the five ranks for the current-season prediction. This allows comparing growth in current ongoing growing season with growth in the median year, which may be useful for making management adjustments in real-time. The long-term median is used instead of the mean because it represents an actual year that has occurred in the past, whereas averaging historical climate data would cause 'smoothed' weather conditions that are unrealistic, particularly with regard to rainfall and temperature patterns.

The current-season prediction mode has an option **Include yield trend**. When this option is checked, the model will make yield predictions since emergence (or shortly after that) until the last day of the ongoing growing season in the weather file. The total number of predictions or the interval (in days) for the predictions are set through **Settings** → **General options** in the main menu. The results of yield trend are plotted in the output tab **Yield trend**. The data for plotting the graph can be saved through **Save results** → **Real time yield trend** on the main menu. Running the current-season prediction with **Include yield trend** allows analysis of how the yield predictions

change during an ongoing growing season, i.e., whether a trend towards above- or below-normal yields exists. However, users should be aware that those simulations will take several minutes to complete.

Batch run utility. Batch runs of any modes and combination can be conducted (Fig. 4). Results, as well as settings on the **Input** page, of individual runs can be viewed like in a normal operation. Batch runs are accessed through **Utilities** on the main menu and batches can be saved as batch run files (.brf).



2.3.4. Crop Management Details

Start from: A simulation of crop growth starts from planting. Set the month and date of planting. Planting depth, 4 cm by default (approx. 1.6 inches), is part of the internal parameters that can be changed as appropriate if the user has more accurate information about planting depth.

The GDD required for germination and for emergence per cm planting depth are set by the **Parameters settings**. User may change the default values when necessary.

m/d

Date of planting 5 1

15	GDD10C requirement for GERMINATION; default = 15
6	GDD10C requirement for emergence per cm depth; default = 6
25	Maximum days allowed from planting to emergence

Seed brand: Choose the appropriate seed brand and Hybrid-Maize will select the appropriate function for describing the relationship between total GDD to physiological maturity and GDD to silking. GDD values differ somewhat among seed companies because of different definitions and methods used to measure them. The functions used by Hybrid-Maize can be viewed and edited by through **Settings** → **Parameter settings** → **Hybrid-specific** in the main menu. If the seed brand you wish to use is not included in the list of choices, choose '**Generic**' for your simulation. In this case, Hybrid-Maize will use a general relationship derived from many different seed brands.

Seed brand Generic

Maturity: This sub-panel is used to specify when physiological maturity and silking are reached in a simulation. Model predictions are *very sensitive to both* and settings on this must be made with great care. *Silking* (R1 stage of maize) begins when any silks are visible outside the husks and 2 to 3 days are required for all silks on a single ear to be exposed and pollinated (Ritchie et al., 1992). In Hybrid-Maize, silking date refers to occurrence of about

Maturity

GDD50F 2650

Relative maturity (days) []

Date (m/d) 8 16

Optional:

Date of silking (m/d) [] []

GDD50F to silking 1350

* Generic estimate

50% silking in the field. *Physiological maturity* (R6 stage or black layer stage of maize) is reached when *all kernels on an ear* have attained their maximum dry weight and a black or brown abscission layer has formed at the kernel base (Ritchie et al., 1992). Note that black layer formation occurs progressively from the tip to the base of the ear, which must be considered when determining the exact date of maturity.

In Hybrid-Maize, crop maturity can be specified by one of the three options: total GDD (growing degree days, or growing degree units) the crop takes to reach physiological maturity, or the actual date of maturity if it is known, or relative maturity (RM, in days). If the date of reaching maturity is not known (e.g., in Long-term runs and Current season prediction modes), maturity is predicted by Hybrid-Maize from available information about the specific hybrid grown (cumulative GDD required to reach maturity) and the weather data during the seasons simulated. The GDD is calculated from the summation of the 'effective daily temperature' during the growing season from planting to maturity. The effective daily temperature is the temperature above a base temperature of 10 °C (50 °F) and below a default upper cutoff temperature of 34 °C (93 °F).

To utilize the GDD option, choose GDD50F (English units option, referring to a base temperature of 50 °F) or GDD10C (Metric units option, referring to a base temperature of 10 °C) and enter the appropriate GDD value for the hybrid grown. This information is readily available for most commercial hybrids from seed companies, either published in their seed catalogues or found online.

*NOTE: We recommend using the GDD to maturity mode for most simulations because errors due to wrong identification of actual occurrence of physiological maturity in the field can be large. To prevent erroneous entries, customizable lower and upper limits of total GDD allowed are specified under **Settings** → **Parameter settings** → **Management**.*

Also note that the starting time for GDD differs among seed companies. After the seed brand is selected, the model will use the corresponding GDD starting time according to the information obtained from the seed companies. For Generic brand, the default GDD starting time is planting, but it can be changed through Parameter settings. The GDD starting time for all other brands can also be viewed through Parameter settings.

If the exact date of maturity is known (e.g., in research studies using **Single year** simulation mode for analysis of a past growing season, see section 3.3.), select 'Date' and enter the date on which physiological maturity is reached in the month/day drop down boxes.

*NOTE: Model results are very sensitive to this setting and simulated yield can be seriously affected by entering an incorrect maturity date. Accurate simulations require precise estimates of physiological maturity (R6 or black layer stage) based on careful field observations. Strictly follow the definition of R6 stage provided above (Ritchie et al., 1992) and monitor the crop during its final stages on a **daily basis**. If unsure, use the GDD option described above.*

The last option for setting maturity is by **Relative maturity** (RM, in days). Enter the RM value for the hybrid and also make sure the seed brand is selected correctly. Note that RM measures the days to the time when grain moisture content is suitable for harvest, instead of the days to the time when grain filling stops (i.e., at blacklayer). Although there exists a correlation between RM and total

GDD for a specific seed brand, the goodness of the correlation does vary across brands (refer to section 4.3 for detailed discussion). For this reason, caution must be taken when using this option to set maturity.

Maturity also has two associated optional parameters: **Date of silking** (50% silking observed in the field) and **GDD to silking**. The time of silking is very important for simulation of grain yield, because it is the time when the crop shifts from vegetative growth to reproductive growth (i.e., grain filling). By default, Hybrid-Maize uses the total GDD (either specified by the user or calculated when the date of maturity is specified) to

predict the GDD required to reach silking, and thus to predict the date of silking. The prediction is based on brand-specific functions between GDD-to-silking and total GDD as derived from data of published seed catalogs. If hybrid-specific information on GDD-to-silking or the exact date of reaching silking (50% silking) is known, entering this information may improve the accuracy of model simulations. Only one option can be set, date of silking or GDD to silking.

The option **Date of silking** is not available in simulation mode **Long-term runs** because silking date differs across different years. In simulation modes **Single year with long-term runs** or **Current season prediction**, setting the date of silking for the year of interest will also affect the long-term runs. The model will determine the occurrence of silking for the long-term runs based on the GDD-to-silking value that corresponds to date of a silking entered for the single year or current season of interest. Similarly, in the **Current season prediction** with the option **Include yield trend**, the yield predictions for the dates prior to the given date of silking are also based on the GDD-to-silking value that corresponds to the date of silking entered for the current season. Although this scheme emphasizes the value of real time information (i.e., the actual date of silking), it also bears the risk of erroneous simulations for those runs that depend on such real-time information.

NOTE: Model results are very sensitive to this setting and simulated yield can be seriously affected by entering an incorrect silking date. Strictly follow the definition of silking stage provided above (Ritchie et al., 1992) and monitor the crop during this period on a daily basis. For most practical applications, we recommend leaving 'Date of silking' and 'GDD to silking' blank or only enter the published 'GDD to silking' from the available hybrid-specific information (see seed catalogs).

Plant population: Enter the final plant density at maturity, in thousand plants per acre (English) or thousand plants per ha (metric), estimated from plant counts. Note that these values are actual stand counts and not the number of seed sown per acre or ha because not all seeds germinate. For greatest accuracy, stand counts should be taken at several locations in the field. If stand counts are not known, use a plant population that is ~94% the number of seed sown. For example, if 32,000 seed were sown per acre, the final plant population would be estimated at 30,080 plants per acre (0.94*32,000). Rounding the estimated plant population to the nearest thousand gives 30 in the window as shown below.

*NOTE: Hybrid-Maize has mostly been tested with plant populations ranging from about 28,000 to 45,000 plants/acre (70,000 to 110,000 plants/ha). An empirical equation derived for this range is used to describe the effect of plant density on the rate of grain filling (see section 4.1.9.). The model should be used with caution outside this range without further verification. Actual crop response to plant population may also vary significantly among maize hybrids. Effects of different **row spacing** are not accounted for in Hybrid Maize. The lower and upper limits of population are specified in **Settings** → **Parameter settings** → **Management** and can be changed to avoid entering values outside the validated range.*

2.3.5. Water

Full irrigation: This option is selected for simulating maize yield potential under non-limiting conditions, assuming adequate water supply throughout the entire growing season (see Chapter 1). When selecting **Full irrigation** water management, the user also has the option to let the model estimate the minimum requirement for irrigation water in order to achieve water stress-free growth. This option requires specification of soil properties as in the **rainfed/ user-set irrigation** option.



*NOTE: In estimating irrigation water requirement, irrigation events are assumed to occur on a single day, which may not be possible with some irrigation systems. The maximum irrigation water amount that can be delivered depends on the irrigation equipment available. This value can be set under **Settings** → **Parameter Settings** → **Management**.*

Rainfed/Use-set irrigation: Select this option to simulate the water-limited yield under either rainfed (dryland) or user-set irrigation, taking into account daily rainfall as well as past or scheduled irrigation events. Selecting this option activates the irrigation scheduler as well as the sub-panel for entering soil and field information. A maximum of 60 irrigations are permitted. The dates must be entered as numeric values for both month (1, 2,...12) and day (1,2,...31). Enter irrigation amounts in inches (English unit mode) or mm (Metric unit mode). Note that a later irrigation event can be entered after an earlier irrigation event and blank rows are allowed. This is particular useful for testing irrigation effects by removing events or adding new events to the end of a schedule. The irrigation schedule entered can be saved/retrieved together with all other model settings. To delete all irrigation events, click **Reset entries** at bottom of the table.

Month	Day	Amount (inch)
6	25	1.5
7	3	1
7	10	1.5
7	20	1.5

NOTE: This version of the model simulates maize growth and yields under optimal water regime (yield potential) as well as water-limited conditions. Most of the model validations so far have been conducted under optimal water conditions in the western and central Corn Belt of the USA, whereas model validation for water-limited conditions is still ongoing. Therefore, caution must be exercised when interpreting simulation results under water-limited conditions, particularly in areas that are prone to severe drought stress at key growth stages.

2.3.6. Soil & Field

Soil properties and field conditions are only required under **Rainfed/User-set irrigation** water management, or in **Full irrigation** water mode when the additional option of **Estimating irrigation water requirement** is selected.

Rooting depth: For soils without constraints to root growth, 150 cm is set as the rooting depth. However, in soils with physical (caliche layer, bedrock, hardpan) or chemical (high/low pH, salinity, B toxicity) constraints to root growth, rooting depth needs to be specified accordingly. A minimum rooting depth is set at 40 cm (or 16 inches) simply because it is unlikely that maize will be grown in fields with a shallower soil depth.

Soil & field

Rooting depth inch

Texture **Top-soil (1 ft)** **Sub-soil**

Bulk density g/cm³

Soil moisture

at planting
 at start of fallow months before planting*
*only for sites without snow during fallow

Soil surface residues coverage (%)

Estimate field runoff

Field slope Soil drainage

Soil surface coverage by crop residues. The amount of crop residues that cover the soil affects soil evaporation and surface runoff. Select a value that represents roughly the residue cover of the specific field based on visual inspection, previous crop, tillage system, etc. Refer to Appendix 6.3 for guidelines to estimate the degree of coverage for maize and soybean residues, or clicking the button **How to estimate** in the program. The default value for maize fields in the U.S. Corn Belt under conservation tillage is 30%.

Texture and bulk density: Select soil texture types for both topsoil (top 30 cm or 1 ft of soil) and subsoil (the soil below the topsoil) from the drop-down list. For each of these texture classes, default soil physical properties will be used for simulating the soil water balance and conversion between soil water pressure and soil water content. In special cases, users may change these texture specific soil properties under **Settings** → **Parameters** → **Soil** (see section 4.2, and Appendix 6.2). For topsoil, also enter the estimated bulk density. The bulk density of topsoil typically ranges from 1.1 to 1.4 g/cm³ depending on soil texture and structure, tillage, and residue management. Subsoil bulk density is estimated based on selected texture class.

Initial soil moisture status: Users have the option of setting soil moisture status either for the time of planting, or for the beginning of a pre-planting fallow period. When using the latter option, the model will estimate soil moisture at planting by tracking soil water balance throughout the fallow period using rainfall data and estimated daily soil evaporation. This component is most useful in semi-arid regions, especially in the tropics and sub-tropics, where rainfall is monsoonal such that there is a relatively long dry period before planting. In such cases, farmers often plant maize after rains begin at the beginning of the rainy season. At the beginning of a fallow period, soil moisture can usually be set at “dry” (see screenshot below) because the previous crop has often depleted soil available water. Caution must be taken, however, when using this option at locations where snowfall is significant during the fallow period (e.g., the winter of temperate regions), because

snowfall can lead to error in estimating water balance computations. For the fallow, when cumulative precipitation that occurs on days with mean freezing temperature accounts for 20% of the total precipitation of the fallow period, the program will issue a message “Warning: snowfall occurred during fallow and estimation of soil moisture at planting may be unreliable”.

For either option, select a soil moisture rating from the dropdown list that reflects initial soil condition. Note that the ratings are based on % of crop-available soil water. Specifications of soil moisture for each rating as % of available water are defined on **Soil & Field** page of **Parameter settings** and can be changed when necessary.

The screenshot shows a window titled "Quantification of initial soil moisture on input page". Below the title is the text "As % of crop available water (AW)". There is a dropdown menu with four options: "100" (very wet), "75" (wet), "50" (moist), and "25" (dry). The "100" option is currently selected.

NOTE: Users in Nebraska of USA can obtain historical and real-time information on soil moisture status from the Nebraska Soil Moisture project at the HPRCC (<http://hprcc.unl.edu/soilm>). Initial soil water can also be estimated based on total precipitation during the non-growing season as reported by Grassini et al. (2010)

Runoff: water lost through surface runoff can be significant, especially during intense rainfall events in sloping fields with poor drainage and little cover with crop residues. The estimation of surface runoff is subjected to many sources of errors. As a result, caution should be taken when using this option. When selected, two inputs are required: average field slope and soil drainage class. Users select one of the four classes of field slope (<2, 2-5, 5-10, and >10%) and one of the three classes of drainage (excellent, good, poor). General guidelines for selection of the drainage class are provided in Appendix 6.4.

2.4. Model Outputs

Once a simulation run has completed, a beep will sound and the **Result** page will show subsequently. Other output pages, including **Chart**, **Growth**, **Weather**, **Water**, and **Yield trend**, can be viewed by clicking on corresponding page tabs.

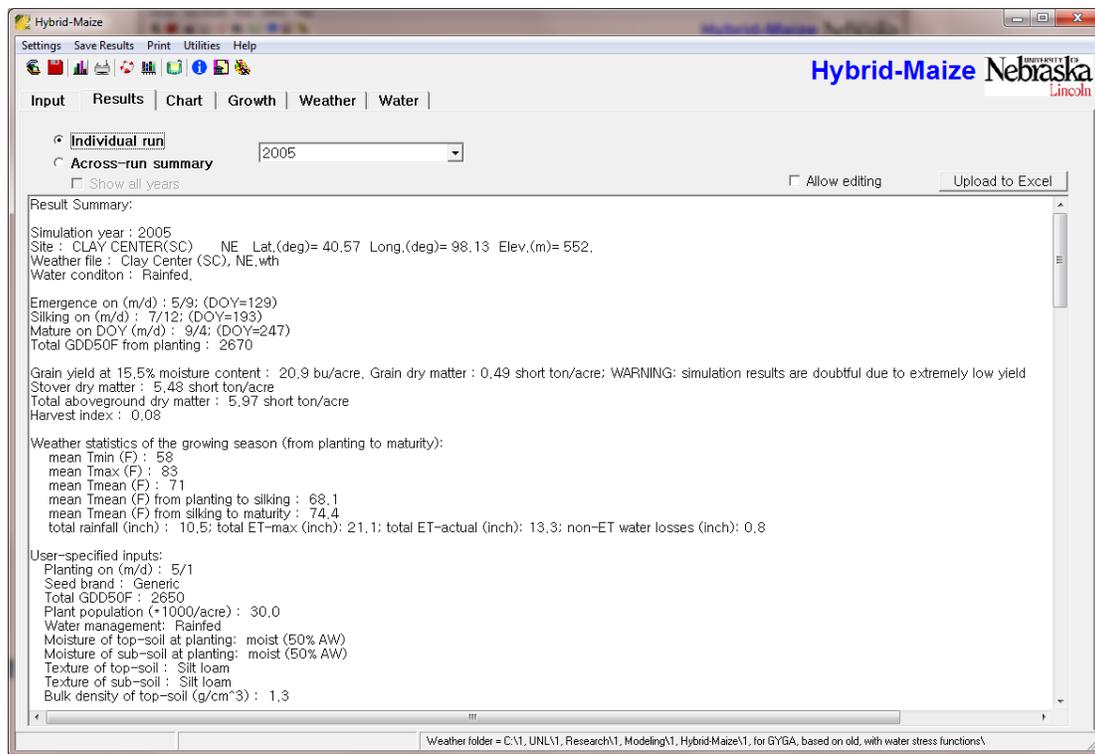
2.4.1. Results

The display of simulation results differs depending on the mode of simulation. In ‘**Single year**’ mode without long-term runs, results are shown on one page (use the scroll bar to view the lower part). In other simulation modes, the ‘**Results**’ display can be toggled between **Individual run** or **Across-run summary** by clicking the appropriate radio button at top left of the results page.

By default, results are for viewing only although it is possible to edit them on-screen by checking the option **Allow editing** on the top right of the **Results** window. The editing option allows users to add notes to the result page, rearrange the data columns, or delete specific data columns for printing. The results can also be opened in MS Excel by clicking the button **Upload to Excel**, provided that either program is installed on the user’s computer.

Individual run display: The results begin with a summary of the year, location, and water management specified for the simulation run. Key predicted dates for emergence, silking, and maturity, yields and harvest index, summary weather statistics, and user-specified input settings are provided. Scrolling down on this page reveals the simulated daily model predictions for key

crop growth variables. If long-term runs were also simulated, results for the best yield, 75%, median, 25% percentile, and worst yield years can be displayed by selecting those runs from the pull-down list of the run selection box.



Predicted or measured variables in the daily output section are (first unit: English; second unit: Metric):

- Date month/day
- DOY day of year (ordinal day number)
- GDD cumulative growing degree days from emergence, GDD50F or GDD10C
- LAI leaf area index, ratio of leaf area to ground area
- Stover stover dry matter (leaves, stalks, cobs), lb/acre or kg/ha
- Grain grain dry matter, lb/acre or kg/ha
- Total total aboveground dry matter (leaves, stalks, cobs, grain), lb/acre or kg/ha
- Root total belowground dry matter (roots), lb/acre or kg/ha
- GAssi daily gross assimilation, lb CH₂O/acre/d or kg CH₂O/ha/d
- Resp daily total respiration (growth and maintenance respiration of all organs), lb CH₂O/acre/d or kg CH₂O/ha/d
- Rain rainfall, inches or mm
- Irri irrigation, inches or mm
- ETmax maximum predicted evapotranspiration for actual canopy coverage, inches or mm
- ETact predicted evapotranspiration for actual canopy and soil moisture status, inches or mm. If ETact < ETmax, crop moisture stress occurs.

TW or AW total or available soil water (depending on user's choice) for 0-1 ft, 1-2 ft, and >2 ft depths, in gravimetric or volumetric fraction (depending on user's choice)

Stress Crop water stress index (0=no stress; 1=full stress)

WtrLos Non-ET water losses as drainage, runoff, and canopy interception, inches or mm

Across-run summary: When this display option is selected, the results are summarized for different years selected from among the years simulated in the historical weather database. Simulated values for yield and various phenological stages are shown for the years with the maximum (best), 75% percentile, median (50% percentile), 25% percentile, and the minimum (worst) grain yield. The summary results table also displays the long-term mean and associated coefficients of variance (CV, in %) calculated from simulations of all years and of a single year chosen for comparison (only in **Single year with long-term runs** mode). Climate parameters that influence crop growth, development, and yield are also shown for each of year in this display.

Results of 2005 along with long-term runs using historical weather data from 1982 to 2005

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean
Best yield	1993	251	6.0	5.1	11.0	0.54	85	75	160	2789	55.7	77.4	66.5	66.1	67.0
75% percentile	1992	202	4.8	4.9	9.6	0.50	86	76	162	3049	53.1	78.6	65.8	65.8	65.9
Median yield	1982	149	3.5	5.1	8.6	0.41	82	68	150	2906	57.3	78.0	67.7	66.6	68.9
25% percentile	1995	91	2.2	3.6	5.7	0.37	85	54	139	2639	57.7	80.1	68.9	65.7	73.9
Worst yield	2002	0	0.0	3.8	3.8	0.00	71	52	123	2429	59.0	83.8	71.4	68.7	75.1
Long-term mean		136	3.2	4.5	7.7	0.39	77	60	137	2800	57.4	81.3	69.4	67.5	72.0
Long-term CV, %		53	53	24	32	36	8	16	10	6	3	3	2	5	5
Task-run	2005	21	0.5	5.5	6.0	0.08	73	54	127	2709	58.2	83.3	70.7	68.1	74.4

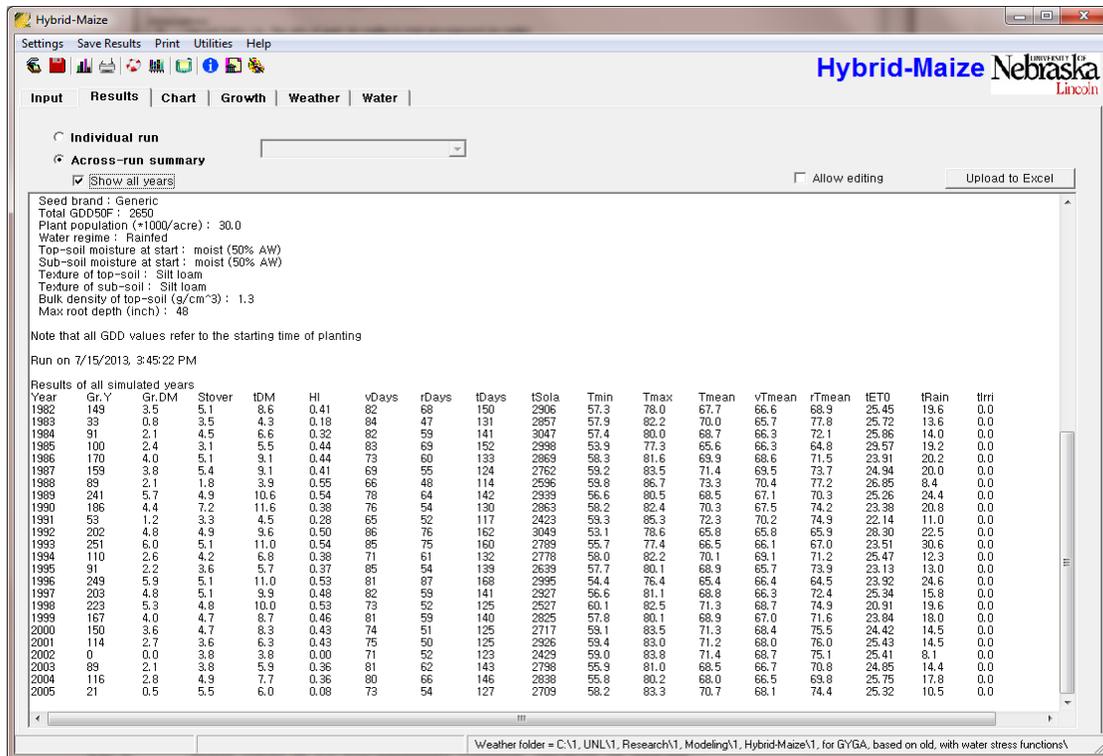
Overall probability of frost occurrence during grain filling (%): 8

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 aboveground 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 planting to silking (i.e., vegetative phase)
 rDays : days from silking to maturity (i.e., reproductive phase)
 V+R : days from planting to maturity
 tSola : total solar radiation from planting to maturity (MJ/m2) tRain : total rainfall from planting to maturity (inch)
 Tmin, Tmax, Tmean: mean daily Tmin, Tmax, Tmean, from planting to maturity (F)
 vTmean, rTmean : mean daily Tmean from planting 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 : Clay Center (SC), NE.wth
 Planting on (m/d) : 5/1 (DOY=121)
 Seed brand : Generic

Users can also choose to show results of all simulated years by checking the option **Show all years**. The results of all years are added to the lower part of the table.



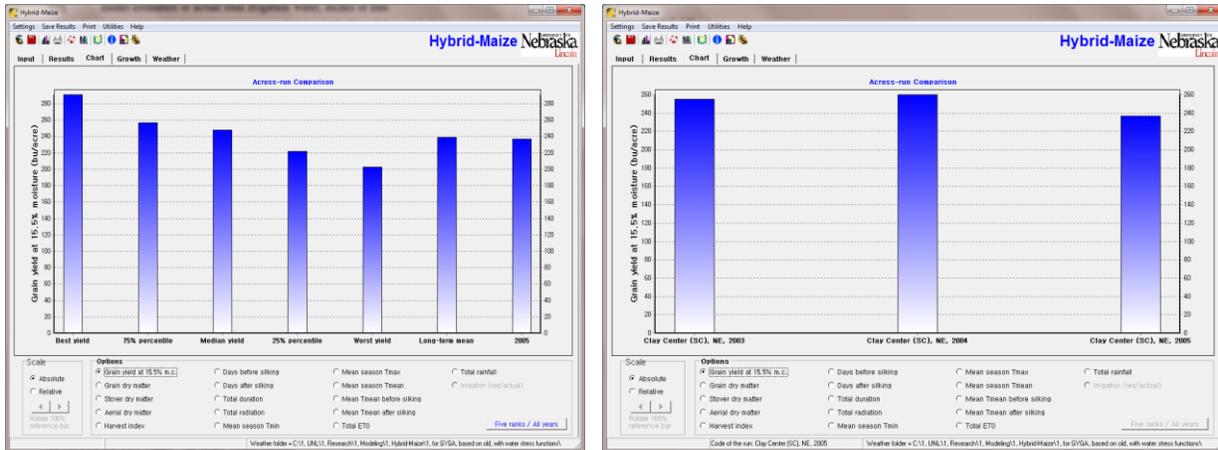
- Gr.Y grain yield at 15.5% moisture content, bu/acre or Mg/ha
- Stover stover dry matter (leaves, stalks, cobs), short ton/acre or Mg/ha
- tDM total aboveground dry matter (leaves, stalks, cobs, grain), short ton/acre or Mg/ha
- HI harvest index = ratio of grain dry matter to total aboveground dry matter
- vDays days from planting to silking (i.e., length of vegetative phase)
- rDays days from silking to maturity (i.e., length of reproductive phase)
- V+R days from planting to maturity (i.e., total length of growing period)
- tSola total solar radiation from planting to maturity, Langley or MJ/m²
- Tmin average daily minimum temperature from planting to maturity, °F or °C
- Tmax average daily maximum temperature from planting to maturity, °F or °C
- Tmean average daily mean temperature from planting to maturity, °F or °C
- vTmean average daily mean temperature from planting to silking, °F or °C
- rTmean average daily mean temperature from silking to maturity, °F or °C
- tETO total grass-referenced evapotranspiration from planting to maturity, inches or mm
- tRain total rainfall from planting to maturity, inches or mm
- tIrr model estimated or actual total irrigation water, inches or mm

NOTE: First unit: English, second unit: Metric option are selected under Settings → General Options.

2.4.2. Chart

This view of the results provides bar graphs of 17 variables. Depending on the simulation mode chosen, this can be a single bar graph for single-year run, a comparison of up to 6 different runs made sequentially, or the five ranked simulations and the long-term mean (with or without an extra

single year) in a long-term simulation. These bar graphs are useful for quick visual evaluation of model results, particularly comparisons of various model runs using different settings for input variables. The variables to choose from include grain and stover yields, total aboveground biomass, harvest index, duration from emergence to silking and from silking to physiological maturity, as well as the total season length and mean weather statistics for climate variables. The variable **Irrigation required** is disabled if there is a mixture of runs with and without the **Estimate Irrigation Water Requirement** option checked on the input page. Two examples are provided below:



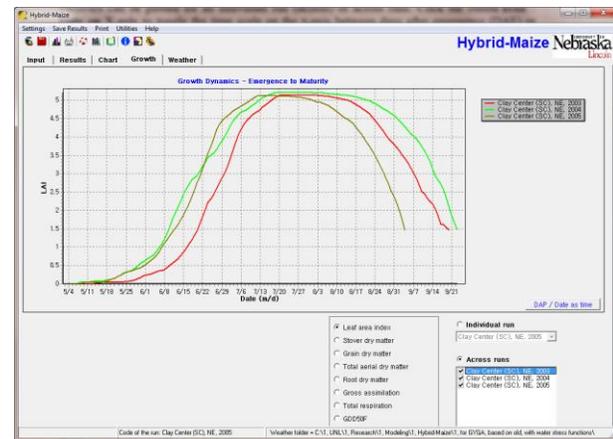
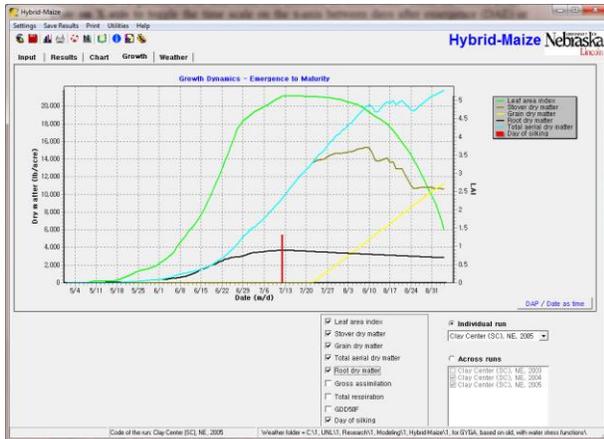
For simulations with long-term runs, results of all simulated years can be shown in the bar chart by clicking the **Five ranks / All years** toggle button.

2.4.3. Growth

This page displays the growth dynamics of the maize crop from emergence to maturity. Eight variables can be displayed: leaf area index (LAI), dry matter of stover, grain and total aboveground biomass, gross assimilation, total respiration, and GDD accumulation. Each of these variables can be plotted for an individual run (default) or across runs. Click the button **DAE / Date on X-axis** to toggle the time scale on the x-axis between days after emergence (DAE) or calendar date

Individual run: For single runs, most of the variables can be plotted simultaneously. The dry matter variables utilize the left axis, whereas other variables utilize the right axis. Because LAI has a different scale than the other three variables that use the right axis (i.e., assimilation, respiration and GDD), LAI cannot be plotted simultaneously with these other variables. A warning message will pop up when the user attempts to do so. The day of silking is marked by a short yellow bar and can be removed by deselecting it from the variable list.

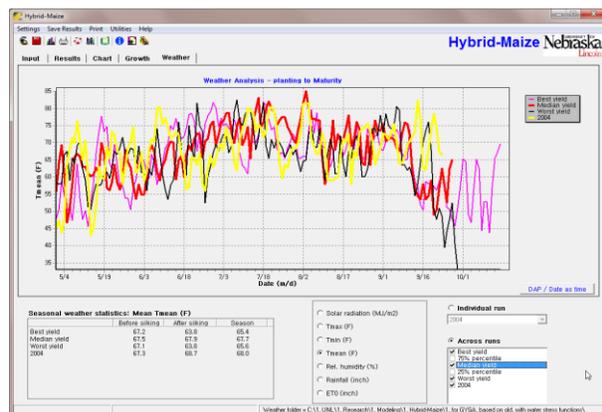
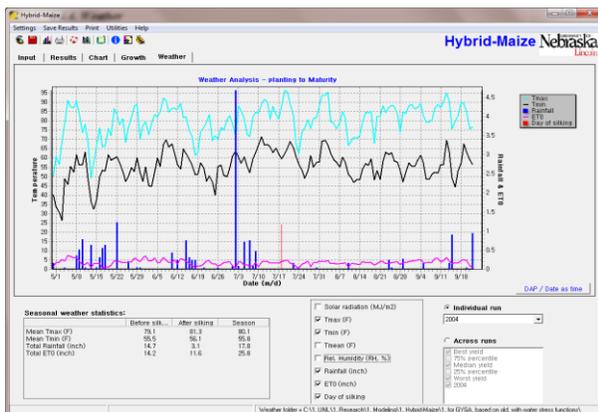
Across runs: One variable at a time is plotted for the selected runs.



When running in **Current season prediction** mode a vertical, a gray bar marks the end of the actual weather data (date on which the real-time simulation is done) and the start of the forecasting phase for the remainder of the growing season. Predictions are shown for the different ranks of all scenarios calculated as well as for the long-term median for the entire growth period (yellow line). Actual growth and the various forecasts shown can be compared with the long-term median growth to evaluate whether an ongoing growing season is above or below normal conditions (see section 3.4. for an example).

2.4.4. Weather

This page displays seven daily weather variables from emergence to maturity: solar radiation, maximum, minimum and mean daily temperatures, relative humidity, rainfall and reference evapotranspiration (ET0). In addition, seasonal weather statistics are also shown in a table for quick visual reference. This page works in the same manner as the graphics on **Growth** with regard to individual (default) and multiple simulation run comparisons, and the x-axis can be toggled between days after planting or calendar date. Due to the difference in scale, rainfall and ET0 use the right axis while the other five variables use the left axis when plotting for single runs. When running in **Current season prediction** mode a vertical, gray bar marks the end of the actual weather data (date on which the real-time simulation is done) and the start of the forecasting phase for the remainder of the growing season.



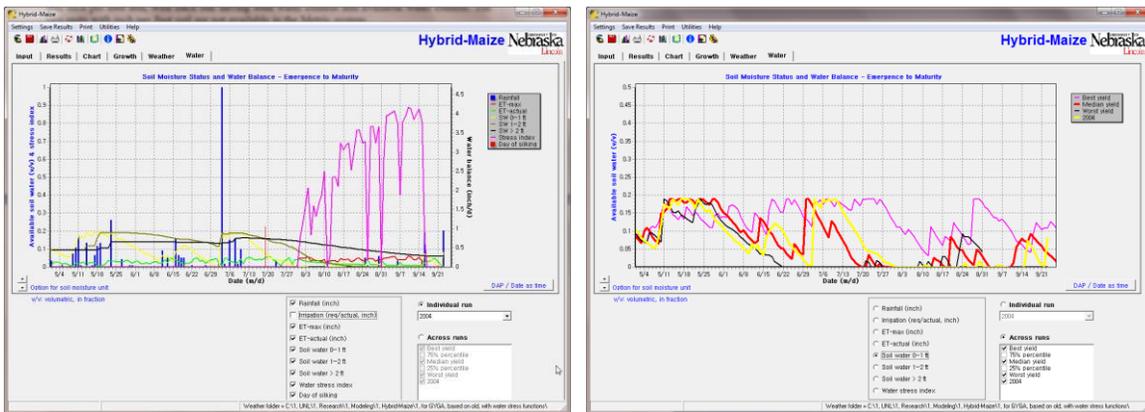
2.4.5. Water

This page only appears when running the model for **Rainfed/User-set irrigation** water conditions. It displays the seasonal dynamics of eight variables that define the water regime: rainfall, amount of irrigation (when there are irrigation events) or estimated irrigation requirement, maximum evapotranspiration (ET-max), actual evapotranspiration (ET-actual), soil water content at three depths, and water stress index for maize crop. Rainfall, irrigation, ET-max and ET-actual use the right axis, while soil water content and water stress index use the left axis. The water stress index is estimated by:

$$\text{Water stress index} = 1 - \text{ET}_{\text{actual}} / \text{ET}_{\text{max}}$$

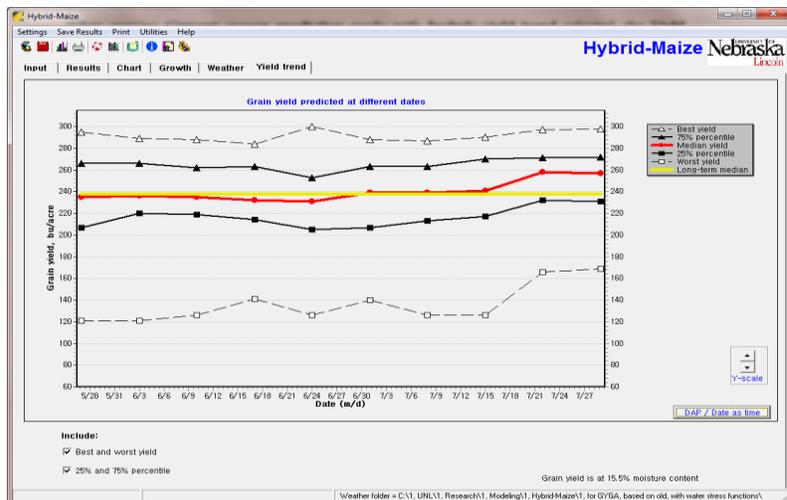
Any time the water stress index > 0, the crop is simulated to be under moisture stress, which is shown as bright pink line in the Water graphs on this page.

As on the **Growth** and **Weather** pages, these graphs can display multiple variables for individual years or one variable across runs. The X-axis can be toggled between DAP and date. For soil water content on the Y-axis, one of the six (in the English system) or four (in the Metric system) units can be selected by clicking the up-down arrows. The units are: volumetric, gravimetric, and inch per foot soil, with each one having total water content and available water content. The two units with inch per foot soil are not available in the Metric system.



2.4.6. Yield trend

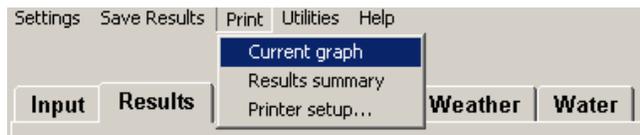
When running **Current season prediction** mode with **Include yield trend** selected, the **Yield trend** output tab becomes available, showing a graph of the yield forecasts made at previous dates during the ongoing growing season. The median yield forecast is shown as a bold red line and can be compared with the long-term median (bold yellow line) to assess whether there is a trend



towards normal or above-/below-normal yields in the current growing season. In addition, the minimum-maximum yield predictions and the 25% and 75% percentiles are shown. The area between the 25% and 75% percentiles represents the most likely yield range (50% of all predictions).

2.4.7. Saving and Printing Results

Numerical results can be loaded to MS Excel by clicking the button **Upload to spreadsheet** on the **Results** page, provided that either software program is already installed in the computer. After working in Excel, the user needs to specify an appropriate format when saving the results, because the results are still in plain text format. Alternatively, click on **Save Results** → **Numerical results** on the main menu, then specify a file name and folder to save the results. The default extension for the saved file is **.xls** for the sake of easy opening in Excel.



All graphs can be saved as one of three graphic formats: bitmap, Windows meta file and Windows enhanced meta file. Click on **Save Results** → **Graph on display** on the main menu, then specify a file name, a folder and select a format.

All output pages can also be printed. For individual run results, only the top part of the numerical results (i.e., the summary) will be printed. For across-run summaries, the whole page will be printed. To print, click **Print** on the main menu, and select the appropriate option. The user can select a printer or set up a printer through this menu. When printing graphs, the user may need to adjust the margins as needed.

3. Model Applications

The following sections provide selected examples of how to use the Hybrid-Maize model to investigate site yield potential and explore the outcome of various management options for specific situations. They are intended to illustrate the logical steps involved in such investigations, to provide general guidance on interpreting model outputs, and how the information produced can be utilized for exploring the predicted outcomes of different crop management options.

3.1. Analyzing Site Yield Potential under Full Irrigation Conditions

At least 10 years of daily long-term weather data are required to estimate the yield potential and its variability at a given site. Such analyses using Hybrid-Maize allows:

- Estimating the site yield potential under non-limiting growth conditions and investigating how year-to-year variation in weather causes higher or lower yield potential in specific years.
- Exploration of how yield potential is affected by the interactions between planting date and maize hybrid, which can help in selecting the best combination of planting date and hybrid for a given site.

Example: Exploring maize yield potential at a given site

This example uses the model to investigate how planting date and hybrid maturity interact to affect yield potential at the UNL East Campus Agronomy Research Plots. Irrigated maize is grown on a deep loess soil (silt loam) with an optimal supply of nutrients and no constraints to growth from pests or diseases. The standard recommendation is to plant corn between April 25 and May 5 at a 30-inch (0.76 m) row spacing and a final population of 32,000 plants/acre (79,000 plants/ha). Common hybrids grown in this environment require 2750 GDD50F (1530 GDD10C) from planting to maturity.

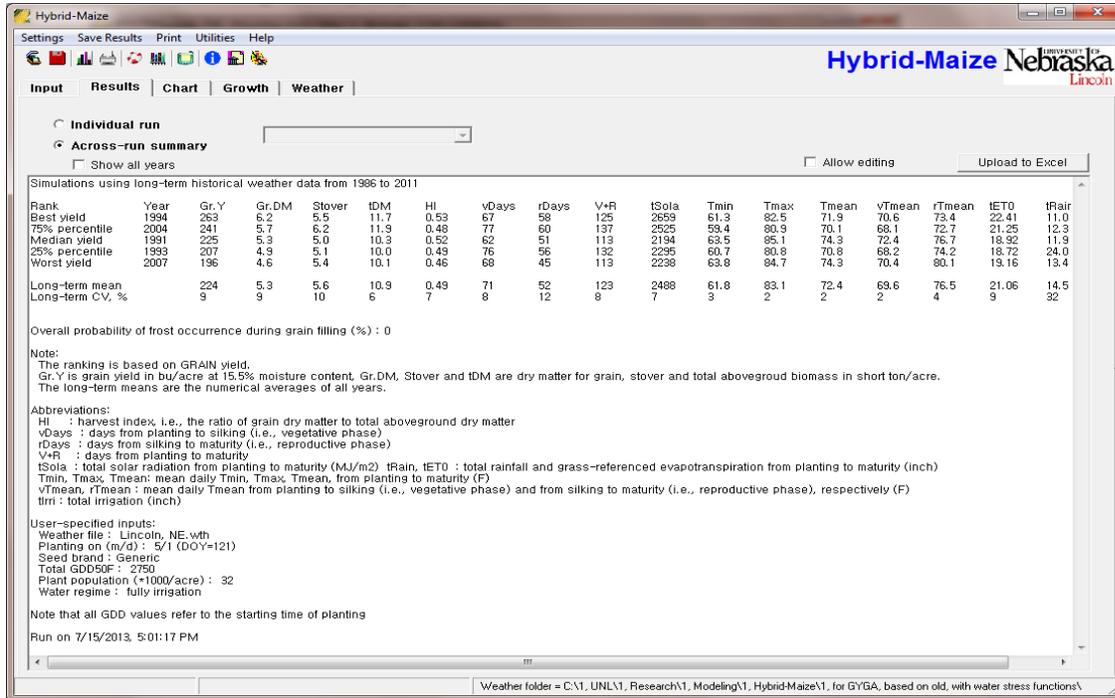
In exploring site yield potential with the model, it is important to note that yield potential can only be achieved under growth conditions that are ‘ideal’ with regard to both crop and soil management. Reasonable soil quality is also required. Although it is theoretically possible to overcome shallow 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 at the site 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, such as soil compaction, shallow soil depth, sandy soil texture, soil acidity or salinity, and so forth. In general, investigation of site yield potential using the Hybrid-Maize model is most appropriate for fields in which soil quality is relatively good and there are no obvious constraints to crop growth.

To begin the investigation of site yield potential at Lincoln, we select English units from **Settings** → **General options**, then the appropriate weather file (Lincoln, NE.wth) and choose the following settings:

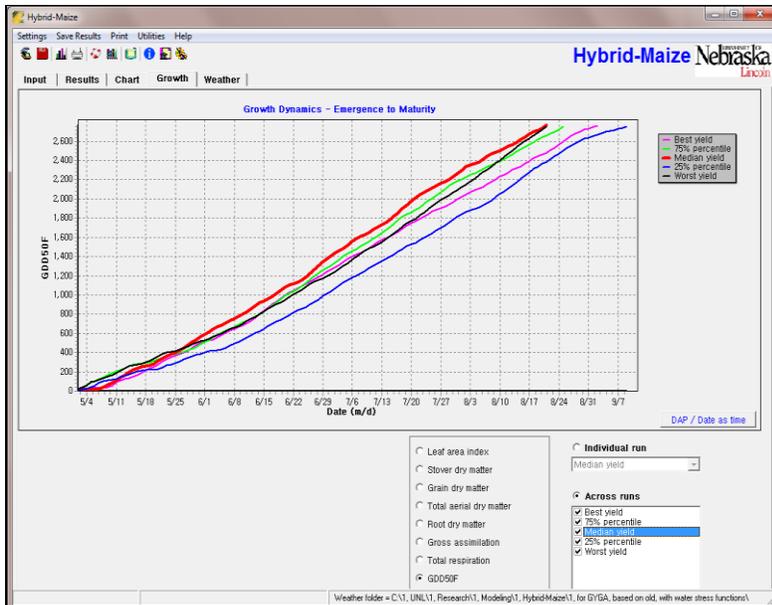
Simulation mode: Long-term runs, from 1986 to 2011
 Plant date: May 1
 Seed brand: Generic
 Maturity: GDD50F of 2750
 Plant population: 32 (x1000)
 Water: Full irrigation

Running this simulation results in the following Across-run summary table:

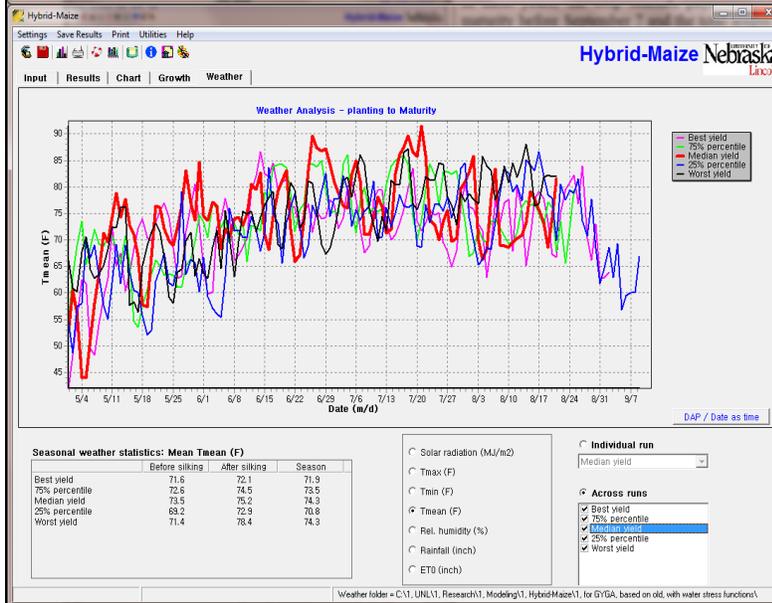
Lincoln, NE, Planting date: May 1, Hybrid: 2750 GDDF50:



The model predicts an average yield potential of about 224 bu/acre, but ranging from 196 to 263 bu/acre during the 26-yr period for which weather data are available. Risk of frost occurrence is reported to be zero because the crop reached full maturity before first frost in all the 26 years. Note that the average temperature during grain filling (**rTmean**) is in the 73 to 74 °F range for 50% of all years (25% to 75% percentile range), whereas the lowest yield occurred in 2007, when **rTmean** was 80 °F. In contrast, the highest yield occurred in 1994, when **rTmean** averaged only 73 °F, resulting in a long grain filling period (**rDays** = 58 days) and a total growth duration (**V+R**) of 125 days. Graphical analysis further illustrates that hot temperatures during grain filling may reduce yield potential under the currently recommended planting conditions:



In most years, the crop reached physiological maturity before September 7 and the total length of the grain filling period was typically less than 52 days (rDays). However, in the year with the highest yield, GDD accumulation proceeded slowly after silking due to cooler temperatures ($rT_{mean} = 73^{\circ}F$), resulting in a long grain filling period (58 d).



Weather data analysis indicates that nighttime temperatures (T_{min}) cool off significantly after August in most years.

Consequently, the question arises of whether yield potential in most years could be increased by shifting grain filling into a cooler period. This could be accomplished by planting somewhat later or by choosing a hybrid with longer growth duration or a combination of both.

We first explore a later planting date of May 10, but keeping the same hybrid ($GDD50F=2750$), which would initiate grainfilling later and extend it into September when nighttime temperatures are cooler.

Simulation mode: Long-term runs, from 1986 to 2011
 Plant date: May 10
 Seed brand: Generic
 Maturity: $GDD50F$ of 2750
 Plant population: 32
 Water: Full irrigation

Lincoln, NE, Planting date: May 10, Hybrid: 2700 GDDF50:

Simulations using long-term historical weather data from 1986 to 2011

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRair
Best yield	1992	276	6.5	5.4	11.9	0.55	75	73	148	2758	57.5	79.8	68.6	68.5	68.8	21.27	17.6
75% percentile	1997	242	5.7	5.1	10.9	0.53	71	55	126	2541	61.1	82.7	71.9	69.6	74.9	21.49	7.9
Median yield	2005	224	5.3	5.1	10.4	0.51	62	49	111	2376	63.8	85.8	74.8	72.2	78.1	20.94	14.4
25% percentile	2011	212	5.0	4.7	9.7	0.52	66	47	113	2021	64.4	84.3	74.3	70.9	79.1	16.94	17.7
Worst yield	2007	195	4.6	5.3	9.9	0.47	64	46	110	2204	64.7	85.6	75.1	71.6	80.0	18.90	11.2
Long-term mean		228	5.4	5.4	10.8	0.50	66	53	119	2394	62.7	84.0	73.4	71.3	76.0	20.29	14.1
Long-term CV, %		9	9	11	7	7	8	14	9	8	3	3	3	2	4	8	33

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

The model predicts a long-term average yield potential of 228 bu/acre, ranging from 195 to 276 bu/acre during the 26-yr period for which weather data are available. Risk of frost occurrence is still zero. Overall, planting the same hybrid 10 days later predicts an increase of 4 bu/acre yield potential, which results from a small increase in the grain filling period (long-term average rDay is 53 for the May 10 planting versus 51 for the May 1 planting).

Next, we study the effect of growing a longer maturity hybrid. Hybrids with a relative maturity rating of about 119 days and a GDD50F of up to 2860 are available for this environment. Assuming the original planting date of May 1, we change our model inputs to:

Simulation mode: Long-term runs, from 1986 to 2011
 Planting date: May 1
 Maturity: GDD50F of 2860
 Plant population: 32
 Water: Full irrigation

Lincoln, NE, Planting date: May 1, Hybrid: 2860 GDDF50:

Simulations using long-term historical weather data from 1986 to 2011

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRair
Best yield	1992	289	6.8	5.7	12.5	0.55	80	76	156	2943	57.0	79.6	68.3	67.9	68.8	23.24	17.7
75% percentile	2009	262	6.2	5.4	11.6	0.54	74	67	141	2565	59.5	80.9	70.2	69.3	71.2	20.59	12.0
Median yield	1999	240	5.7	5.3	10.9	0.52	77	53	130	2473	62.2	81.9	72.0	68.5	77.2	21.10	16.4
25% percentile	2011	223	5.3	5.0	10.3	0.51	73	49	122	2221	63.1	83.6	73.4	69.5	79.1	18.86	17.7
Worst yield	1988	209	5.0	7.6	12.6	0.39	61	48	109	2637	64.7	87.7	76.2	73.6	79.5	24.59	5.9
Long-term mean		241	5.7	5.7	11.4	0.50	73	56	129	2579	61.7	83.0	72.4	69.8	75.9	21.81	15.4
Long-term CV, %		9	9	11	6	8	8	14	9	7	3	3	3	2	4	8	31

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

The model predicts an average yield potential of about 241 bu/acre, with a range of 209 to 289 bu/acre, which represents a 13 bu/acre (6%) increase compared to planting a 2750 GDD hybrid. Note how the average length of grain filling has now increased by four days to 56 days, which is the major reason for the increased yield compared to simulations with the earlier maturing hybrid.

It can then be asked whether growing a hybrid with longer maturity in combination with a later planting date could further increase yield potential. We change the model inputs to:

Simulation mode: Long-term runs, from 1986 to 2011
 Planting date: May 10
 Seed brand : Generic
 Maturity: GDD50F of 2860
 Plant population: 32
 Water: Full irrigation

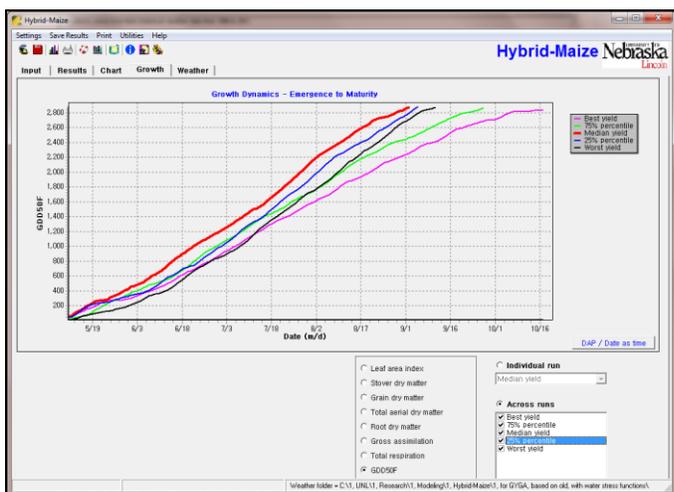
Lincoln, NE, Planting date: May 10, Hybrid: 2860 GDDF50:

Simulations using long-term historical weather data from 1986 to 2011

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+r	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tET0	tRair
Best yield	1992	289	6.8	5.5	12.4	0.55	78	83	161	2895	56.1	78.5	67.3	68.6	66.2	22.29	19.1
75% percentile	2009	264	6.3	5.2	11.4	0.55	70	71	141	2488	59.5	81.0	70.2	70.5	70.0	19.95	12.2
Median yield	1987	242	5.7	5.7	11.4	0.50	62	54	116	2606	63.8	85.4	74.6	73.2	76.2	21.67	13.8
25% percentile	2001	225	5.3	6.9	12.2	0.44	69	50	119	2602	63.7	84.5	74.1	71.1	78.3	22.40	11.6
Worst yield	1995	212	5.0	5.5	10.5	0.48	74	51	125	2423	62.6	83.3	72.9	69.7	77.5	21.02	9.6
Long-term mean		244	5.8	5.6	11.3	0.51	67	57	125	2491	62.5	83.8	73.1	71.5	75.3	21.07	14.9
Long-term CV, %		9	9	11	6	8	8	17	11	8	4	3	3	2	5	8	33

Overall probability of frost occurrence during grain filling (%) : 4

Planting the 119-d hybrid on May 10 further increases the average yield potential to 244 bu/acre and also narrows the overall range to 212~289 bu/acre. The average length of the grain filling period has increased slightly to 57 days. Note, however, that there is now a small risk of frost occurrence before reaching maturity (4%, i.e., frost damage occurred in once in the 26 years for which data are available).



Under this scenario, physiological maturity is reached after September 7 in most years, which prolongs the grainfilling period because of the cooler temperature. In the median yield scenario, the crop reaches maturity on September 11. The latest maturity date is October 16 for the 'Best yield' scenario. Note that planting the full-season hybrid on May 10 has also made the patterns of GDD accumulation more uniform across most years (runs).

Additional combinations of planting dates, hybrid choice, and plant population can be explored, but other factors must be considered in selecting the most appropriate combination. For example, the model suggests that planting the 119-d hybrid on May 30 may further increase yield potential at Lincoln to an average of 259 bu/acre, but at the cost of increased frost risk (16%) and reaching maturity only in later September or early October. This may increase occurrence of pests and the long grain-filling period (67 days) could increase the risk of stalk rot and lodging. Harvest losses and grain drying costs should also be considered. In summary, although the model predicts that small gains in yield potential may result from planting dates in late May or use of a hybrid with maturity longer than GDD50F of 2860, such a tactic would increase yield variability and drying costs, resulting in less profit and greater risk, which are not acceptable outcomes.

3.2. Analyzing Water Requirements for Achieving Yield Potential

If at least 10 years of daily long-term weather data are available, Hybrid-Maize can be used to:

- Quantify the attainable water-limited yield (rainfed) and its variability from year to year to assess risks and potential benefits from investing in irrigation, and
- Estimate average irrigation water requirements and the year-to-year variability in water requirements for achieving optimal growth.

Example: Irrigation water requirements for growing maize in southwest Nebraska

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 (500 mm), but is highly variable from year to year. Rainfall during the growing season averages 10 inches (250 mm). Standard practices on irrigated corn are: planting around May 1 at 30-inch (0.76 m) row spacing and a final population of 30,000 plants/acre (74,000 plants/ha). Common hybrids grown in this environment require 2670 GDD50F (1480 GDD10C) from planting to maturity. A weather station representing that area is located at Champion, NE, with daily climate data available for the 1982-2004 period in the Hybrid-Maize climate database. 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.

We select English units from **Settings → General options**, then the appropriate weather file (Champion, NE.wth), and choose the following model settings for a first run to assess the overall site yield potential:

Simulation mode: Long-term runs, from 1982 to 2004
 Planting date: May 1
 Seed brand: Generic
 Maturity: GDD50F of 2670
 Plant population: 30
 Water: Full irrigation

Champion, NE, Planting date: May 1, Hybrid: 2670 GDDF50, irrigated maize:

Simulations using long-term historical weather data from 1982 to 2004															
Rank	Year	Gr.Y	Gr,DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean
Best yield	1996	296	7.0	5.8	12.8	0.55	86	85	171	3326	51.5	77.4	64.5	65.4	63.5
75% percentile	1992	259	6.1	6.9	13.0	0.47	89	80	169	3377	49.0	79.1	64.1	65.1	62.9
Median yield	1984	239	5.7	7.3	13.0	0.44	84	60	144	3390	53.6	83.2	68.4	65.9	71.8
25% percentile	1982	216	5.1	7.5	12.6	0.41	95	69	164	3548	50.9	77.1	64.0	64.3	63.6
Worst yield	1995	180	4.3	6.5	10.8	0.39	96	48	144	2938	52.6	80.8	66.7	63.8	72.4
Long-term mean		240	5.7	6.8	12.5	0.45	83	63	145	3151	53.0	82.6	67.8	66.3	70.0
Long-term CV, %		12	12	10	6	11	8	16	9	7	3	4	3	2	6

Overall probability of frost occurrence during grain filling (%) : 39

Average yield potential for the selected planting conditions is 240 bu/acre, but with a very wide range (180 to 296 bu/acre) and a 39% probability of premature frost. The grain filling period is relatively long (average of 63 days) due to cooler average temperatures than at Lincoln (see section 3.1.), particularly cooler nighttime temperature during grain filling (rTmean averages 70 °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.

To illustrate the severity of water stress in this region, we simulate the water-limited yield without irrigation, based on actual rainfall and ET data in the weather file. Model settings include:

Simulation mode: Long-term runs, from 1982 to 2004
 Planting date: May 1
 Maturity: GDD50F of 2670
 Plant population: 30

Water: Rainfed/User-set irrigation (no entries in irrigation schedule)
 Soil: Rooting depth: 60 inches (152 cm)
 Soil texture: silt loam for both topsoil and subsoil
 Topsoil moisture at planting: 100% of available water
 Subsoil moisture at planting: 100% of available water
 Topsoil bulk density: loam, 1.3 g cm⁻³

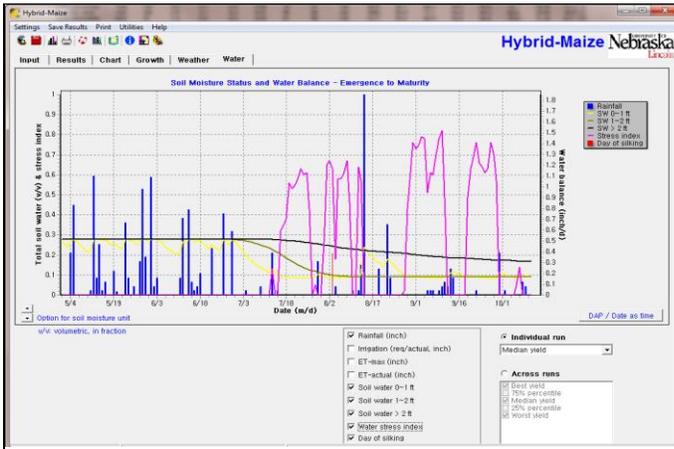
Champion, NE, Planting date: May 1, Hybrid: 2670 GDDF50, rainfed maize:

Simulations using long-term historical weather data from 1982 to 2004

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tET0	tRain
Best yield	1996	249	5.9	5.0	10.9	0.54	86	85	171	3326	51.5	77.4	64.5	65.4	63.5	28.40	20.9
75% percentile	1998	133	3.2	3.7	6.9	0.46	79	57	136	3074	54.7	84.2	69.4	66.8	73.1	29.26	11.1
Median yield	1982	106	2.5	3.7	6.2	0.41	95	69	164	3548	50.9	77.1	64.0	64.3	63.6	29.64	16.9
25% percentile	2003	78	1.9	2.5	4.3	0.43	81	58	139	3117	53.2	84.9	69.0	66.6	72.4	31.26	6.3
Worst yield	1984	35	0.8	3.2	4.0	0.21	84	60	144	3390	53.6	83.2	68.4	65.9	71.8	32.63	5.7
Long-term mean		108	2.6	3.8	6.3	0.40	83	62	145	3150	53.0	82.6	67.8	66.3	70.1	30.79	11.6
Long-term CV, %		40	41	31	29	23	8	16	9	7	3	4	3	2	5	7	39

Overall probability of frost occurrence during grain filling (%) : 39

Without irrigation, attainable yield averages 108 bu/acre, but may be as little as 35 bu/acre or as much as 249 bu/acre. Note that long-term average rainfed yield at this site is 132 bu/acre less than the average yield potential with full irrigation as shown in the previous **Results** table. For the different ranks (i.e. years) shown in the above table of **Results** for the rainfed simulations, rainfall from planting to maturity (tRain) varied from 5.7 inches for the worst yield scenario (in 1984) to 20.9 inches for the maximum rainfed yield observed in 1996.



Rainfall, soil moisture in three depths, and the crop water stress index for the year with the simulated median rainfed yield (1982) during the 1982-2004 period. Note the uneven rainfall distribution and how water stress occurs throughout the crop growth period although it is most severe during grain filling.

To overcome the typical water deficit that occurs in this region, irrigation is needed at critical growth stages. We can let the model simulate 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 32 mm (1.25 inches) by going to **Settings** → **Parameter settings** → **Management**:



NOTE: Due to rounding errors, actual amount of irrigation may slightly exceed this value in the summary report.

Other model settings for this simulation run are:

Simulation mode: Long-term runs, from 1982 to 2004

Planting date: May 1
 Maturity: GDD50F of 2670
 Plant population: 30
 Water: Full irrigation, with *Estimate irrigation water requirement*
 Soil: Rooting depth: 60 inches (152 cm)
 Soil texture: silt loam for both topsoil and subsoil
 Topsoil moisture at planting: 100% of available water
 Subsoil moisture at planting: 100% of available water
 Topsoil bulk density: loam, 1.3 g cm⁻³

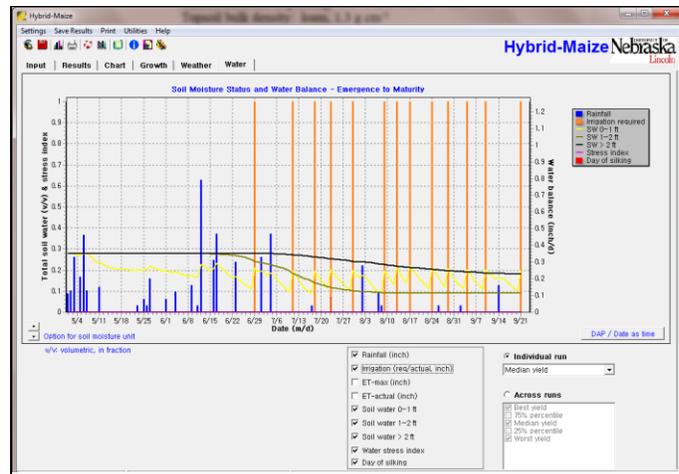
Champion, NE, Planting date: May 1, Hybrid: 2670 GDFF50, irrigated maize:

Simulations using long-term historical weather data from 1982 to 2004

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRain	tIrr
Best yield	1996	296	7.0	5.8	12.8	0.55	86	85	171	3326	51.5	77.4	64.5	65.4	63.5	28.40	20.9	3.8
75% percentile	1992	259	6.1	6.9	13.0	0.47	89	80	169	3377	49.0	79.1	64.1	65.1	62.9	37.26	17.6	7.6
Median yield	1984	239	5.7	7.3	13.0	0.44	84	60	144	3390	53.6	83.2	68.4	65.9	71.8	32.63	5.7	16.4
25% percentile	1982	216	5.1	7.5	12.6	0.41	95	69	164	3548	50.9	77.1	64.0	64.3	63.6	29.64	16.9	8.8
Worst yield	1995	180	4.3	6.5	10.8	0.39	96	48	144	2938	52.6	80.8	66.7	63.8	72.4	27.67	13.2	8.8
Long-term mean		240	5.7	6.8	12.5	0.45	83	63	145	3151	53.0	82.6	67.8	66.3	70.0	30.80	11.6	10.5
Long-term CV, %		12	12	10	6	11	8	16	9	7	3	4	3	2	6	7	39	30

Overall probability of frost occurrence during grain filling (%) : 39

Simulation output for yield and growth is the same as in the first run under full irrigation, but an additional column is available on the far right, which reports the total irrigation water requirement (tIrr). On average, 10.5 inches of water is required to achieve stress-free growing conditions, but the water requirement varies from about 3.8 to 16.4 inches in various years. The variation in water requirement can be assessed by looking at ‘tIrr’ within individual rank years.



Rainfall, soil moisture in three depths, and required irrigation events for the year with the simulated median yield (1984) during the 1982-2004 period. Beginning in late June, 13 irrigations of about 1.27 inches each are required to meet the total water demand of 16 inches in that year, more or less in weekly intervals. Note that soil moisture in the subsoil declines steadily even with irrigation.

Because water needs are difficult to predict in advance, the only way of fine-tuning irrigation in an ongoing growing season is through monitoring rainfall and soil moisture or using Hybrid-Maize in the in-season yield forecasting mode (see section 3.4.). Fortunately, there are well established methods for predicting water use, soil water depletion, and the need for irrigation based on relatively straightforward soil water balance models and estimated ET (Eisenhauer and Fischbach, 1984; Klocke et al., 1991; Yonts and Klocke, 1997; Benham, 1998) and we recommend using these approaches for scheduling irrigations.

3.3. Analysis of Yield Determinants in Past Cropping Seasons and Cropping Systems

Data for a single year can be used to conduct an in-depth analysis of a past growing season to help identify factors that affected yield potential; to estimate the size of the yield gap in a particular field (see section 1); and to explore alternative management scenarios that might contribute to increased yield, for example, with regard to planting date and hybrid maturity. This application is also useful for analyzing research data collected in field experiments. In most cases, the hybrid grown is known and actual dates of crop emergence and silking may have been observed in the field. An exact date of when physiological maturity was reached may or may not be known. Actual irrigation schedules can be entered. Location-specific soil physical properties may have been measured and can be entered under **Settings** → **Parameter settings** → **Soil & Field**.

Example: Investigation of potential factors that may have caused low yields in an irrigated corn field

2002 was a dry and hot year in many parts of Nebraska. In some cases, irrigation may have been insufficient to keep up with the high crop use and we wish to gain a better understanding of how much yield may have been lost due to water stress. Our site is a field on a loamy sand in Northeast Nebraska, near O’Neill. Rainfall during the growing season averages 12 inches (305 mm). Standard practices at this site include planting corn around May 1 at a 30-inch (0.76 m) row spacing and a final population of 30,000 plants/acre (74,000 plants/ha). Common hybrids grown in this environment require 2570 GDD50F (1430 GDD10C) from planting to maturity. The best weather station representing that area is located at O’Neill, NE, with daily climate data available for the 1985 to 2005 period. In a first step, we quickly compare yield potential in 2002 with all other years for which climate data are available. Model settings for this are:

Simulation mode: Single year, 2002, check ‘With long-term runs’
 Plant date: May 1
 Maturity: GDD50F of 2570
 Plant population: 30
 Water: Full irrigation

O’Neill, NE, Planting date: May 1, Hybrid: 2570 GDDF50, irrigated maize, optimal conditions

Results of 2002 along with long-term runs using historical weather data from 1985 to 2005																	
Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRain
Best yield	1986	281	6.6	5.3	12.0	0.55	79	96	165	3285	53.0	77.4	65.2	66.7	63.8	27.07	21.9
75% percentile	1996	244	5.8	5.3	11.1	0.52	89	75	164	3247	52.6	75.6	64.1	64.2	64.0	24.84	14.9
Median yield	1988	215	5.1	8.2	13.3	0.38	72	54	126	3044	56.4	84.4	70.4	68.1	73.5	28.39	8.9
25% percentile	2000	206	4.9	5.7	10.6	0.46	79	50	129	2775	57.2	82.5	69.9	66.6	75.0	26.86	8.9
Worst yield	1990	130	3.1	7.1	10.2	0.30	100	46	146	3145	48.4	80.0	64.2	62.8	67.3	26.58	14.2
Long-term mean		220	5.2	5.9	11.2	0.47	84	60	143	2950	54.6	79.8	67.2	65.7	69.6	26.28	13.6
Long-term CV, %		17	16	15	8	15	9	18	9	7	5	3	3	2	6	7	30
Task-run	2002	210	5.0	4.7	9.7	0.51	75	48	123	2694	57.6	83.4	70.5	66.9	76.1	27.76	8.5

Overall probability of frost occurrence during grain filling (%): 48

Simulated yield potential in 2002 was 210 bu/acre, which was significantly below the long-term average of 220 bu/acre with similar management. Average growing season temperature in 2002 was 71 °F or 4 °F above the long-term average. Only 8.5 inches rain fell from planting to maturity in the 2002 (**tRain**), indicating high demand for irrigation. At issue is whether actual irrigation in 2002 kept up with the higher demand. The farmer at this site started irrigating on June 30. He irrigated weekly (1.2 inches each time) until late July, but stopped irrigation thereafter because

some rain fell in August. We enter all this information on the main page and then simulated the 2002 year in more detail:

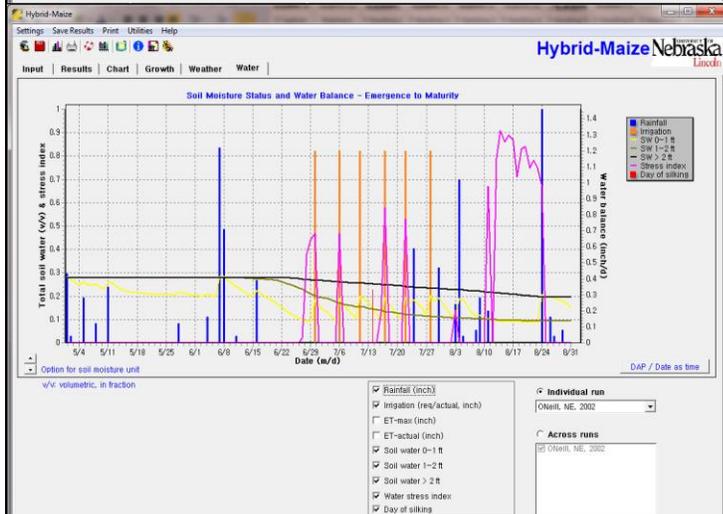
Run 1: Detailed model inputs for the 2002 growing season. Note how the date of emergence, the irrigation schedule, and soil properties were entered and that the option ‘with long-term runs’ is unchecked because we are only interested in evaluating the 2002 year.

Predicted values:

Grain yield: 139 bu/acre

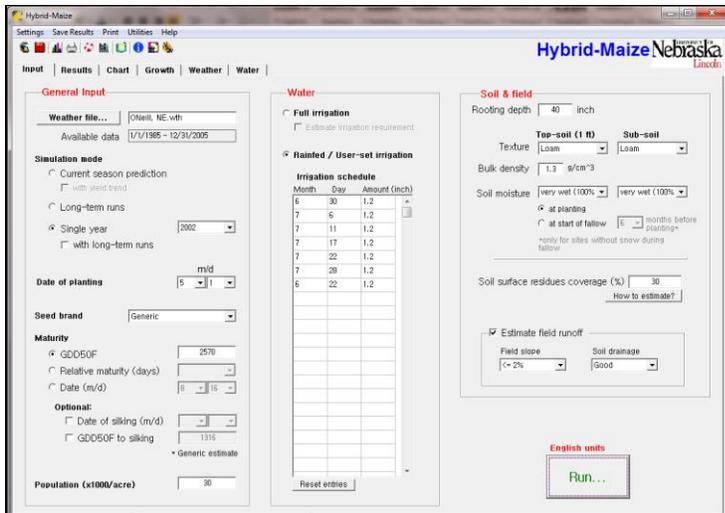
Total aboveground dry matter: 7.3 short tons/acre

Harvest index: 0.45



Run 1: Rainfall and irrigation events and their effect on predicted dynamics of soil moisture in three depths and the water stress index. Note the long period with no rainfall from June 17 to July 24 and the occurrence of crop water stress (pink line) during early growth in late June and during grain filling in late August.

Based on the actual irrigation management, the predicted grain yield is 139 bu/acre. However, a short period of moisture stress affected late vegetative growth in June and a more significant yield reduction may have occurred due to lack of irrigation in mid to late August because the assumption that rainfall in the first half of August was sufficient to match crop needs until maturity was not correct. We test this hypothesis by conducting two more runs of the 2002 data: first we add an earlier irrigation event on June 22 (**Run 2**), and then we add an additional, late irrigation in August (**Run 3**).



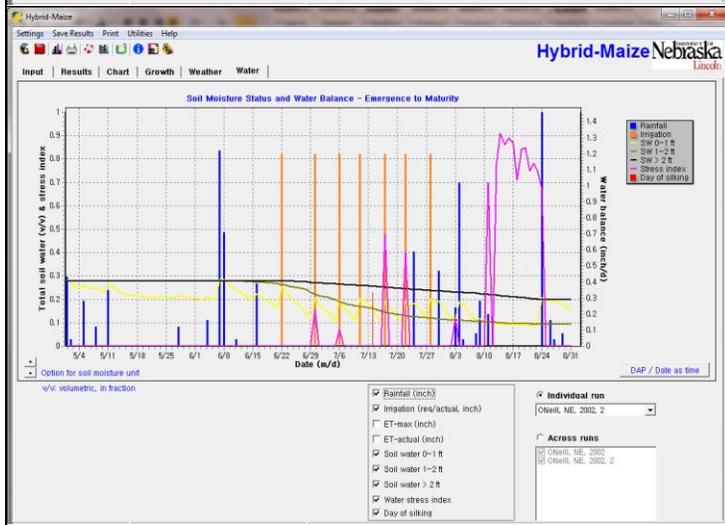
Run 2: Detailed model inputs for the 2002 growing season. Note how an additional irrigation event has been entered on June 22.

Predicted values:

Grain yield: 143 bu/acre

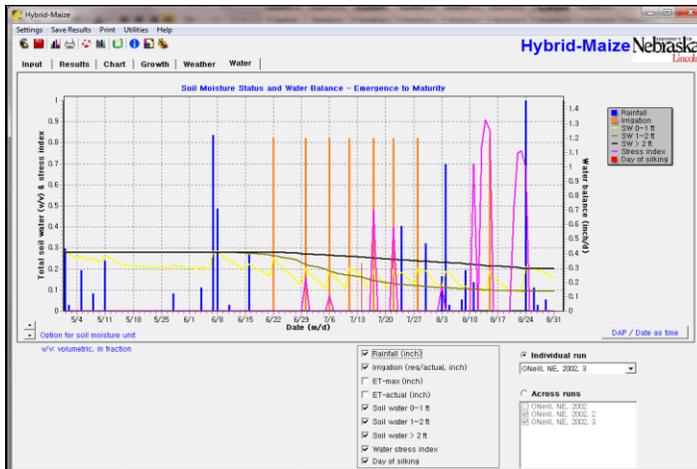
Total aboveground dry matter: 7.8 short tons/acre

Harvest index: 0.43



Run 2: Rainfall and irrigation events and their effect on predicted dynamics of soil moisture in three depths and the water stress index.

Starting the irrigation one week earlier in June increased crop biomass from 7.3 to 7.8 short tons/acre, and increase yield by 4 bu/acre (139 vs. 143 bu/acre). Note that nearly all water stress during vegetative growth was avoided by starting to irrigate on June 22, but the drought stress in late August remained and was the most likely cause of yield loss. Thus, we add one more irrigation event on August 15 and obtain:

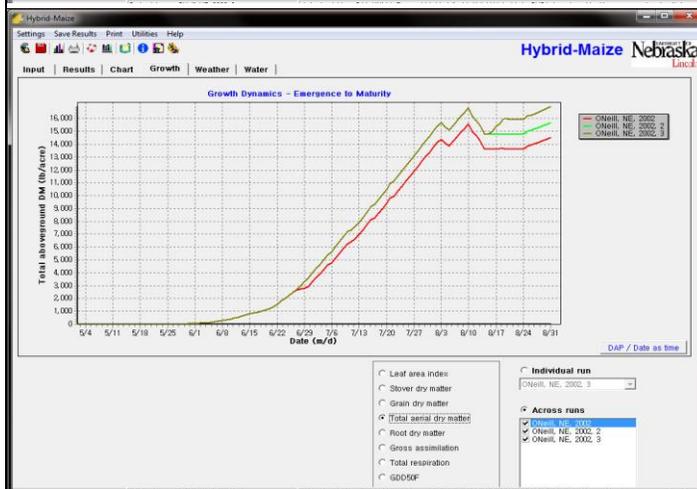


Run 3: Rainfall and irrigation events and their effect on predicted dynamics of soil moisture in three depths and the water stress index. An additional irrigation event was entered on August 15.

Predicted values:
Grain yield: 168 bu/acre

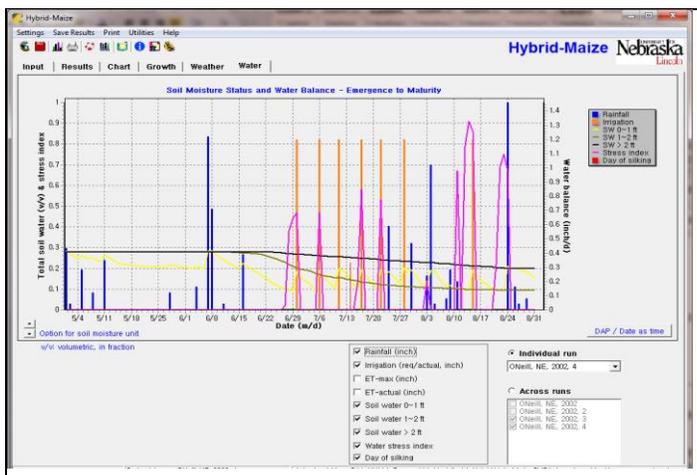
Total aboveground dry matter: 8.5 short tons/acre

Harvest index: 0.47



Runs 1, 2 and 3: Simulated total aboveground biomass for all three runs. Note how the late irrigation in run 3 increased biomass accumulation (grain filling) during the last two weeks of grain filling, resulting in significant yield increase as compared to runs 1 and 2.

An additional late irrigation on August 15 increased grain yield from 143 to 168 bu/acre. Nearly all water stress during vegetative and reproductive growth was avoided. Since Run 3 included the June 22 irrigation, the question arises whether this early irrigation was necessary. To test this hypothesis, we conduct another run with all irrigations except the June 22 irrigation:



Run 4: Rainfall and irrigation events and their effect on predicted dynamics of soil moisture in three depths and the water stress index. No irrigation on June 22, but late irrigation on August 15 was kept.

Predicted values:
Grain yield: 165 bu/acre

Total aboveground dry matter: 7.9 short tons/acre

Harvest index: 0.49

Although the delay of irrigation until June 30 caused a brief period of water stress in late June, this had only a small impact on the simulated yield, which was 165 bu/acre.

This example demonstrates how important it is to monitor soil moisture or predict crop water needs throughout the entire growing season. It also shows that irrigating more than what was done in Run 3 would have been inefficient because no further yield increase was possible, as confirmed by the simulated results of an extra run with only additional August 15 irrigation but without the June 22 irrigation. Over irrigation would incur extra costs and may increase the risk of nitrate leaching on this soil, which could cause N deficiency and yield loss. The table below provides a comparison of corn yield and irrigation water use efficiency (IWUE) under different irrigation schemes in each run. IWUE is calculated as the yield gain per unit of irrigation water compared with rainfed conditions.

Irrigation scheme	Water input (inch)			Yield (bu/acre)	IWUE (bu/inch)
	rainfall	irrigation	total		
Rainfed	8.5	0	8.5	77	
Farmer irrigation (Run 1)	8.5	6.0	14.5	139	10.3
Additional 6/22 irrigation (Run 2)	8.5	7.2	15.7	143	9.2
Additional 6/22 and 8/15 irrigations (Run 3)	8.5	8.4	16.9	168	10.8
Additional 8/15 irrigation (Run 4)	8.5	7.2	15.7	165	12.2

Because water needs are difficult to predict, we recommend monitoring rainfall and soil moisture and using other established methods (Eisenhauer and Fischbach, 1984; Klocke et al., 1991; Yonts and Klocke, 1997; Benham, 1998) in combination with a model such as Hybrid-Maize for making decisions on irrigation scheduling.

3.4. Current Season Simulation of Maize Growth and Yield Forecasting

Corn production fluctuates significantly from one year to another due to temporal and spatial variation in weather conditions, soils, and the availability of irrigation water. The interaction of these factors makes it difficult to make timely and reliable predictions of corn yield and total production in both irrigated and dryland fields. Forecasting of crop yields is important for several reasons. First, producers can use such predictions for evaluating drought risks, helping to guide in-season adjustments to crop management, and to provide additional information to crop marketing decisions. Major grain users, such as feedlots and ethanol plants, can utilize yield forecasts to refine grain purchasing plans. Politicians, insurance agencies and financial institutions may wish to predict farm income. At present, most information on expected maize production in the U.S. is obtained from the USDA crop reports, which are based on monitoring systems that mainly rely on field scouting, climatic data and empirically defined indices. Use of a crop simulation model provides an additional source of information. However, it is important to note that predictions from crop models, like other forecasting approaches, should not be considered infallible and will deviate from actual values. Therefore, crop model predictions should be used along with other sources of information and common sense and experience to guide management and marketing decisions. **Do not make decisions solely upon the basis of predictions from the Hybrid-Maize model!**

Running the Hybrid-Maize model in ‘**Current season prediction**’ mode allows real-time, in-season simulation of maize growth up to the date of the simulation run, and forecasting of the possible outcomes in final yield based on historical weather data for the remaining crop growth

period. The prediction is based on the up-to-date weather data of the current growing season, supplemented by the previously collected historical weather data for the site (or the nearest weather station) for the remainder of the season. When the option **Include yield trend** is included, yield forecasts will be made for each specified interval since emergence (or shortly after that) until the last day of the current season in the weather file. The results will be plotted in the output page **Yield trend**. Knowing predicted yield trends for the current season helps adjusting water and fertilizer management.

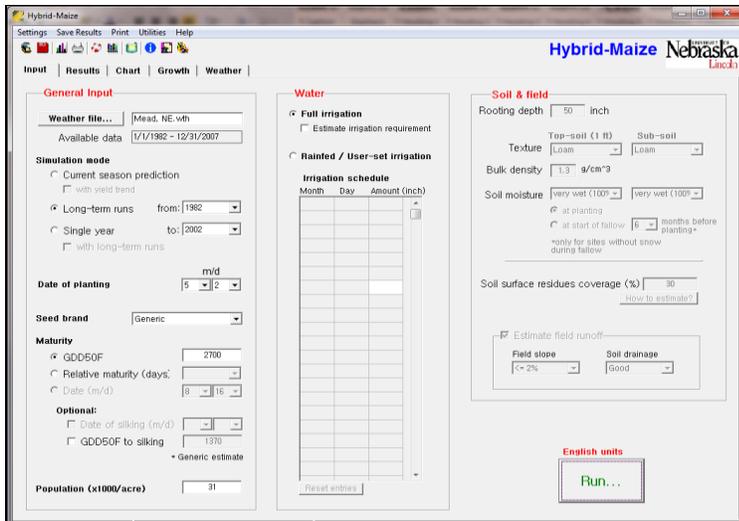
To use the yield forecasting mode, we recommend that the weather data file contain at least ten years of reliable historical weather data for the site (or a nearby weather station), in addition to weather data for the current year. Management decisions derived from in-season simulations could include adjusting the yield goal during the growing season in comparison with normal years and making subsequent adjustments in fertilizer amounts (sidedress, fertigation), or to help make replant decisions. During grain filling, yield forecasting can provide additional information to help guide marketing decisions on marketing.

Example: In-season simulation of irrigated maize growth

Our site is a field on a deep silt loam in eastern Nebraska, near Mead. Corn following soybean is grown in a no-till system. The field is equipped with a center-pivot irrigation system and an injection pump for fertigation. A commercial corn hybrid with a relative maturity of 109-d and 2700 GDD50F (1500 GDD10C) from planting to maturity was planted on May 2, 2003 at a 30-inch (0.76 m) row spacing with a seed drop rate of 32,000 seeds/acre (79,000 seeds/ha). Emergence was observed to occur on May 12 and actual measurement of stand counts three weeks later indicated an average plant population of 31,000 plants/acre (76,600 plant/ha). The crop reached 50% silking on July 19.

The soil, a Tomek silt loam, has 3% organic matter, 4 ppm nitrate-N in the top 3 ft of soil (depth weighted average), 12 ppm available P (Bray-1), 395 ppm available K and a pH of 6.4. Soil texture is silt loam throughout the profile and there are no impediments to root growth. Initial soil moisture status in the topsoil represents a normal year, about 27% gravimetric water content. A weather station is located at Mead, NE, with daily climate data available since 1982. This station is within 5 miles of the field and rainfall data measured there are representative of the actual field location. Alternatively, more location specific rainfall data could be used to supplement the weather station data, i.e., by editing the weather data file (see section 2.3.2.)

We first evaluate the site yield potential (see section 3.1.) for corn planted on May 2 and a final plant stand of 31,000 plants/acre, using 1982-2002 weather data:



Model inputs for simulating the long-term site yield potential.

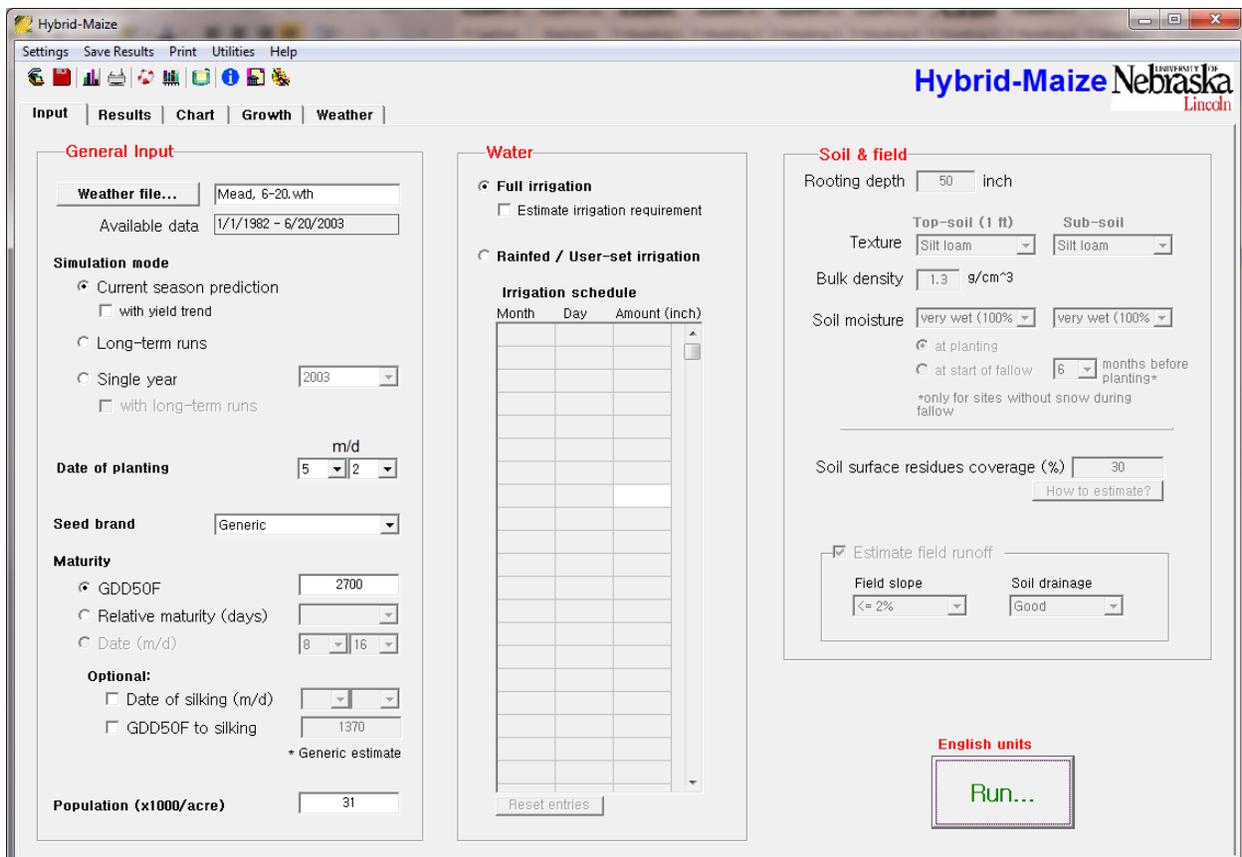
Simulations using long-term historical weather data from 1982 to 2002

Rank	Year	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tET0
Best yield	1994	280	6.6	7.1	13.7	0.48	72	64	136	3107	58.2	81.6	69.9	69.1	70.7	25.31
75% percentile	1985	259	6.1	5.3	11.5	0.53	74	63	137	2817	58.4	80.9	69.7	68.4	71.2	23.92
Median yield	1989	233	5.5	5.3	10.8	0.51	72	56	128	2615	58.1	84.2	71.1	69.0	73.9	22.94
25% percentile	1998	228	5.4	5.2	10.6	0.51	71	51	122	2437	61.7	82.6	72.1	69.6	75.6	18.80
Worst yield	1983	196	4.6	6.1	10.7	0.43	80	44	124	2686	60.2	82.8	71.5	67.2	79.4	21.81
Long-term mean		238	5.6	5.6	11.3	0.50	74	58	132	2666	58.9	82.3	70.6	68.7	73.3	22.97
Long-term CV, %		10	10	12	8	8	8	16	10	8	3	3	3	2	5	9

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

Average yield potential under optimal conditions is 238 bu/acre and risk of frost is low. To achieve the yield potential, we need to ensure sufficient water and nutrient supply during the growing season. Using the actual soil test results and assuming a yield goal of 238 bu/acre, the current fertilizer recommendation algorithms for corn (Shapiro et al., 2001) suggest the application of 150 lbs N and 40 lbs P₂O₅, with the nitrogen split into 90 lbs applied pre-plant and 60 lbs at the V6-stage of corn development. This is the nutrient management practice implemented in 2003. However, if the predicted in-season yield potential is substantially higher than the long-term average, it is possible to make a small additional N application through the pivot to ensure adequate N supply for a higher yielding crop. However, such a decision should be made no later than the V12 to R1 (silking) stage window.

The goal of this exercise is to conduct weekly simulations during the ongoing 2003 growing season, beginning about 1 month after emergence. In addition, we wish to decide whether additional N topdressing should be applied through fertigation at later growth stages (in the V12 to R1 growth stages window). Therefore, we assume that no water stress occurs during the forecasting period and our simulation is mainly a prediction of in-season yield potential for the actual planting date, hybrid, and plant density used at the site. Weather data are obtained weekly from the HPRCC web site at <http://www.hprcc.unl.edu> (see section 2.3.2. and note that a subscription is needed for access to real-time climate data).

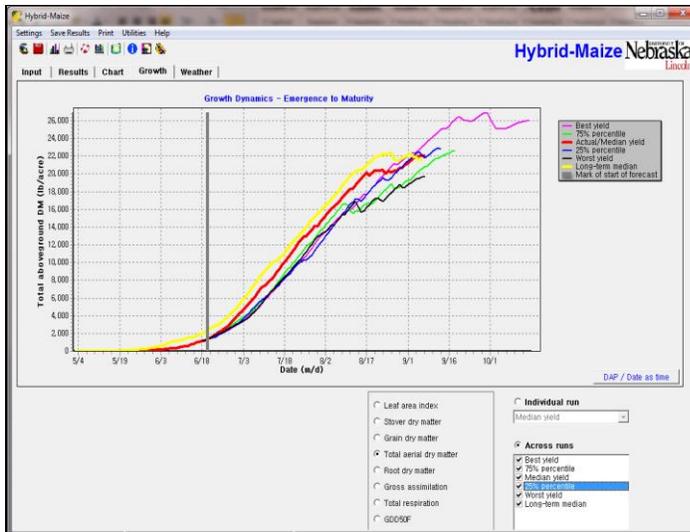


The following text provide examples of selected outputs from real-time simulations conducted at different dates throughout the growing season, including some interpretation. See section 4.4.3 (below) for more examples and how yield forecasts converge as the growing season progresses. The screenshot below shows how the data were entered in the **Current season prediction** mode, in this case for the final simulation done near maturity stage.

Simulation as of **June 20, 2003, about V6 (6-leaf) stage**

The weather file was downloaded on June 21. Model inputs included date of planting on May 2 and GDD to maturity of 2700, and full irrigation.

Real-time predictions of the current season																	
Rank	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRain	tIrr
Best yield	296	7.0	6.0	13.0	0.54	86	81	167	3385	54.3	78.0	66.1	66.2	66.2	25.79	20.7	0.0
75% percentile	254	6.0	5.3	11.3	0.53	81	59	140	2803	57.8	80.8	69.3	66.9	72.6	22.75	16.1	0.0
Median yield	241	5.7	5.3	11.0	0.52	77	52	129	2694	58.9	83.3	71.1	67.9	75.8	24.65	17.2	0.0
25% percentile	225	5.3	6.1	11.4	0.47	81	54	135	2753	58.1	81.9	70.0	67.3	74.1	23.26	12.9	0.0
Worst yield	198	4.7	5.1	9.8	0.48	81	48	129	2544	59.1	82.9	71.0	67.0	77.7	23.30	12.0	0.0
Long-term median	233	5.5	5.3	10.8	0.51	72	56	128	2615	58.1	84.2	71.1	69.0	73.9	22.94	12.3	0.0

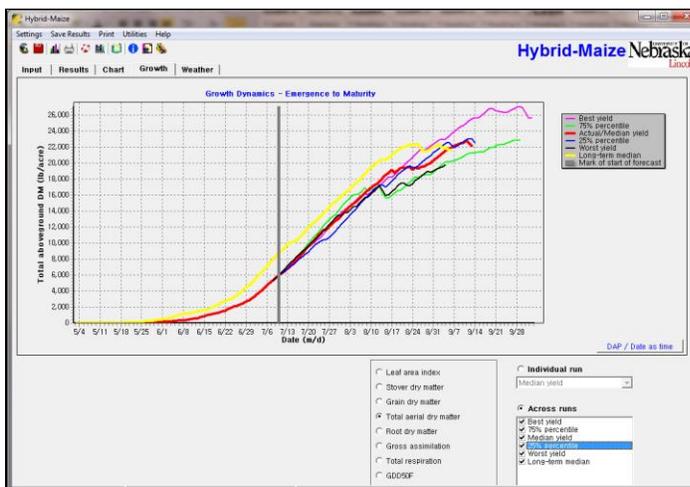


Growth tab. The long-term median growth scenario (yellow) is shown compared to the five rank years for the current growing season. 2003 appears to be a season with normal to slightly below normal biomass accumulation as of the simulation date (June 20). Because only one month of actual growth has occurred, predicted final yield potential varies widely (198-296 bu/acre). Median forecasted yield potential is 241 bu/acre, which is close to the long-term median of 233 bu/acre (see Results table above).

Simulation as of July 10, 2003, about V12 stage

The weather file was downloaded on July 11 to extend the climate data for the current year up to July 10.

Real-time predictions of the current season																	
Rank	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRain	ttiri
Best yield	289	6.9	6.0	12.8	0.53	83	72	155	3160	55.5	79.3	67.4	66.7	68.1	24.97	14.5	0.0
75% percentile	259	6.1	5.3	11.5	0.53	80	71	151	2897	57.4	78.5	67.9	67.3	68.7	22.43	19.8	0.0
Median yield	246	5.8	5.3	11.1	0.53	80	55	135	2726	58.0	82.2	70.1	67.1	74.4	24.17	17.0	0.0
25% percentile	229	5.4	5.8	11.3	0.48	81	55	136	2730	58.1	81.7	69.9	67.2	73.9	23.04	12.5	0.0
Worst yield	202	4.8	5.1	9.9	0.48	79	47	126	2545	59.5	83.4	71.4	67.5	78.1	22.92	10.8	0.0
Long-term median	233	5.5	5.3	10.8	0.51	72	56	128	2615	58.1	84.2	71.1	69.0	73.9	22.94	12.3	0.0

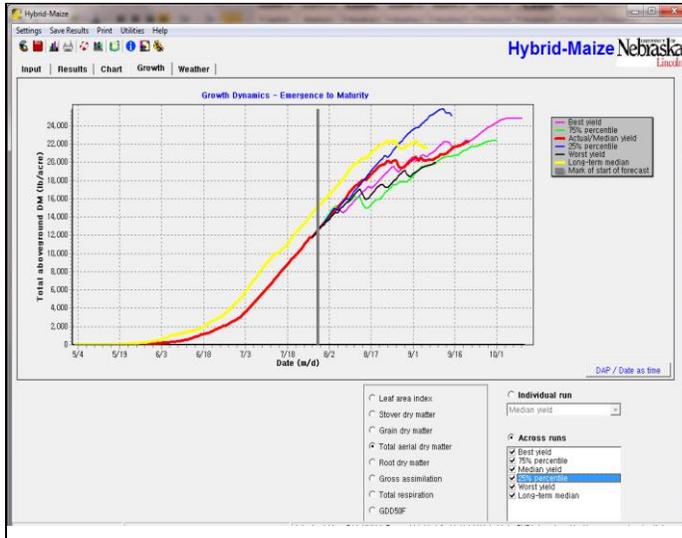


Growth tab. Growth up to July 10 has lagged the long-term median due to cooler temperatures. Silking is forecasted for July 19-20, so management must ensure that no stress occurs in upcoming two weeks. Median forecasted biomass and yield are projected to be similar to the long-term median. Because the median scenario projects a yield similar to the yield goal used in calculating the N amount that was applied, there is no need for additional N topdressing in the

Simulation up to July 30, 2003, about 10 days after silking

The weather file was downloaded on July 31. Observed silking on July 19 is added to input setting.

Real-time predictions of the current season																	
Rank	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tET0	tRain	tTri
Best yield	311	7.4	5.0	12.4	0.59	79	83	162	3088	53.8	79.3	66.5	66.9	66.2	24.55	15.2	0.0
75% percentile	268	6.3	5.0	11.4	0.56	79	65	144	2828	56.9	80.7	68.8	66.9	71.1	24.52	46.5	0.0
Median yield	255	6.0	5.0	11.0	0.55	79	72	151	2814	56.5	78.2	67.4	66.9	67.9	22.86	15.7	0.0
25% percentile	239	5.7	6.7	12.4	0.46	79	58	137	2888	56.6	82.9	69.7	66.9	73.6	25.73	9.1	0.0
Worst yield	209	5.0	5.1	10.1	0.49	79	52	131	2601	58.8	82.4	70.6	66.9	76.2	22.88	10.8	0.0
Long-term median	241	5.7	6.8	12.5	0.46	76	53	129	2832	59.3	82.6	70.9	67.5	75.9	24.53	16.2	0.0

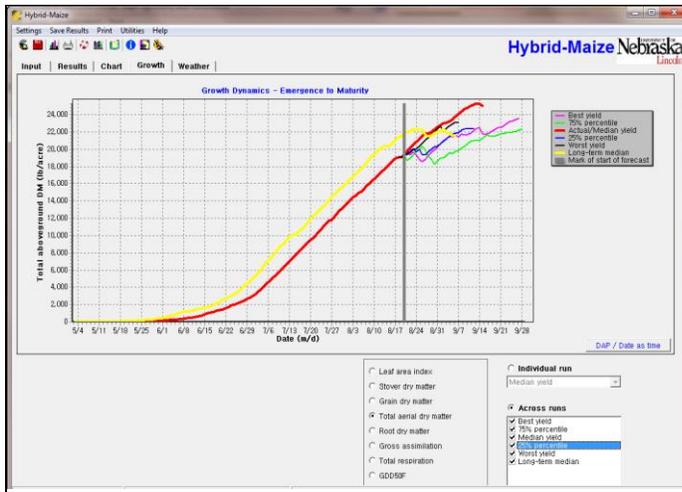


Growth tab. Actual biomass accumulation has approached the long-term median due to warmer than normal weather during the past three weeks. We are still on track for a normal or above normal yield, provided that sufficient water can be supplied. All scenarios suggest that maturity will be reached from 1 to 4 weeks later than normal (see 'V+R' column). Median forecasted yield potential is 255 bu/acre, but the range of possibilities still remains quite large (209 to 311 bu/acre).

Simulation up to **August 20, 2003, about R3 stage**

The weather file was downloaded on August 21.

Real-time predictions of the current season																	
Rank	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tET0	tRain	tTri
Best yield	284	6.7	5.1	11.8	0.57	79	70	149	2935	55.7	80.5	68.1	66.9	69.5	24.18	16.1	0.0
75% percentile	263	6.2	5.0	11.2	0.55	79	71	150	2850	55.7	80.2	67.9	66.9	69.1	23.47	16.6	0.0
Median yield	255	6.0	5.2	11.2	0.54	79	59	138	2771	57.1	82.0	69.5	66.9	73.1	23.31	12.7	0.0
25% percentile	244	5.8	5.3	11.0	0.52	79	55	134	2713	57.5	82.9	70.2	66.9	74.9	22.83	12.0	0.0
Worst yield	218	5.2	6.3	11.4	0.45	79	50	129	2673	58.2	83.6	70.9	66.9	77.2	22.59	10.1	0.0
Long-term median	241	5.7	6.8	12.5	0.46	76	53	129	2832	59.3	82.6	70.9	67.5	75.9	24.53	16.2	0.0

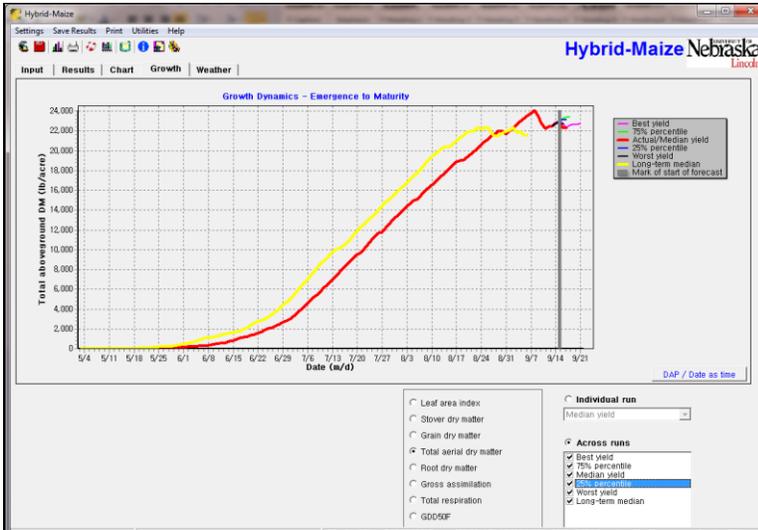


Growth tab. During the past three weeks, maximum temperature has largely been above normal (on 'Weather' tab, not shown). Biomass accumulation is simulated to be slightly above the long-term median but still on track for a normal yield. All scenarios suggest that maturity will be reached from 1 to 3 weeks later than normal. Median forecasted yield potential remains at 255 bu/acre and the range has narrowed to 218 to 284 bu/acre.

Simulation up to **September 15, 2003, near physiological maturity (R6)**

The weather file was downloaded on September 16, and output screen shots are on next page.

Real-time predictions of the current season																	
Rank	Gr.Y	Gr.DM	Stover	tDM	HI	vDays	rDays	V+R	tSola	Tmin	Tmax	Tmean	vTmean	rTmean	tETO	tRain	tIrr
Best yield	262	6.2	5.2	11.4	0.55	79	64	143	2853	55.9	81.7	68.8	66.9	71.2	23.99	13.2	0.0
75% percentile	257	6.1	5.1	11.2	0.54	79	62	141	2808	56.3	82.0	69.2	66.9	72.0	23.82	13.7	0.0
Median yield	256	6.1	5.2	11.2	0.54	79	60	139	2802	56.5	82.5	69.5	66.9	72.9	23.81	12.4	0.0
25% percentile	255	6.0	5.4	11.4	0.53	79	60	139	2806	56.3	82.4	69.4	66.9	72.7	23.88	12.4	0.0
Worst yield	252	6.0	5.3	11.2	0.53	79	59	138	2790	56.6	82.5	69.5	66.9	73.1	23.74	12.4	0.0
Long-term median	241	5.7	6.8	12.5	0.46	76	53	129	2832	59.3	82.6	70.9	67.5	75.9	24.53	16.2	0.0



Growth tab. All scenarios suggest that maturity will be reached within the next 1 to 3 days. Median forecasted yield potential is 256 bu/acre, ranging from 252 to 262 bu/acre. For comparison, measured final yield in a field experiment treatment that exactly represented the crop management followed in this real-time simulation was 251 bu/acre.

3.5. Simulation using input settings in Excel file

Sometimes, especially in research, users need to run a great number of simulations. In that case, users can use the option of setting up inputs in Excel spreadsheet. When using this option the first time, the user needs to use a template file to set input settings. The template file “Template row input settings.xls”, is available in the folder where the program is installed. Open that file, set up each simulation following the instructions in column title comments. After setting all runs, save the file in a new folder. Then go to “Settings”, “Use row input settings from Excel file” on the main menu. The simulation results are automatically saved to the same file but with “Output” added to the end of the setting file name.

4. Detailed Information about the Hybrid-Maize Model

Crop simulation models are mathematical representations of plant growth processes as influenced by interactions among genotype, environment, and crop management. They have become an indispensable tool for supporting scientific research, crop management, and policy analysis (Fischer et al., 2000; Hammer et al., 2002; Hansen, 2002). Simulation models serve different purposes, and the intended purpose influences the level of detail needed for mechanistic description of key processes, sensitivity to environment and management, data requirements, and model outputs. All cereal crop models must simulate plant growth and development, biomass partitioning among organs (leaves, stem, root, and reproductive structures), and yield formation. The accuracy of simulating the outcome of these processes across a wide range of environments depends on basic understanding of the key ecophysiological processes and incorporating this knowledge in the mathematical formulations that constitute the model.

Our objective was to develop a model that can provide robust simulation of maize yield potential in different environments with a minimum number of location- or hybrid-specific input parameters (Yang et al., 2004). Agronomists need such robust crop models to improve the efficiency of research that investigates interactions among crop management options in favorable rainfed and irrigated environments, while crop producers and crop consultants need such models for use in computer-based decision-support tools to improve crop management decisions.

The Hybrid-Maize model builds on the strengths of existing models by combining the crop-specific attributes of CERES-Maize (Jones and Kiniry, 1986; Kiniry et al., 1997; Lizaso et al., 2003b) related to phenology and organ growth with explicit photosynthesis and respiration functions from assimilate-driven generic crop models such as SUCROS, WOFOST and INTERCOM (Van Diepen et al., 1989; Kropff and van Laar, 1993; Lindquist, 2001; van Ittersum et al., 2003). Hybrid-Maize also includes additional modifications for several functions based on calibration with experimental data from a field study that produced maize with minimal possible stress—conditions that are required to achieve yield potential (Yang et al., 2004).

Hybrid-Maize simulates maize growth on daily basis from emergence to physiological maturity. It features temperature-driven maize phenological development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. The functions for crop growth and development in Hybrid-Maize were largely adapted from CERES-Maize, but the inclusion of gross assimilation, growth respiration and maintenance respiration makes the Hybrid-Maize model potentially more responsive to changes in environmental conditions than models such as CERES-Maize. Hybrid-Maize also requires fewer genotype-specific parameters without sacrificing prediction accuracy. A linear relationship between growing degree-days (GDD) from emergence to silking and GDD from emergence to physiological maturity is used for prediction of day of silking when the former is not available.

Detailed descriptions of major model components are provided in the following sections, focusing mainly on the modified or new components in Hybrid-Maize that differ from CERES-Maize or INTERCOM. Default values of user-modifiable parameters used in Hybrid-Maize are listed in Appendix 6.1. Default values of soil physical properties used in Hybrid-Maize are listed in Appendix 6.2. A general comparison with other models is provided in Appendix 6.3.

4.1. Crop Growth and Development Processes

4.1.1. Daily GDD Computation

The model runs on a daily time-step. Growing degree days (GDD) accumulation is the first procedure to be estimated each day. In CERES-Maize, GDD refers to a base temperature of 8 °C (GDD₈). However, such a GDD scheme is inconvenient for practical use because most of the GDD values are reported for maize hybrids by seed companies, and these values predominantly use a base temperature of 10 °C (GDD₁₀). As the conversion of GDD based on one temperature to GDD based on another temperature requires the number of days for the GDD accumulation, there is no simple way to convert GDD₈ to GDD₁₀. In order to preserve the GDD related growth functions from CERES-Maize, and, at the same time, directly use the available hybrid-specific GDD₁₀, the two schemes of GDD co-exist in the Hybrid-Maize: all the GDDs for model inputs and outputs are expressed in GDD₁₀, whereas internally GDD₈ is used in functions derived from CERES-Maize.

Daily GDD is computed using the single-sine method (<http://www.ipm.ucdavis.edu/WEATHER/ddconcepts.html>). This method assumes the temperature curve is symmetrical around the maximum temperature. It uses daily minimum (T_{\min}) and maximum (T_{\max}) temperatures to produce a sine curve over a 24-hour period, and then estimates GDD for that day by calculating the area above the lower threshold (T_L) and below the curve or the upper threshold (T_U). The default upper threshold is 34 °C (Kropff and van Laar, 1993). GDD_{10} is calculated using $T_L = 10$ °C, and GDD_8 is subsequently calculated by adding 2 to GDD_{10} . Six possible relationships can exist between the daily temperature cycle and the upper and lower thresholds. Using two common parameters calculated as

$$T_{mean} = (T_{\max} + T_{\min})/2 \quad \text{and} \quad \alpha = (T_{\max} - T_{\min})/2$$

the six possible cases are mathematically described and visualized below.

(1) Intercepted by both thresholds T_L and T_U :

$$GDD = \frac{1}{\pi} \left((T_{mean} - T_L)(\theta_2 - \theta_1) + \alpha [\cos(\theta_1) - \cos(\theta_2)] + (T_U - T_L) \left(\frac{\pi}{2} - \theta_2 \right) \right)$$

with

$$\theta_1 = \sin^{-1}[(T_L - T_{mean})/\alpha]$$

$$\theta_2 = \sin^{-1}[(T_U - T_{mean})/\alpha]$$

(2) Intercepted by the upper threshold T_U :

$$GDD = \frac{1}{\pi} \left((T_{mean} - T_L) \left(\theta_2 + \frac{\pi}{2} \right) + (T_U - T_L) \left(\frac{\pi}{2} - \theta_2 \right) - [\cos(\theta_2)] \right)$$

with

$$\theta_2 = \sin^{-1}[(T_U - T_{mean})/\alpha]$$

(3) Entirely between both thresholds T_L and T_U :

$$GDD = T_{mean} - T_L$$

(4) Intercepted by the lower threshold T_L :

$$GDD = \frac{1}{\pi} \left((T_{mean} - T_L) \left(\frac{\pi}{2} - \theta_1 \right) + \alpha \cos(\theta_1) \right)$$

with

$$\theta_1 = \sin^{-1}[(T_L - T_{mean})/\alpha]$$

(5) Completely above both thresholds T_L and T_U :

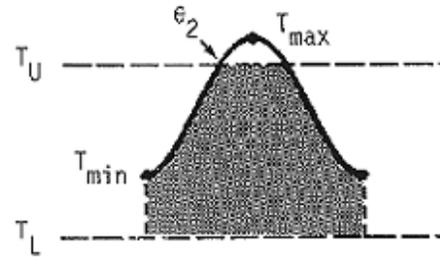
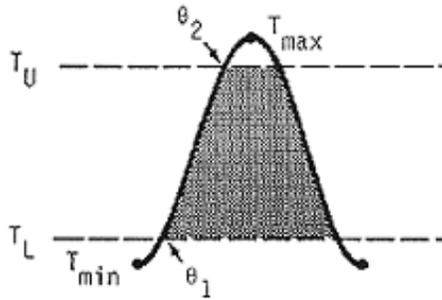
$$GDD = T_U - T_L$$

(6) Completely below both thresholds T_L and T_U :

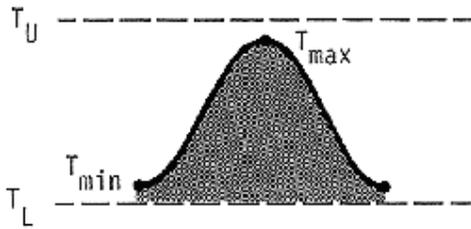
$$GDD = 0$$

Case (1)

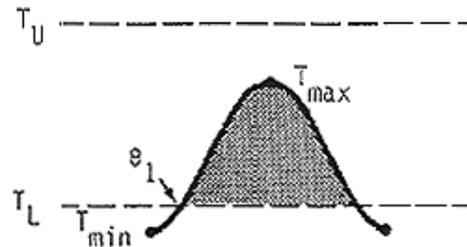
Case (2)



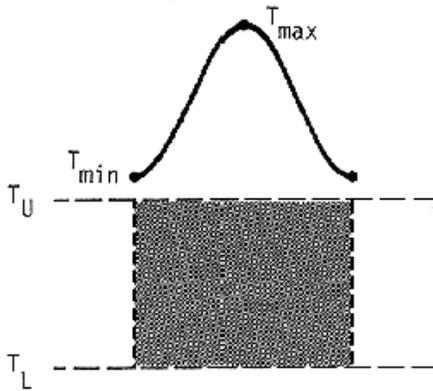
Case (3)



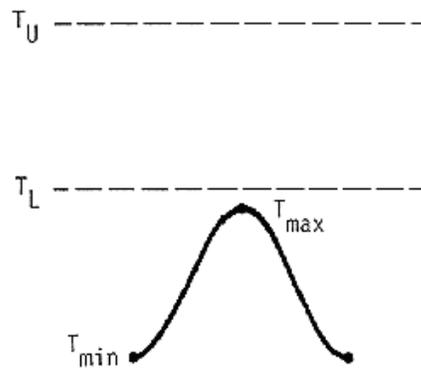
Case (4)



Case (5)



Case (6)



4.1.2. Daily CO₂ Assimilation

Daily CO₂ assimilation is computed according to Goudriaan (1986), Kropff and van Laar (1993), and Goudriaan and van Laar (1994). The photosynthetically active radiation (PAR, MJ m⁻² ground h⁻¹) is assumed to be 50% of the total solar radiation:

$$PAR = 0.5 * I / DL$$

in which I is the daily total incoming radiation (MJ m⁻² ground d⁻¹) and DL is the daytime length (hours). DL is computed as (Driessen and Konijn, 1992):

$$DEC = -23.45 \cos(2\pi * (DOY + 10) / 365)$$

$$RAD = \pi / 180$$

$$CCOS = \cos(Lat * RAD) * \cos(DEC * RAD)$$

$$SSIN = \sin(\text{Lat} * \text{RAD}) * \sin(\text{DEC} * \text{RAD})$$

$$SSCC = SSIN / \text{CCOS}$$

$$DL = 12 [2\pi * \text{arcSin}(SSCC)] / \pi$$

in which DOY is day of year, Lat is the latitude of the site, and DEC, RAD, CCOS and SSIN are intermediate variables. For the southern hemisphere, the value of latitude is negative.

Using L to represent the depth of canopy with L = 0 at the top and L = LAI (leaf area index) at the bottom of the canopy, the PAR interception by the layer of canopy at position L (PAR_{i,L}) equals the decrease of PAR at that depth following the Beer's law:

$$\text{PAR}_{i,L} = d\text{PAR} / dL = \text{PAR} * k * \exp(-k * L)$$

in which k is the light extinction coefficient. The default k value of 0.55 is based on data from Lizaso et al. (2003b), Maddonni et al. (2001), and our own measurements made in a field experiment at Lincoln (J.L. Lindquist, unpublished data). This value can be changed under **Settings** → **Parameter Settings** → **Crop growth**. The corresponding CO₂ assimilation by that layer (A_L) follows a saturation function of the form:

$$A_L = A_{\text{max}} * [1 - \exp(-\varepsilon * \text{PAR}_{i,L} / A_{\text{max}})]$$

in which ε is the initial light use efficiency (g CO₂ MJ⁻¹ PAR) and A_{max} is the maximum assimilation rate (g CO₂ m⁻² leaf hr⁻¹). The value of ε = 12.5 g CO₂ MJ⁻¹ PAR was adapted from Kropff and van Laar (1993) and can be changed under **Settings** → **Parameter Settings** → **Resp & Photosyn**. The maximum assimilation rate represents the rate of photosynthesis at light saturation, and is a function of day-time mean temperature (T_{day}, °C) (Driessen and Konijn, 1992; Kropff and van Laar, 1993). A_{max} is zero below a threshold temperature (T_{zeroA}). From T_{zeroA} upwards A_{max} increases linearly until a plateau (A_{plateau}) is reached at a certain temperature (T_{1, plateau}). From T_{1, plateau} upwards to another temperature (T_{2, plateau}), A_{max} remains at A_{plateau}. Above T_{2, plateau}, A_{max} decreases linearly. The formulations are:

$$T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}}) / 2$$

$$\text{AMPL} = (T_{\text{max}} - T_{\text{min}}) / 2$$

$$\text{Sunrise} = 12 - DL / 2$$

$$\text{Sunset} = 12 + DL / 2$$

$$\text{AUX} = \pi (\text{Sunset} - 14) / (\text{Sunrise} + 10)$$

$$T_{\text{day}} = T_{\text{mean}} + (\text{Sunset} - 14) * \text{AMPL} * \sin(\text{AUX}) / (DL * \text{AUX})$$

if T_{day} < T_{1, plateau}

$$A_{\text{max}} = (T_{\text{day}} - T_{\text{zeroA}}) * A_{\text{plateau}} / (T_{1, \text{plateau}} - T_{\text{zeroA}})$$

else if T_{day} ≤ T_{2, plateau}

$$A_{\text{max}} = A_{\text{plateau}}$$

else

$$A_{\text{max}} = A_{\text{plateau}} - 0.2 * (T_{\text{day}} - T_{2, \text{plateau}})$$

in which AMPL, sunrise, sunset and AUX are intermediate variables. $A_{\text{plateau}} = 7 \text{ g CO}_2 \text{ m}^{-2} \text{ leaf hr}^{-1}$ was adapted from Kropff and van Laar (1993) and consistent with those reported by Sinclair and Horie (1989) and Hammer et al. (2009) for maize, but this value can be changed under **Settings** → **Parameter Settings** → **Resp & Photosyn**.

The CO_2 assimilation by the whole canopy in a day (A , $\text{g CO}_2 \text{ m}^{-2} \text{ ground d}^{-1}$) is obtained by integration of the A_L along L :

$$A = DL * \int_{L=0}^{\text{LAI}} A_{\text{max}} [1 - \exp(-\varepsilon * \text{PAR}_{i,L} / A_{\text{max}})]$$

Two numerical integration methods are available in the model. The default method is the three-point Gaussian method (Goudriaan, 1986):

$$L_1 = 0.1127 * \text{LAI}$$

$$L_2 = 0.5 * \text{LAI}$$

$$L_3 = 0.8873 * \text{LAI}$$

$$I_1 = k * \text{PAR} * \exp(-k * L_1)$$

$$I_2 = k * \text{PAR} * \exp(-k * L_2)$$

$$I_3 = k * \text{PAR} * \exp(-k * L_3)$$

$$A_1 = A_{\text{max}} * [(1 - \exp(-\text{epsi} * I_1 / A_{\text{max}}))]$$

$$A_2 = A_{\text{max}} * [1 - \exp(-\text{epsi} * I_2 / A_{\text{max}})] * 1.6$$

$$A_3 = A_{\text{max}} * [1 - \exp(-\text{epsi} * I_3 / A_{\text{max}})]$$

$$A = (A_1 + A_2 + A_3) / 3.6 * \text{LAI} * \text{DL}$$

in which L_1 to L_3 , I_1 to I_3 , and A_1 to A_3 are intermediate variables. Alternatively, a user can choose the standard Simpson's rule. In this method, the number of integration steps (or intervals) is self progressed until a user-defined maximum negligible gain in A (in %) is reached. In most cases this method is much slower than the three point Gaussian method. Gross CO_2 assimilation rate is then converted to gross carbohydrate production ($\text{Carbo}_{\text{gross}}$). Because the organ growth functions are on a per plant basis, $\text{Carbo}_{\text{gross}}$ is also expressed on a per plant basis ($\text{g plant}^{-1} \text{d}^{-1}$):

$$\text{Carbo}_{\text{gross}} = A / \text{plantPop} * 30 / 44$$

in which plantPop is plant population density (plants m^{-2}).

4.1.3. Maintenance Respiration and Net Carbohydrate Production

Some of the gross assimilation will be lost to plant maintenance respiration. The rate of maintenance respiration ($m\text{Resp}$, $\text{g CH}_2\text{O respired d}^{-1}$) differs among different organs, and is affected by the amount of live biomass and temperature. The amount of live biomass of vegetative organs (DM_{live} of leaves, stems, roots) is assumed to be 100% of the organ mass at silking; after silking, the proportion of live biomass of a vegetative organ is assumed to be equal to the ratio of green leaf area (at that moment) to the green leaf area at flowering (Kropff and van Laar, 1993). The effect of temperature (Coef_T) on $m\text{Resp}$ follows the Q_{10} function (Kropff and van Laar, 1993):

$$\text{Coef}_T = 2^{(T_{\text{mean}} - T_{\text{ref}}) / 10}$$

in which T_{mean} is the daily mean temperature, T_{ref} is the reference temperature. As there is unlikely a fixed reference temperature that a plant ‘feels’, we adapted the approach by Driessen and Konijn (1992) that assumes T_{ref} is the average temperature a plant ‘gets used to’ in the past 10 days. The duration of this period can be changed under **Settings** → **Parameter Settings** → **Resp & Photosyn**.

Each organ has a specific coefficient of maintenance respiration ($\text{Coef}_{\text{resp}}$, g CH_2O respired g^{-1} DM d^{-1}), which is the respiration rate per unit of live biomass at T_{ref} . Suggested values for maize plants at 25°C are: 0.03, 0.015, 0.01 & 0.01 g CH_2O respired g^{-1} DM d^{-1} for leaf, stem, root and grain, respectively, as compiled by Penning de Vries et al. (1989) and as also used by Kropff and van Laar (1993). However, those values were derived nearly two decades ago, based on a combination of theoretical considerations, experimental measurements, and model studies (Penning de Vries et al., 1989; van Ittersum et al., 2003). We suspected that those earlier values are too large for modern maize hybrids because Earl and Tollenaar (1998) provided evidence that recent maize hybrids had smaller respiration losses than older hybrids, which also agrees with the measurements conducted by Kiniry et al. (1992). Therefore, the default values of mResp in the Hybrid-Maize model were obtained by calibrating the model prediction of dry matter yields against observed yields of 1999 in a high-yield field experiment at Lincoln. The average of the maintenance respiration coefficients obtained from this calibration (0.007 g g^{-1} d^{-1}) was comparable to the whole-plant respiration value of 0.008 g g^{-1} d^{-1} at silking observed by Kiniry et al. (1992). Default values used in Hybrid-Maize are: 0.010, 0.006, 0.005, and 0.005 g CH_2O g^{-1} DM d^{-1} for leaf, stem, root and grain maintenance respiration, respectively. They can be changed under **Settings** → **Parameter Settings** → **Resp & Photosyn**.

The mResp for each organ is computed as

$$\text{mResp} = \text{DM}_{\text{live}} * \text{Coef}_{\text{resp}} * \text{Coef}_T$$

and the total losses from maintenance respiration for a plant equal the summation of all organs. The net production of carbohydrate (Carbo, g CH_2O d^{-1} plant $^{-1}$) is then computed:

$$\text{Carbo} = \text{Carbo}_{\text{gross}} - \Sigma \text{mResp}$$

Carbo is the amount of assimilates that is available for growth of all organs, during which a further loss of carbohydrate will occur due to growth respiration.

4.1.4. Growth Stages

In term of model structure, the entire maize growth from emergence to physiological maturity is divided into four stages, following largely CERES-Maize (Jones and Kiniry, 1986), but with a merger of stages 1 and 2 into one stage. The four periods used in the Hybrid-Maize model are:

Stage 1: from emergence to tassel initiation

Stage 2: from tassel initiation to silking

Stage 3: from silking to effective grain filling

Stage 4: from effective grain filling to physiological maturity.

In Hybrid-Maize, the end of Stages 1 and 2 is determined differently from CERES-Maize. The end of Stage 2 is when GDD_{10} reaches $\text{GDD}_{10\text{silking}}$ (GDD_{10} from emergence to silking). $\text{GDD}_{10\text{silking}}$ is

either a direct user input or estimated from the total GDD_{10} of a hybrid. Refer to section 4.3 for detailed discussion on estimation of $GDD_{10\text{silking}}$.

The duration of Stage 2 in terms of GDD equals P3 whose value is determined at the end of Stage 1:

$$TLNO = GDD_8 / 21 + 6$$

$$P3 = (TLNO - 2) * 38.9 + 96 - GDD_8$$

in which GDD_8 is for the duration of Stage 1, and TLNO is the total number of leaves that will eventually appear.

As the total duration of Stages 1 and 2 is known (i.e., when GDD_{10} reaches $GDD_{10\text{silking}}$) and the duration of Stage 2 is a function of the duration of Stage 1, the duration of Stage 1 is then determined by an iteration procedure in the model, in which one day is added to Stage 1 until the GDD_{10} at the end of Stage 2 reaches $GDD_{10\text{silking}}$.

Stage 3 ends when the GDD_8 accumulated during this stages reaches 170, and Stage 4 ends when the GDD_{10} reaches $GDD_{10\text{total}}$, which is a hybrid-specific value entered by the user (see 2.3.4.).

In addition, crop phenology stages, including vegetative stages (V stages) and reproductive stages (R stages), are also simulated. The simulation of V stages and R stages are based largely on Nielson RL (2001) and Hicks, DR (2004), respectively. Basically, the interval is 47 GDD_{10} between appearance of each leaf from emergence to V10, while the interval drops to 28 GDD_{10} thereafter till silking (i.e., the final leaf). This scheme is assumed to work for all maturities. For R stages, the following scheme was derived from a hybrid maturity with a total GDD_{10} from silking to maturity of 660: the interval from R1 (silking) to R2 (blister) and R2 to R3 (milk) is 89 GDD_{10} , 100 GDD_{10} from R3 to R4 (dough), and 167 GDD_{10} from R4 to R5 (dent), and 217 GDD_{10} from R5 to R6 (blacklayer, or physiological maturity). For hybrids of other maturities, the intervals for R stages are adjusted proportionally based on the total GDD_{10} from R1 to R6.

4.1.5. Leaf Growth and Senescence

Leaves grow both in number and total area until flowering, and most of the functions describing this were adapted from CERES-Maize (Jones and Kiniry, 1986). The growth of leaf number is a function of daily temperature:

if $cumPh < 5$

$$PC = 0.66 + 0.068 * cumPh$$

if $cumPh \geq 5$

$$PC = 1$$

$$TI = GDD_8 / (38.9 * PC)$$

$$cumPh = cumPh + TI$$

$$XN = cumPh + 1$$

in which TI is the fraction of daily increase in leaf number, cumPh is the number of fully expanded leaves, XN is the leaf number of the oldest expanding leaf, and PC is an intermediate variable. At emergence $cumPh = 1$ and $XN = 3$.

The daily expansion of leaf area (PLAG) and growth of leaf biomass is driven by temperature, and the choice of functions depends on growth stage. For Stage 1 (from emergence to tassel initiation):

if $XN < 4$

$$PLAG = 3 * XN * TI$$

if $XN \geq 4$

$$PLAG = 3.5 * XN^2 * TI$$

$$PLA = PLA + PLAG$$

$$\text{leafWtToday} = PLA / SLA$$

$$\text{leafWtGrow} = \text{leafWtToday} - \text{leafWt}$$

in which PLA ($\text{cm}^2 \text{ plant}^{-1}$) is the total leaf area per plant, SLA ($\text{cm}^2 \text{ g}^{-1}$, $\leq 400 \text{ cm}^2 \text{ g}^{-1}$) is the specific leaf area, leafWtToday (g plant^{-1}) is the leaf biomass after update, and leafWt is the leaf biomass of the previous day, leafWtGrow (g plant^{-1}) is the daily growth in leaf biomass. For Stage 2 (from tassel initiation to flowering):

if $XN \leq 12$

$$PLAG = 3.5 * XN^2 * TI$$

$$\text{leafWtGrow} = 0.00116 * PLAG * PLA^{0.25}$$

$$\text{stemGrow} = \text{leafWtGrow} * 0.0182 * (XN - XNTI)^2$$

if $12 < XN \leq (TLNO - 3)$

$$PLAG = 595 * TI$$

$$\text{leafWtGrow} = 0.00116 * PLAG * PLA^{0.25}$$

$$\text{stemGrow} = \text{leafWtGrow} * 0.0182 * (XN - XNTI)^2$$

if $XN > (TLNO - 3)$

$$PLAG = 595 * TI / (XN + 5 - TLNO)^{0.5}$$

$$\text{leafWtGrow} = 0.00116 * PLAG * PLA^{0.25}$$

$$\text{stemGrow} = 10.85 * TI$$

in which XNTI is the value of XN at the end of Stage 1. Note that both PLAG and leafWtGrow are the values projected based on temperature, but whether they can be realized depends on (a) availability of net carbohydrate from photosynthesis and (b) crop water stress (Section 4.2.4). Leaf growth stops at the end of Stage 2 when silking occurs.

Leaf senescence occurs naturally in the course of plant development and can be accelerated due to competition for light and stresses from low temperature and water deficit (Section 4.2.4). The functions of leaf senescence before silking are largely adapted from CERES-Maize (Jones and Kiniry, 1986), but the functions after silking differ significantly from CERES-Maize.

During vegetative phase before silking (stage 1), the accumulated leaf senescence caused by natural development (SLAN, $\text{cm}^2 \text{ plant}^{-1}$) is computed as

$$SLAN = GDD_8 * PLA / 10000$$

and during grainfilling phase after silking (stage 2) as

$$SLAN = PLA / 1000$$

Daily leaf senescence due to competition for light and temperature stress (PLAS, $\text{cm}^2 \text{ plant}^{-1} \text{ d}^{-1}$) is computed from a stress rate factor (LSR, 0~1):

if $LAI < LAI_{critical}$

$$SLFC = 1$$

else

$$SLFC = 1 - 0.008 * (LAI - LAI_{critical}) \quad 1 \geq SLFC \geq 0$$

if $T_{mean} > 6$

$$SLFT = 1$$

else

$$SLFT = 1 - (6 - T_{mean}) / 6 \quad 1 \geq SLFT \geq 0$$

if $SLFC \leq SLFT$

$$LSR = 1 - SLFC$$

else

$$LSR = 1 - SLFT$$

in which SLFC and SLFT are the leaf stress factors due to competition for light and low temperature, respectively. LSR = 0 means no stress and 1 full stress. Leaf area senesced in a day (PLAS, $\text{cm}^2 \text{ plant}^{-1} \text{ d}^{-1}$) is computed as

$$PLAS = PLAG * LSR$$

The actual leaf senescence is determined by comparing the accumulated PLAS with SLAN; whichever is larger is then taken as the actual leaf senescence. Green leaf area and LAI can then be computed as the difference of PLA and total leaf senescence.

Leaf senescence after silking is described by

$$\text{sumDTT}_8 = \sum[\text{DTT}_8 / (1 - LSR)]$$

$$SF = LAI_{mature} * (\text{sumDTT}_8 / P5)^{SG}$$

in which DTT_8 is daily accumulation of GDD_8 , sumDTT_8 is the DTT_8 accumulation after silking, and SF (0 to 1) is the fraction of senesced leaf of the maximum green leaf area, which is achieved at silking, LAI_{mature} is the fraction of LAI at maturity of the maximum LAI, and SG is a 'stay-green' factor, which controls how fast leaf senescence proceeds after silking. LAI refers to green leaf area, and green leaf area is PLA minus total senesced leaf area. Since leaf area is on a per plant basis in the model, converting from green leaf area to LAI requires multiplication by plant density.

LAI_{mature} and SG are likely to be cultivar-specific and affected by management conditions such as water and nutrient conditions. The default values for LAI_{mature} and SG are 0.7 and 4, respectively. They apply to high-yielding maize in well-managed field, but they can be changed under **Settings** → **Parameter Settings** → **Crop growth**.

4.1.6. Stem and Cob Growth

Stem growth starts from the beginning of Stage 2 until the end of Stage 3, when effective grain filling starts. As adapted from CERES-Maize (Jones and Kiniry, 1986) with modifications, the choice of functions describing stem growth (stemGrow, g plant⁻¹ d⁻¹) depends on the development stage:

if $XN \leq (TLNO - 3)$

$$\text{stemGrow} = \text{leafWtGrow} * 0.0182 * (XN - XNTI)^2$$

if $XN > (TLNO - 3)$

$$\text{stemGrow} = 10.85 * TI$$

after silking:

$$\text{stemGrow} = 0.22 * DTT_8$$

As in CERES-Maize, the start of cob growth is not specified, but the function for cob growth (cobGrow, g plant⁻¹ d⁻¹) starts from silking with an initial cob biomass set at 16.7% of the stem biomass at silking:

$$\text{cobGrow} = 0.088 * DTT_8$$

Cob growth stops at the end of Stage 3 when effective grain filling starts.

The functions of stem growth after silking and cob growth were modified from those in CERES-Maize based on field measurements in experiment at Lincoln (Yang et al., 2004). Essentially, cob growth was reduced by 60% compared with that in CERES-Maize, and stem growth after silking was increased accordingly. This was based on the observation that CERES-Maize grossly overestimated measured cob dry matter. The modified functions more accurately predicted measured cob harvest index (ratio of cob dry matter to cob+grain dry matter) over a range of experimental conditions.

4.1.7. Root Growth and Biomass

The functions for root growth from emergence until it stops shortly after silking were adapted from Kropff and van Laar (1993). Root growth rate is measured by a dry matter allocation coefficient (AC_{root}) to roots from the net assimilation. AC_{root} is assumed to be highest at emergence and decreases during the course of crop development until root growth stops. The course of crop development is measured by development stage (DS) on a scale ranging from 0 to 2, with 1 at silking. DS is computed as

$$DS = GDD_{10} / GDD_{10\text{silking}} \quad \text{if } GDD_{10} \leq GDD_{10\text{silking}}$$

or:

$$DS = 1 + (GDD_{10} - GDD_{10\text{silking}}) / (GDD_{10\text{total}} - GDD_{10\text{silking}})$$

Then AC_{root} is computed as

$$AC_{\text{root}} = ACE_{\text{root}} - DS * ACE_{\text{root}} / DS_{\text{stop}}$$

in which ACE_{root} is the AC_{root} at emergence (=biomass allocation coefficient for root at emergence), and DS_{stop} is the development stage when root growth stops. The default values for ACE_{root} and DS_{stop} are 0.35 and 1.15, respectively. They can be modified under **Settings** → **Parameter Settings** → **Crop growth**. Besides, a small fraction of total root biomass is lost each day. The default value for this daily root death rate (fraction) is 0.005 as in CERES-Maize, which can also be modified under **Settings** → **Parameter Settings** → **Crop growth**.

4.1.8. Adjustment of Growth Rates for Leaf, Stem, Cob and Roots

So far, the growth rates for leaf, stem, cob and root have been determined independent from the amount of daily net assimilation (NetAssim) and without including growth respiration costs, which occur during the conversion from carbohydrate to organ-specific substances. The default coefficients of growth respiration of the five organs were adapted from Kropff and van Laar (1993):

leaf: 0.47 g CH₂O g⁻¹ DM

stem: 0.52 g CH₂O g⁻¹ DM

root: 0.45 g CH₂O g⁻¹ DM

grain: 0.49 g CH₂O g⁻¹ DM

They can be modified under **Settings** → **Parameter Settings** → **Resp & Photosyn**. Taking a leaf for example, for accumulation of 1 g leaf dry matter, 0.47 g carbohydrate is lost during the conversion. In other words, growth of 1 g leaf dry matter requires total 1.47 g carbohydrate.

In stage 1, only leaves and roots grow and the following three constrains are imposed:

- (1) in case of insufficient daily NetAssim, root growth must be satisfied,
- (2) if leafWtGrow is less than 0.5*NetAssim, then 0.5*NetAssim is allocated to leaf, and
- (3) the maximum NetAssim allocated to roots is 0.5*NetAssim. Growth in leaf area is then adjusted accordingly.

In stage 2, stem starts to grow. The growth rates of leaf and stem are equally adjusted after meeting the need for root. Note that the need for root decreases continuously from emergence. In Stage 3, stem and cob grow, as well as root (for part of this period). The growth rates of stem and cob are equally adjusted after meeting the need for root.

4.1.9. Grain Filling

Grain filling, as adapted from CERES-Maize with modifications, is an active process in which the potential daily filling rate is determined by temperature. When daily NetAssim is insufficient to meet the potential grain-filling rate, translocation of carbohydrate from stem and/or leaf will occur as long as there is carbohydrate reserve in these two organs. The amount of carbohydrate reserve in leaf and stem is determined at the start of effective grain filling. For leaf, the amount is equivalent to 15% of the leaf biomass; for stem, the amount is equivalent to 60% of the dry matter accumulation from silking to start of effective grain filling (the remaining 40% goes to cob growth). The request for translocation is first to stem; after the reserve in stem is exhausted, the reserve in leaf will be used. But each day only up to 0.5% of leaf biomass can be translocated. The efficiency of carbohydrate translocation is 0.26 as observed by Kiniry et al. (1992). The cost of translocation

is the cause for occasional negative daily accumulations of dry matter during grain filling. If there is more NetAssim than needed to satisfy daily demand for grain filling, the surplus will be stored in stem as part of the carbohydrate reserve for future translocation.

Actual grain filling rate (grainGrow, g plant⁻¹ day⁻¹) is computed as:

$$\text{grainGrow} = \text{RGfill} * \text{GPP} * \text{G5} * \text{FilleEffi} * 0.001$$

in which G5 is the potential grain filling rate (mg d⁻¹ kernel⁻¹), GPP is the number of viable grain per plant (assuming one ear per plant), FilleEffi is the filling efficiency related to plant density, RGfill (0 to 1) is the temperature driven filling scale.

As in CERES-Maize, G5 is a cultivar-specific genetic coefficient. For high yielding maize hybrids in North America, a default value of 8.7 mg d⁻¹ is used in Hybrid-Maize, which can be modified under **Settings** → **Parameter Settings** → **Crop growth**.

In Hybrid-Maize, a curvilinear function, adapted from Otegui *et al.* (1995), Andrade *et al.* (1999) and Otegui and Andrade (2000), is used to set the number of viable grains per plant (GPP) based on the average plant growth rate (PSKER) during a critical kernel set window of 340 sumDTT8 centered on silking date:

$$\text{PSKER} = \text{sumP} / (1 + \text{GRRG}) * 1000 / \text{IDURP} * 3.4 / 5$$

$$\text{GPP} = \text{G2} - 676 / (\text{PSKER} / 1000)$$

in which sumP (g CH₂O plant⁻¹) is the cumulative net assimilation adjusted for maintenance respiration of grain (GRRG; 0.49 g CH₂O g⁻¹ DM), IDURP is the duration in days of the 340 sumDTT8 period, PSKER is the average daily biomass accumulation per plant (mg d⁻¹) during this period, and G2 is the potential number of grains per plant. As in CERES-Maize, G2 is a cultivar-specific genetic coefficient. For high yielding maize hybrids grown at plant densities common in North America (25-35,000 plants/acre or 60 to 85,000 plants/ha), a default value of 676 grains plant⁻¹ is used in Hybrid-Maize. This value can be modified under **Settings** → **Parameter Settings** → **Crop growth**. The threshold value of PSKER for grain setting is 1000 mg d⁻¹ plant⁻¹, as found by Tollenaar *et al.* (1992) and Andrade *et al.* (1999, 2002), which is higher than the threshold for grain setting used in the original version of CERES-Maize (Jones and Kiniry, 1986) and subsequent versions (Lopez Cedron *et al.*, 2003).

FilleEffi is for adjusting the potential grain filling rate based on plant population, and its function was derived from a high-yield maize experiment at Lincoln, Nebraska (Yang *et al.*, 2004):

$$\text{FilleEffi} = 1.47 - 0.09 * D + 0.0036 * D^2$$

in which D is plant population (plants m⁻²).

RGfill is computed as a sum of eight consecutive 3-hour interval filling scales (RGfill_i):

$$\text{TMFAC}_i = 0.931 + 0.114 * i - 0.0703 * i^2 + 0.0053 * i^3$$

$$\text{TTMP}_i = \text{Tmin} + \text{TMFAC}_i * (\text{Tmax} - \text{Tmin})$$

if TTMP_i > 6

$$\text{RGfill}_i = [1 - 0.0025 * (\text{TTMP}_i - 26)^2] / 8$$

else

$$\text{RGfill}_i = 0$$

in which i ranges from 1 to 8.

Grain filling stops and the crop matures early if (a) $RG_{fill} = 0$ for two consecutive days due to low temperatures, or (b) when T_{min} drops below $-2^{\circ}C$.

4.1.10. Initiation of a Simulation Run

Five variables, i.e., $leafWt$, PLA , $rootWt$, $cumPh$, and XN , need to be initiated at emergence before the first step of computations. Their initial values are derived by assuming a 100-seed weight of 32 g, and 1/3 of the seed weight is lost during germination, and 1/3 emerges as leaf, and the remaining 1/3 is root. $cumPh = 1$, and $XN = 3$. The leaf area is converted from leaf area via $PLA = 267 * leafWt^{0.8}$.

4.2. Water Balance and Soil Water Dynamics

Soil water dynamics is computed as water balance between input and output. Water input include precipitation and/or irrigation and water output includes losses through surface runoff, canopy interception, soil evaporation, crop transpiration, and deep drainage. Water fixed by biochemical reactions is relatively small and thus ignored. The crop is assumed to take up water only from the active rooting zone and when soil water content is above the permanent wilting point. Active rooting depth increases until shortly after silking.

The whole rooting zone is divided into layers of 10 cm, and water balance is computed layer by layer from the top to bottom. For the top layer, water input is the daily precipitation and/or irrigation minus water losses through surface runoff and canopy interception. For other layers, water input equals water drain from the layer immediately above it. The soil holds water only up to field capacity and excess water drains to the subsequent soil layer underneath. Water that drains from the bottom the final rooting depth is lost as deep drainage. The formulations in this section are largely based on Driessen and Konijn (1992).

4.2.1. Rooting Depth and Water Uptake Weighting Factor

Crop rooting depth increases throughout the vegetative growth period until DS reaches 1.15 (i.e., shortly after silking, see 4.1.7., Dardanelli *et al.*, 1997). The increase of rooting depth ($Depth_{root}$) from emergence to DS of 1.15 is described by:

if $Depth_{root} < Depth_{max}$

$$Depth_{root} = sumGDD10 * RGR$$

else

$$Depth_{root} = Depth_{max}$$

in which $Depth_{max}$ is the user-specified maximum soil rooting depth (see Section 2.3.6.), $sumGDD10$ is from germination to that moment, and RGR is the root growth rate (cm per $GDD10$). RGR is calculated as hybrid potential rooting depth divided by $sumGDD10$ to DS 1.15. Hybrid potential rooting depth is one of the internal parameters (on page “Crop growth” of Parameter Setting; c.f. Section 2.3.1) with a default value of 150 cm. Although there is not much data on genotypic differences in potential rooting depth of modern hybrids, we expect most commercial

hybrids can extract water from 1.5 m depth, which is the default setting for the hybrid-specific potential rooting depth in hybrid maize. We do not recommend that users modify this default value unless they have strong evidence that the hybrid they wish to simulate has a deeper or shallower potential rooting depth. $Depth_{max}$ represents the depth of soil without physical or chemical restrictions to root growth. The default value is 1.5 m because root systems of modern hybrids extract water to that depth in unrestricted soil profiles (Dardanelli et al, 1997; Djaman and Irmak, 2012). Users should reduce the default value for simulations on soils with restrictions to root growth at a shallower depth. For example, if there is a hard pan at 75 cm depth that roots do not penetrate, then root zone depth should be set at 75 cm.

Although rooting depth increases steadily before root growth stops, root biomass and root length density (i.e., root length per volume of soil) concentrate more in the upper layer of soil profile and declines with depth. The proportion of water uptake by roots from each layer is assumed to follow approximately the root length density distribution. When the plant is small and rooting depth is shallow (< 30 cm), root distribution is assumed to be V shaped as described as Jones and Kiniry (1986):

$$WUweight_{absolute} = \exp[-VDC * Depth_{layer} / Depth_{root}]$$

$$WUweight_{relative} = WUweight_{absolute} / \sum WUweight_{absolute}$$

where $WUweight_{absolute}$ and $WUweight_{relative}$ are the absolute and relative water uptake weight of the layer, respectively, $Depth$ is the depth of the layer (to its lower end), $Depth_{root}$ is the current rooting depth, and VDC is the vertical distribution coefficient that determines the shape of the exponential function. The greater the VDC , the greater the $WUweight$ for upper layers. The default value of VDC was set at 3.

When roots grow larger and deeper (> 30 cm), the upper part of the roots will cross into neighboring roots space, and as a result, the effective space for individual plants will become a rectangle on top and a V shape underneath, similar to the semicircular root profiles reported by Hammer et al. (2009). It is assumed that this situation occurs when roots are deeper than 30 cm:

$$WUweight^1_{absolute} = WUweight^2_{absolute} = WUweight^3_{absolute}$$

$$WUweight_{relative} = WUweight_{absolute} / \sum WUweight_{absolute}$$

In which superscript 1, 2 and 3 denote layers 1, 2 and 3 with a depth of 10 cm each layer.

Maize roots can reach 150 cm or deeper when constraints to root growth are absent (Dardanelli et al, 1997; Djaman and Irmak, 2012). The Hybrid-Maize model uses 150 cm (by default) as potential root depth to define the shape of the layer weight over depth. When users set a maximum soil rooting depth shallower than the default value, the absolute weight of each layer at a given growth stage will remain the same, but the curve is truncated at the maximum soil rooting depth.

4.2.2. ET₀ adjustment, Maximum Transpiration and Maximum Soil Evaporation

Computation of crop transpiration and soil evaporation is based on adjustment of grass-referenced evapotranspiration (ET₀, cm d⁻¹) from the weather file. A well-watered maize field at LAI greater than 3.5 typically has greater ET than that of grass field. As a result, ET₀ must be adjusted to reflect ET of a maize field. Based on FAO Report 56 (Allen *et al.*, 1998), the adjustment is performed as:

if LAI <= 3.5 then adjCoef = 1
else adjCoef = 1 + (LAI - 3.5) * (1.2 - 1) / (4.5 - 3.5)
if adjCoef > 1.2 then adjCoef = 1.2
adjET0 = ET0 * adjCoef

in which adjET0 is the ETO adjusted for maize canopy.

Maximum transpiration ($Transp_{max}$) is then estimated to account for canopy size (i.e., LAI):

$$Transp_{max} = adjET0 * (1 - \exp(-LAI * k))$$

in which k is the light extinction coefficient. Potential evaporation ($Evap_{pot}$) is estimated as:

$$Evap_{pot} = adjET0 - Transp_{max}$$

Maximum evaporation ($Evap_{max}$) is estimated by accounting for the effect of soil coverage by crop residues (Rosenberg et al., 1983):

$$Evap_{max} = Evap_{pot} * \exp(-soilCoverFrac)$$

in which soilCoverFrac is the fraction of soil surface that is covered by crop residues.

4.2.3. Actual Soil Evaporation

Actual evaporation ($Evap_{act}$, $cm\ d^{-1}$) is estimated using the 2-step evaporation scheme as in FAO Report 56 (Allen *et al.*, 1998). According this scheme, soil evaporation occurs in the top 10 cm soil depth, and evaporation rate will be at maximum when soil is wet (i.e., first step):

$$Evap_{act} = Evap_{max}$$

Evaporation rate will start to decrease, and continuously so, when soil water content is below a threshold (step-2). This threshold (stage2EvapWater) is estimated as:

$$EvapWater_{max} = (soilFCtheta - 0.5 * soilPWPtheta) * 10$$

$$step2EvapWater = step2threshold * EvapWater_{max}$$

$$waterForEvap = (soilTheta - 0.5 * soilPWPtheta) * 10$$

$$Evap_{act} = Evap_{max} * waterForEvap / step2EvapWater$$

in which $EvapWater_{max}$ is the maximum amount of water that can evaporate, soilTheta, soilFCtheta and soilPWPtheta are the topsoil volumetric water content (in fraction), and its values at field capacity and permanent wilting point, respectively, 10 is the depth (in cm) of the evaporating soil depth, and stage2threshold is a fraction typically ranging around 0.5 ~ 0.7.

4.2.4. Actual Transpiration and Water Stress Index

Actual transpiration ($Transp_{actual}$, $cm\ d^{-1}$) is estimated from the maximum water uptake by roots from all layers where roots have reached in comparison with maximum transpiration ($Transp_{max}$). For each layer (10 cm in depth), its available water ($Water_{avail}$, cm) is estimated by:

$$\text{Water}_{\text{avail}} = (\text{Theta} - \text{Theta}_{\text{pwp}}) * 10$$

in which Theta is the volumetric water content of the layer, Theta_{pwp} is volumetric water content at permanent wilting point. Then the soil water potential (PSI) of the layer is estimated from Theta:

$$\text{PSI} = \exp(\text{GAM}^{-1} * \ln(\text{Porosity}/\text{Theta}))^{1/2}$$

in which GAM is a soil texture-specific constant (cm⁻², see Appendix 6.2.), and Porosity of the layer (in fraction, see Appendix 6.2.). Then the hydraulic conductivity of the layer (K) is estimated from PSI:

if PSI_{mulch} <= PSI_{max}, then

$$K = K_{\text{sat}} * \exp(-\text{alfa} * \text{PSI}_{\text{mulch}}),$$

else:

$$K = \text{AK} * \text{PSI}^{-1.4}$$

where K_{sat} is the saturated hydraulic conductivity (cm d⁻¹), alfa is a soil texture-specific geometry constant (cm⁻¹, see Appendix 6.2.), PSI_{max} is a soil texture-specific boundary potential (cm, see Appendix 6.2.), and AK is a soil texture-specific empirical constant (cm^{-2.4} d⁻¹, see Appendix 6.2.).

After that, the root resistance to transpiration (R_{root}, d⁻¹) is estimated as:

$$R_{\text{root}} = 13 / (\text{Depth}_{\text{root}} * K)$$

and the maximum water uptake (Uptake_{max}, cm d⁻¹) from this layer is estimated as:

$$\text{Uptake}_{\text{max}} = (\text{PSI}_{\text{leaf}} - \text{PSI}) / (R_{\text{plant}} + R_{\text{root}}) * \text{WUweight}$$

in which PSI_{leaf} is the leaf water suction at permanent wilting point (=17000 cm), R_{plant} (d⁻¹) is the resistant of plant to water flow (=9690 d⁻¹). If Uptake_{max} > Water_{avail} then Uptake_{max} = Water_{avail}.

Water uptake for other layers is computed similarly. Then the total maximum water uptake (Uptake_{total}, cm d⁻¹) is compared with Transp_{max}:

if Uptake_{total} >= Transp_{max} then

$$\text{Transp}_{\text{actual}} = \text{Transp}_{\text{max}}$$

else

$$\text{Transp}_{\text{actual}} = \text{Uptake}_{\text{total}}$$

Finally the water stress index (Stress, in fraction, 0 to 1) is estimated as:

$$\text{Stress} = 1 - \text{Transp}_{\text{actual}} / \text{Transp}_{\text{max}}$$

Following Keating *et al.* (2003), the water stress index is used as a reduction factor for CO₂ assimilation and leaf area expansion, as well as an acceleration factor for leaf area senescence after silking (see Section 4.1.2.). A value of Stress=0 indicates absence of water stress that limits crop growth so that CO₂ assimilation is not reduced, whereas at Stress=1 CO₂ assimilation stops completely.

For leaf area expansion before silking, daily leaf area expansion (PLAG) occurs at the maximum rate when Stress=0; leaf area expansion decrease linearly until Stress=0.5 when leaf area expansion

stops completely. After silking, in addition to the leaf senescence due to leaf age and heat stress (Section 4.1.5), leaf area senescence accelerates due to water stress: no leaf area senesces due to water stress at Stress=0, whereas 5% of current green leaf area senesces at Stress=1.

4.2.5. Water losses through canopy interception and surface runoff

A portion of rainfall or overhead sprinkler irrigation is intercepted by the canopy foliage and evaporates without entering the soil, with a maximum value of intercepted rainfall under full cover equal to 1.5 mm. With modern, low-pressure pivot irrigation or surface irrigation, there is little or no interception of applied irrigation water by the canopy.

Surface runoff calculation follows Soltani and Sinclair (2012) simplified curve number procedure:

if rain + irrigation \leq 0.2 x S

$$\text{Runoff} = 0$$

else

$$\text{Runoff} = (\text{rain} + \text{irrigation} - 0.2 * S)^2 / (\text{rain} + \text{irrigation} + 0.8 * S)$$

in which S (in cm) is the retention parameter and is estimated as:

$$S = 25.4 * (100 / \text{CN}_{\text{adj}} - 1)$$

$$\text{CN}_{\text{adj}} = \text{CN} - \min(\text{Cover}_{\text{soil}} * 25, 20)$$

in which CN is the curve number for a particular combination of slope and drainage class (Table 6.3a,b) and CN_{adj} is the adjusted CN after accounting for the fraction of soil covered by crop residue ($\text{Cover}_{\text{soil}}$).

4.2.6. Estimation of soil moisture at planting through fallow period soil water balance

When choosing the option of setting soil moisture status at beginning of a fallow period, the model can estimate soil moisture at the time of planting by tracking soil water balance during the fallow period. For each day of the fallow period, water input to soil is the rainfall minus runoff. Water losses are estimated by soil evaporation from the soil top layer of 10 cm depth (see sections 4.2.2 and 4.2.3), and drainage beyond soil rooting zone. At locations where significant snowfall occurs during the fallow period, snow cover and frozen ground will lead to errors in estimation of water balance. As a result, when the program detects a freezing-day precipitation, i.e., precipitation on days with mean temperature below freezing (i.e. 0°C or 32°F), over 20% of total precipitation of the fallow period, a warning message will be included in the output from

estimation of soil moisture at planting. In those cases, users should specify soil moisture at time of planting rather than estimate it from water balance during the fallow period.

4.3. Correlations of total GDD to RM and GDD-to-silking to total GDD

Total GDD or GDU (growing degree units) measures the cumulative effective temperature from planting or emergence to physiological maturity (i.e. blacklayer), whereas RM (relative maturity or comparative relative maturity, in days) measures the duration from planting or emergence to the stage when grain moisture content is suitable for harvest (Hall, 1995; Nielsen and Thomison, 2003). RM ratings vary across seed companies, depending on the operational procedures and criteria, as well as geographic locations (Hall, 1995). In comparison, GDD values for hybrids of similar maturity are more stable across companies, although the starting time for GDD computation differs. Most seed companies compute GDD starting from planting, but some start from emergence.

We compiled RM and total GDD data, as of January 2005, from 12 major maize seed companies in the US. The data are published by those companies either in print format or online sources (Table 4.1). For hybrids from the same company (i.e., the same seed brand), there exists a strong brand-specific correlation between total GDD values and RM ratings (Fig. 4.1, Table 4.1). For the pooled data, however, total GDD spreads into a wider band over RM and the variation in total GDD corresponding to a same RM is significant. The user must exercise caution when comparing RM values across brands, or when using RM to set maturity for unknown brands (i.e., **Generic**).

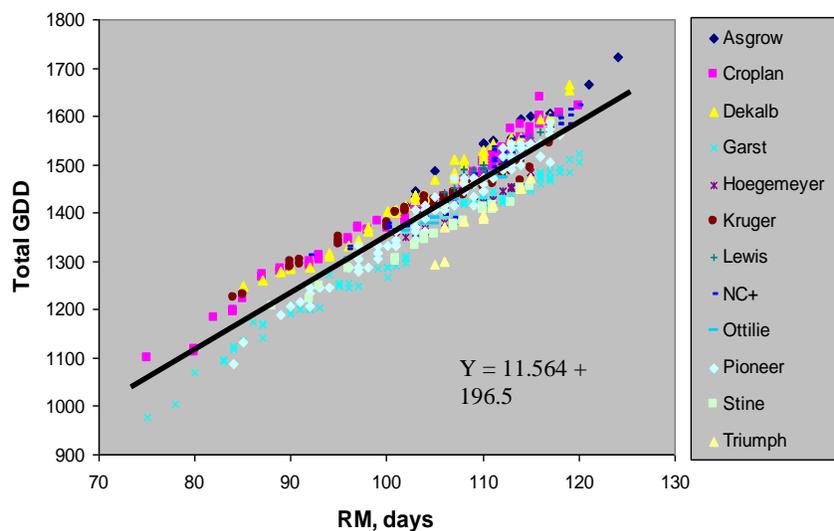


Fig. 4.1. Relationship of total GDD with relative maturity (RM, in days) for 12 commercial maize brands. The black line and the equation represent the regression of the pooled data. The GDD values refer to °C.

Table 4.1. Data sources for RM ratings, total GDD and GDD-to-silking, and regression functions of total GDD to RM and GDD-to-silking to total GDD. All GDD values refer to °C (by dividing the original °F-based GDD values by 1.8).

Company	Data source	Total # of hybrid entries, range of RM (d), range of total GDD	Regression of total GDD (Y) to RM (X)	Regression of GDD-to-silking (Y) to total GDD (X)
Asgrow	www.monsanto.com/m/monsanto/us_ag/	27 102 – 124	$Y = 12.764X + 119.6$ $r^2 = 0.92$	$Y = 0.514X - 30.4$ $r^2 = 0.80$

	layout/seed/default. asp#	1417 - 1722		
Croplan	www.croplangeneti cs.com/	155 75 - 120 1100 - 1639	$Y = 11.576X + 222.5$ $r^2 = 0.98$	N/A*
DeKalb	www.monsanto.co m/monsanto/us_ag/ layout/seed/default. asp#	93 85 - 119 1250 - 1667	$Y = 0.0801X^2 -$ $4.334X + 1025.5$ $r^2 = 0.99$	$Y = 0.308X + 273.3$ $r^2 = 0.86$
Garst	www.garstseed.co m/GarstClient/	161 75 - 120 978 - 1522	$Y = 11.28X + 176.9$ $r^2 = 0.97$	N/A
Hoegemeyer	Seed Guide 2005 (print)	30 101 - 115 1350 - 1483	$Y = 0.3991X^2 -$ $77.002X + 5057.5$ $r^2 = 0.99$	N/A
Kruger	www.krugerseed.co m/	63 84 - 117 1225 - 1544	$Y = 8.729X + 505.2$ $r^2 = 0.98$	N/A
Lewis	www.lewishybrids. com/	61 105 - 118 1436 - 1600	$Y = 11.704X + 206.2$ $r^2 = 0.96$	N/A
NC+	www.nc- plus.com/corn/corn. html	84 92 - 120 1311 - 1622	$Y = 0.1792X^2 -$ $25.807X + 2147.5$ $r^2 = 0.96$	$Y = 0.52X - 2.3$ $r^2 = 0.87$
Otilie	www.ottilieseed.co m/	44 96 - 114 1306 - 1533	$Y = 14.037X - 77.6$ $r^2 = 0.97$	N/A
Pioneer	Pioneer Brand Products for 2004- 2005 (print)	107 84 - 118 1089 - 1589	$Y = 13.419X - 5.9$ $r^2 = 0.97$	$Y = 0.453X + 97.1$ $r^2 = 0.97$
Stine	www.stinseed.com /	35 88 - 115 1206 - 1456	$Y = 9.546X + 353.1$ $r^2 = 0.99$	N/A
Triumph	www.triumphseed.c om/	21 105 - 115 1294 - 1472	$Y = 15.1X - 265.8$ $r^2 = 0.88$	N/A
GENERIC	pooling of sources above	881 75 - 124 978 - 1722	$Y = 11.564X + 196.5$ $r^2 = 0.85$	$Y = 0.41X + 145.4$ $r^2 = 0.78$

* : data of GDD-to-silking are not available.

As reported by Yang et al (2004), GDD-to-silking of maize tends to correlate with total GDD for the same maize brand. Among the 12 seed brands in Table 4.1, four of them have published data of GDD-to-silking. The corresponding regressions of GDD-to-silking to total GDD proved to be brand specific (Fig. 4.2). In addition, the goodness of fit of the regression varies among the four brands. As a result, a correct seed brand should be selected when only total GDD is known in order to obtain an accurate estimate of GDD-to-silking for yield simulation. When all data are pooled, the corresponding linear regression function is $y = 0.41X + 145.4$, $r^2 = 0.78$. This function is used

for the **Generic** brand choice in the model input settings. Although the regression r^2 of the pool data is low (0.78), it might provide a general guideline for estimating GDD-to-silking when such information is not available.

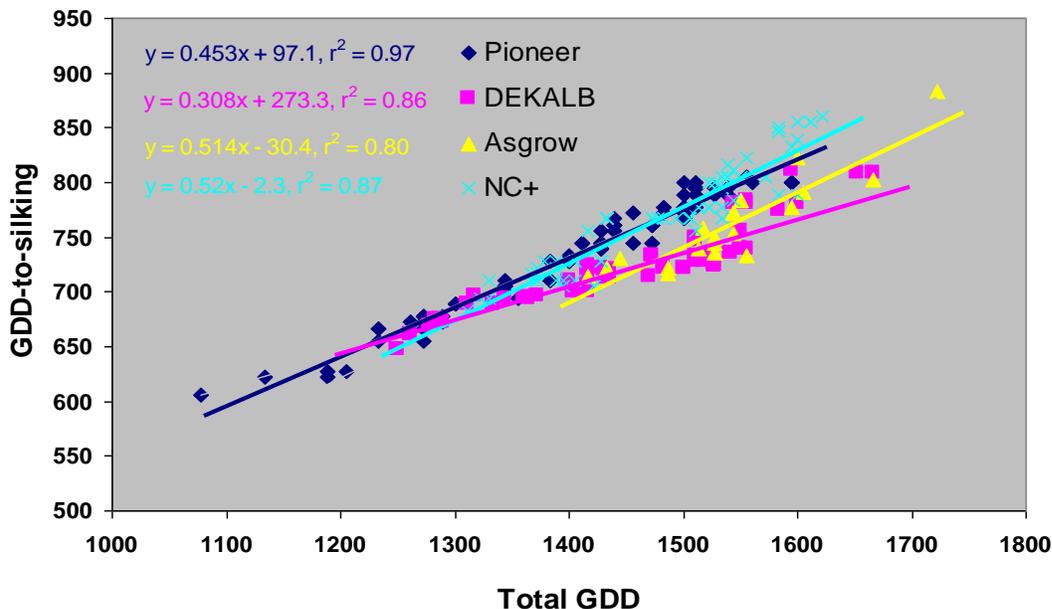


Fig. 4.2. Relationship of GDD-to-silking to total GDD for four commercial maize seed brands. The GDD values refer to °C.

4.4. Sensitivity Analysis and Model Validation

So far, validation of Hybrid-Maize has mainly been conducted for maize grown under irrigated and favorable and to mild-severe rainfed conditions in North America (Yang et al., 2004; Grassini *et al.*, 2009; Setiyono *et al.*, 2012), and subtropical and tropical regions (Achim Dobermann, and Jagadish Timsina, personal communications, <http://yieldgap.org/>).

Most of the validation work has focused on (i) understanding model sensitivity to key parameters used, and (ii) predicting dates of silking and maturity, dynamics of LAI and crop biomass, and grain yield under near-yield potential conditions. Less work has been done on validating specific components of the water balance or simulation of root growth. First examples of model validation studies are described below.

4.4.1. Sensitivity to Selected Model Parameters

A sensitivity analysis of the Hybrid-Maize model was conducted based on 17-year mean weather data for Lincoln, Nebraska (Yang et al., 2004). Parameters tested were potential number of kernels per ear (G2), potential kernel filling rate (G5), light extinction coefficient (k), CH_2O translocation efficiency (TE), initial light use efficiency (ϵ), mean maintenance respiration coefficient (MRC), and occurrence of silking (day of silking). Except for day of silking, the changes in parameter were ± 10 , ± 20 and $\pm 30\%$ of the default values listed in Appendix 6.1. The changes for day of silking were ± 2 , ± 5 and ± 10 days. Each point represents the mean relative change in simulated yields

across the 17-year simulation compared to the simulated yields using the default values. Plant density was set to 10 plants m⁻² and total GDD10C from emergence to maturity was 1500. The model was run in **Optimal** (yield potential) mode.

Under growth conditions with minimal stress, total biomass yield simulated by Hybrid-Maize was most sensitive to changes in the initial light use efficiency (ϵ) (Fig. 4.3.a). Changes in other parameters tested had relatively little effect on total biomass yield. Grain yields were most sensitive to changes in the two genetic coefficients potential number of kernels per ear (G2) and potential grain filling rate (G5), and ϵ , all of which increased yield with increasing values (Fig. 4.3.b). Grain yields were also very sensitive to time of silking, which highlights the importance of accurate specification or estimation of GDD_{silking} to obtain reliable estimates of grain yield from maize simulation models.

The predicted grain yield and aboveground biomass for each of the scenarios in the sensitivity simulations were remarkably stable across the 17 years of climate data. For example, the standard error for the magnitude of difference in total biomass and grain yield simulated over 17 years for each of the modified scenarios in Fig. 4.3. (n=84) was less than 1% in all but three cases. This stability suggests that typical year-to-year variation in climate has relatively small effects on the sensitivity of the parameters tested.

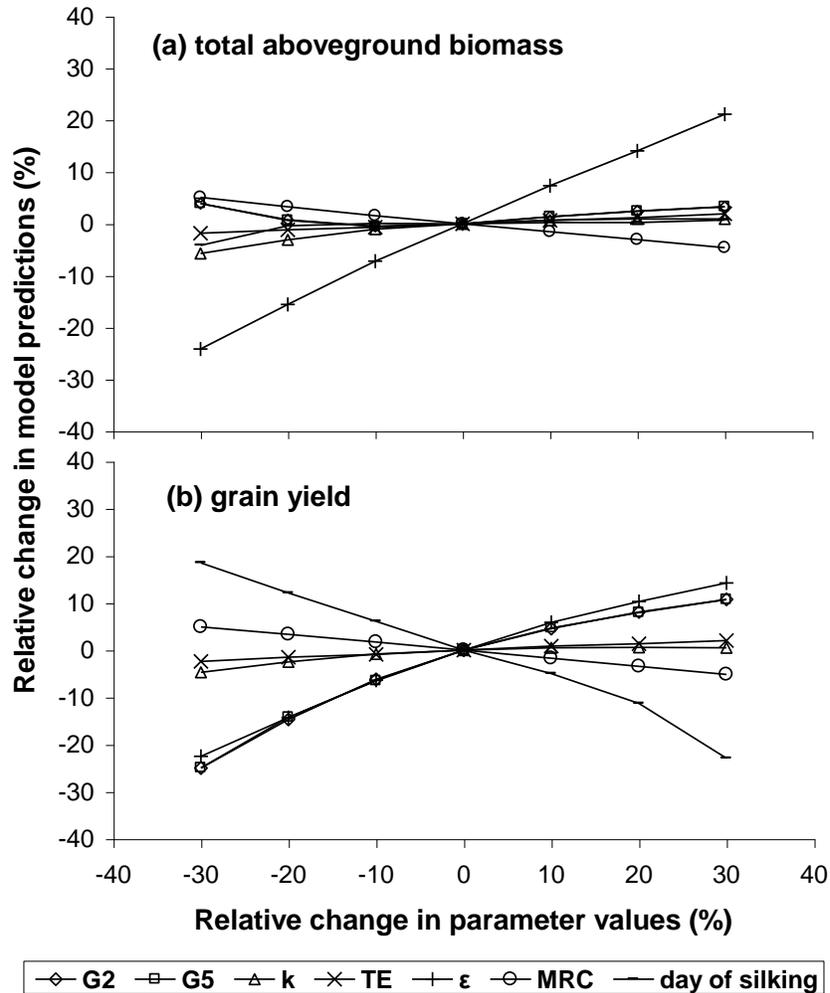


Figure 4.3. Sensitivity analysis of the Hybrid-Maize model using weather data for Lincoln, NE (from: Yang et al., 2004).

4.4.2. Prediction of LAI and Aboveground Biomass Dynamics

Yang et al. (2004) conducted a detailed evaluation of the Hybrid-Maize model under **Optimal** growth conditions (irrigated maize) at Lincoln, Nebraska and a site in Iowa for several years and a range of plant densities (7 to >11 plants m⁻²). LAI simulated by Hybrid-Maize, INTERCOM, CERES-Maize was in close agreement with observed values for the first 30 or 40 d after emergence (Fig. 4.4.). At later development stages, simulated LAI values were more accurate at low plant density than at high plant density, but all models tended to under-predict maximum LAI during mid-season, particularly when measured LAI values exceeded about 6. Leaf area index remained near maximum levels for about 40 d after silking, which indicates active canopy assimilation during grain filling and lack of stress from inadequate water or N supply. Overall, predictions of LAI dynamics by Hybrid-Maize were closer to measured values than LAI simulated by CERES-maize or INTERCOM. Both CERES-Maize and INTERCOM were also less consistent in predicting LAI patterns in different years.

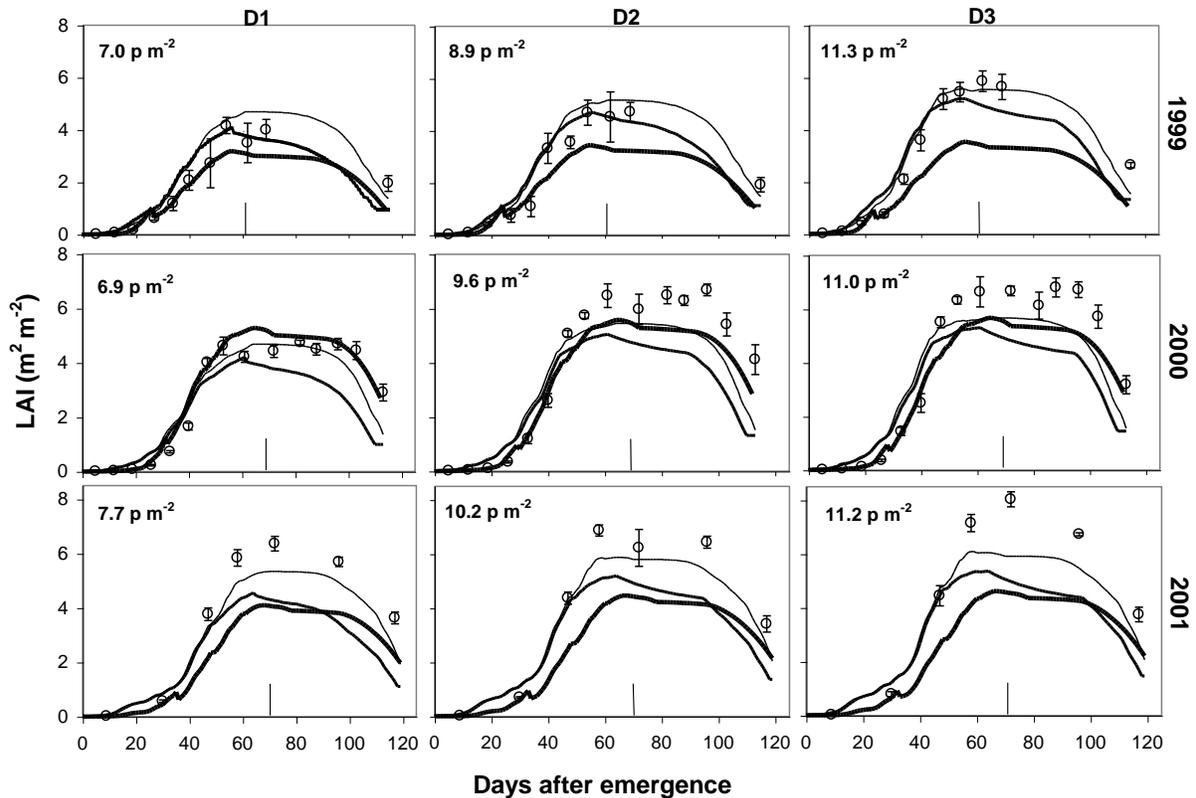


Figure 4.4. Observed (symbols and error bars = mean and SE) leaf area index (LAI) of maize and LAI predicted by Hybrid-Maize (fine line), CERES-Maize (medium line), and INTERCOM (thick line) for three plant density treatments (D1, D2, and D3) at Lincoln during 1999 to 2001. Actual plant densities are shown at upper left of each panel, and vertical bars along the x-axis indicate the date of silking. (from: Yang et al., 2004).

All three models were capable of predicting early-season aboveground dry matter, but they differed in their prediction of biomass after silking (Fig. 4.5.). In general, Hybrid-Maize closely predicted total aboveground dry matter after silking at both sites and at all plant densities, whereas both CERES-Maize and INTERCOM consistently under-predicted dry matter accumulation during the reproductive phase. Note that the short periods of simulated decreases in dry matter accumulation after silking in Hybrid-Maize and CERES-Maize result from the periods of low light intensity or high temperatures when daily requirements for grain filling are not met by net assimilation and translocation of stem carbohydrate reserves makes up the difference.

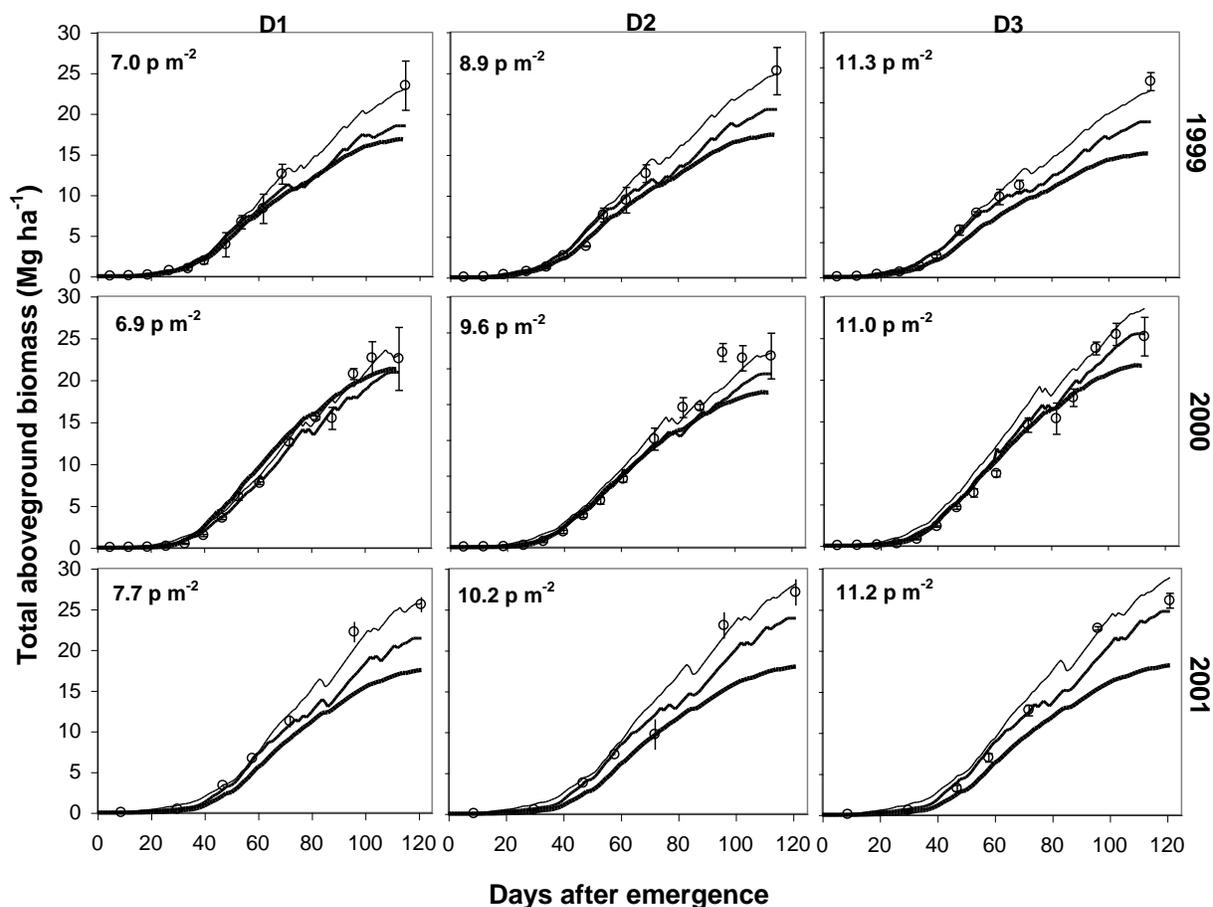


Figure 4.5. Observed (symbols and error bars = mean and SE) total aboveground biomass of maize and biomass predicted by Hybrid-Maize (fine line), CERES-Maize (medium line) and INTERCOM (thick line) models for three plant density treatments (D1, D2, and D3) at Lincoln during the 1999 to 2001 cropping seasons. (from: Yang et al., 2004).

4.4.3. Prediction of Grain Yield

In most studies conducted so far, grain and stover yields and harvest index simulated by Hybrid-Maize were in closer agreement with measured values than simulations by CERES-Maize or INTERCOM (Yang et al., 2004). The improvement in simulation accuracy was especially notable for stover yields for which simulations by CERES-Maize and INTERCOM averaged 18% and 28% less than measured yields.

At Lincoln (NE) and Manchester (IA), grain yields simulated by Hybrid-Maize were within -5% to $+12\%$ of the measured yields across treatments and years (Table 4.2.). Maximum yields in single experimental plots were 14.4 Mg ha^{-1} in 1999 (in a plot with $11.4 \text{ plants m}^{-2}$), 14.0 Mg ha^{-1} in 2000 (in a plot with $9.8 \text{ plants m}^{-2}$), and 14.5 Mg ha^{-1} in 2001 (in a plot with $11.2 \text{ plants m}^{-2}$). These maximum measured yields were in close agreement with the yield potential simulated by Hybrid-Maize of 14.3 Mg ha^{-1} , 14.0 Mg ha^{-1} , and 14.1 Mg ha^{-1} for these same treatment-year combinations. The model was also robust in accounting for differences in grain yield associated with plant density in most years. The largest discrepancy between measured and simulated grain yield occurred at the

highest plant density in 2000, when measured yield at 11.0 plants m⁻² (12.5 Mg ha⁻¹) was smaller than that at a density of 9.6 plants m⁻² (13.6 Mg ha⁻¹). In that year, unusually high temperatures in the second half of grain filling shortened the grain filling period by almost 10 days. It appears that Hybrid-Maize was not sensitive enough to effects of heat stress at very high plant density.

Table 4.2. Measured (M) and predicted (HM, Hybrid-Maize model) grain and stover yields, and harvest index of maize grown at Lincoln, Nebraska (1999 to 2001) and Manchester, Iowa. In both cases, maize growth was under near-optimal conditions. (from: Yang et al., 2004).

Site - year	Plants m ⁻²	Grain dry matter Mg ha ⁻¹		Stover dry matter Mg ha ⁻¹		Harvest index	
		M	HM	M	HM	M	HM
Lincoln 1999	7.0	12.8	12.6	11.3	10.8	0.53	0.55
	8.9	13.4	13.5	12.6	11.9	0.52	0.54
	11.3	14.0	14.3	14.7	12.8	0.49	0.54
Lincoln 2000	6.9	12.5	12.0	10.7	11.3	0.54	0.52
	9.6	13.6	13.4	13.9	14.1	0.50	0.50
	11.0	12.5	14.0	12.7	15.0	0.50	0.49
Lincoln 2001	7.7	13.4	12.7	12.9	13.4	0.51	0.49
	10.2	13.8	13.8	14.2	14.8	0.49	0.49
	11.2	13.6	14.1	13.3	15.2	0.51	0.49
Manchester 2002	8.4	13.5	14.7	10.7	11.8	0.53	0.55
Mean		13.3	13.5	12.7	13.1	0.51	0.52

Predictions of stover yield and harvest index by Hybrid-Maize were also in good agreement with observed values for most year x plant density treatment combinations at Lincoln and Manchester (Table 4.2.). The greatest disagreement between predicted and measured values for stover biomass occurred at the highest plant population in 2000 and 2001 when temperatures during the reproductive phase were above the 17-year mean for the Lincoln site. We suspect that increased respiration losses associated with above-average temperatures during grain filling and high plant density may have reduced yields, and this interaction may not be fully accounted for by Hybrid-Maize.

In 2003, an evaluation was conducted to simulate yields at several field locations in North America (Dobermann and Walters, 2004), including irrigated and rainfed sites (Table 4.3.). Hybrid-Maize closely predicted grain yield of irrigated maize at several locations in Kansas and Nebraska under near-optimal growth conditions. Agreement between measured and predicted yields was less for rainfed maize grown at Champaign, IL, probably because some yield loss occurred due to water stress. However, because no measured information on occurrence of critical growth stages, soil properties, rooting depth and initial soil moisture was available, simulation of the actual rainfed yield was less accurate.

Table 4.3. Measured and predicted (Hybrid-Maize model) grain yields of maize grown in 2003 under near-optimal conditions.

Location – treatment	Grain yield (bu/acre)
----------------------	-----------------------

	Measured	Predicted
Lincoln, NE – silt loam, corn following soybeans, 35000 plants/acre, irrigated, 223 lbs N/acre, 4-way split, +P and K	285	287
Bellwood, NE – loamy sand, continuous corn, 31000 plants/acre, irrigated, 335 lbs N/acre, 5-way split, +P and K	268	273
Cairo, NE – silt loam, continuous corn, 32500 plants/acre, irrigated, 300 lbs N/acre, 2-way split, +P and K	276	275
Paxton, NE – loamy sand, continuous corn, 31800 plants/acre, irrigated, 300 lbs N/acre, 3-way split, +P and K	258	257
Brunswick, NE – silt loam, corn following soybeans, 35000 plants/acre, irrigated, 259 lbs N/acre, 3-way split, +P and K	277	279
Scandia, KS - 28000 plants/acre, irrigated, 300 lbs N/acre, 4-way split, +P, K, and S	223	219
Scandia, KS - 42000 plants/acre, irrigated, 230 lbs N/acre, 4-way split, +P, K, and S	251	252
Champaign, IL, corn/oats/hay rotation, rainfed corn, lime plus fertilizer (Morrow Plots long-term experiment) ¹	261	286

¹ Predicted= simulated yield potential of maize. Actual yield was reduced somewhat by mild water stress. Predicted rainfed yield was 240 bu/acre, using model-defaults for initial soil moisture, bulk density, and maximum rooting depth because those were not measured.

Several studies have been conducted to evaluate the yield-forecasting capabilities of Hybrid-Maize, when run in ‘**Current season prediction**’ mode (see section 2.3.3 and section 3.4 on yield forecasting). In 2003, irrigated or rainfed maize was grown at several sites in Nebraska. Measurements included grain yield, harvest index, dates of phenological events, biomass, LAI, actual and historical daily weather data (1982-2003), and soil moisture dynamics. Yield forecasts were made in intervals of 5 days, beginning shortly after planting. At each prediction date, actual weather data were used in Hybrid-Maize to simulate growth until that date. From that point forward to maturity, the model utilized all measured long-term weather records to simulate all possible growth scenarios for the remainder of the season. No calibration to specific sites or maize hybrids grown was done because that is not realistic for a practical forecasting situation.

At Lincoln, maize was grown at near yield potential levels with full irrigation and nutrient supply and a density of 8.7 plants m⁻². Early in the season, yield forecasts mainly relied on historical weather data so that the median predicted yield was close to the long-term median. As the season progressed, more actual weather data were used, indicating above-normal growth conditions. Predicted median yield approached the final measured grain yield of 17.9 Mg ha⁻¹ shortly after silking. With progressing grain filling, the overall range of predicted possible yields gradually decreased (Fig. 4.6.). At Mead (NE), rainfed maize was grown in a production field at 5.9 plants m⁻². Early in the season, median predicted yield was close to the long-term median. However, very little rain fell in July and August. As the season progressed, drought evolved and the predicted median yield decreased well below the long-term median, approaching the final measured grain

yield of 8.0 Mg ha^{-1} (Fig. 4.6.). Median predictions were close to the final yield about one month before physiological maturity or $1 \frac{1}{2}$ to 2 months before combine harvest. Results from other sites showed similar trends and also good agreement between predicted and measured dynamics of crop biomass accumulation. Figure 4.7. provides an example for a high-yielding maize crop in Argentina.

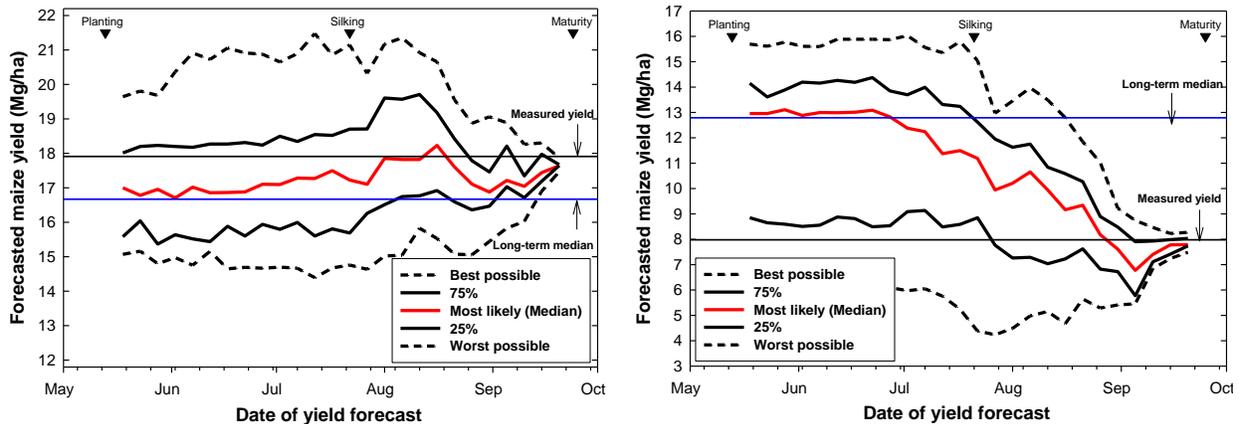


Figure 4.6. In-season forecasting of maize yields in two fields in Nebraska, 2003. LEFT: Irrigated maize at Lincoln. RIGHT: Rainfed maize grown at Mead.

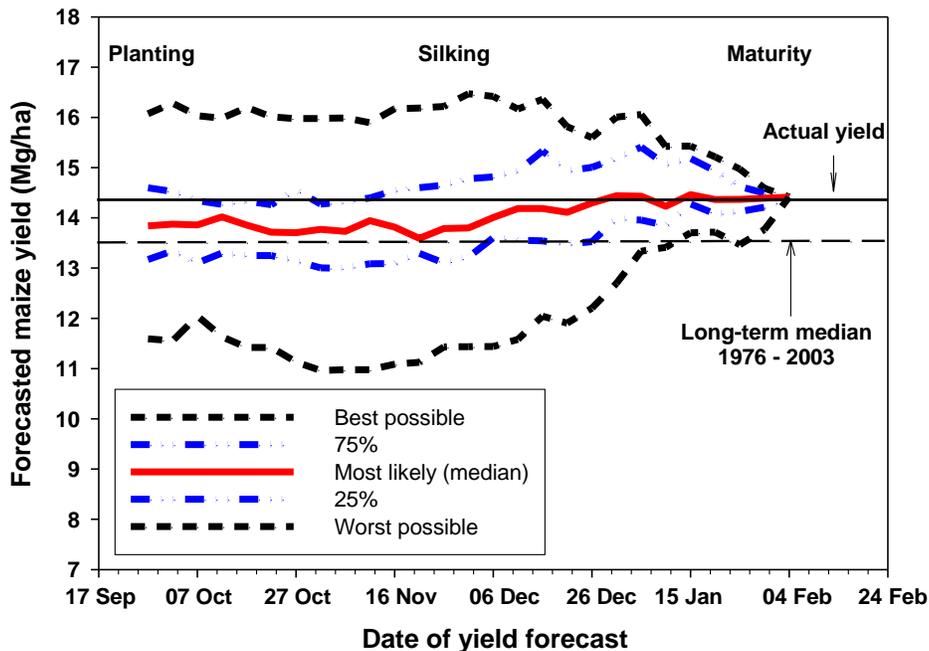


Figure 4.7. In-season forecasting of irrigated maize yield at Oliveros, Argentina, 2003-2004 growing season (data provided by Fernando Salvaggiotti, INTA).

4.5. Uncertainties and Future Improvements

This section is intended to provide a brief summary of major uncertainties or weaknesses in the Hybrid-Maize model that will have to be addressed in future research and, hopefully, can be

overcome in subsequent model releases. Users should always be aware that a crop simulation model is not likely to predict growth and yield under all possible circumstances and that some applications may require a certain degree of local model adaptation. Major known issues are:

- Under optimal conditions, maximum LAI at high plant density was consistently under-predicted by Hybrid-Maize and other crop models (Fig. 4.4.), which indicates that the description of leaf area expansion is still not sufficiently robust when plant densities exceed 9 plants m⁻². Because larger LAI implies greater C and N construction and maintenance costs as well as larger N storage capacity, underprediction of LAI could potentially affect plant C balance and late-stage leaf senescence dynamics.
- The coefficients for maintenance respiration of different organs (see 4.1.3.) are largely unverified under field conditions.
- Hybrid-Maize has mostly been tested with plant populations ranging from about 28,000 to 45,000 plants/acre (70,000 to 110,000 plants/ha). An empirical equation derived for this range is used to describe the effect of plant density on the rate of grain filling (see 4.1.9.). The model should not be used outside this range without further verification. Actual crop response to plant population may also vary significantly among maize hybrids.
- Over-prediction of yield at very high plant density (>100,000 plants/ha) may occur in years with higher than normal temperatures during grain filling (Table 4.1.). The interactive effects of plant density and temperature on gross assimilation and assimilate loss from maintenance respiration are apparently not well accounted for. Addressing this deficiency will require experimental data on respiration costs of different organs at different development stages for a representative range of temperatures and plant density.
- Hybrid-Maize does not account for effects of varying row spacing on growth and yield. All development and validation research was done with maize planted at 30" row spacing (0.76 m).
- Hybrid-Maize has mainly been validated using commercial hybrids that predominantly have a single ear, with relatively little prolificacy. It does not use the formulations proposed by Ritchie and Alagarswamy (2003) for Ceres-Maize because those would add more genetic coefficients and their effects on simulating crop biomass and harvest index are unknown. Moreover, we suspect that prolificacy is not a favorable trait for high-yield maize production systems where high plant density and uniform plant spacing within rows is crucial for achieving yields that approach the yield potential ceiling.
- Model results are sensitive to dates of critical growth stages entered or predicted, particularly dates of silking and physiological maturity. Those dates should only be entered if accurate measurements have been taken. Otherwise, the model appears to do a reasonable job of estimating the date of these events. Date of silking refers to 50% silking, whereas physiological maturity strictly follows the definition provided by Ritchie et al. (1992). Simulated yield can be seriously affected by entering a wrong silking or maturity date. In some cases, however, we have noticed that this may lead to unrealistically long growing season predicted, particularly if maize was planted late, a full-season hybrid with more than 2800 GDD50F from emergence to maturity is grown, and cool weather is predominant during the second half of grain filling. Always verify predicted maturity dates with your own observations

- Simulation results under harsh water-limited conditions must be interpreted and used with caution, particularly in areas that are prone to severe drought stress at different growth stages because the model has not been rigorously validated under such conditions. In the current version of Hybrid Maize, if simulated grain yield is < 2 Mg/ha, a message appears: “WARNING: simulation results are doubtful due to extremely low yield”.
- In stress environments, under-prediction of LAI is likely to have a larger impact on simulated yield than in favorable environments. In Hybrid-Maize, canopy leaf area is simulated by a discontinuous set of equations as in the original CERES-Maize model: one for the period before tassel initiation and another for the period thereafter to silking. This approach provides few opportunities to account for genotypic differences or to simulate the interactive effects of stresses on leaf expansion and senescence (Lizaso et al., 2003a). Such interactions were identified as constraints to accurate prediction of maize growth under stressed conditions (Carberry et al., 1989; Keating et al., 1992). We therefore suspect that the functions for describing leaf expansion during rapid vegetative growth will need improvement in Hybrid-Maize if the model is to be used to simulate maize growth in stress environments. While Lizaso et al. (2003a) have proposed a more detailed, cultivar-specific leaf area model for maize, it requires three additional cultivar-specific input parameters related to leaf growth and expansion that are not typically available for commercial hybrids.
- The original development and validation of Hybrid Maize was mainly done using data sets from the U.S. Corn Belt. Because the model is based on process-based descriptions of crop growth and development it is expected to perform well in a wide range of environments. Nevertheless, caution should be exercised when using Hybrid-Maize outside the U.S. Corn Belt because this may require changes in some of the default model parameters. **International users** should particularly pay attention to the following issues:
 - Users should validate the model in terms of accurate prediction of silking dates. Specifically, validation of the empirical relationship between $GDD_{10\text{silking}}$ and $GDD_{10\text{total}}$ of a hybrid (see 4.1.4.) is required for the most common cultivars grown in a certain region. In some environments, modifying the intercept-offset value (see **Settings → Parameter settings → Crop growth**) or entry of a known GDD to silking (**Maturity → Optional → GDD to silking**) may greatly improve such local customization of the model in terms of accurately predicting silking dates.
 - Hybrid-Maize has not been tested with open-pollinated varieties (OPV) or prolific cultivars bred for two ears per plant. Those may require adjustment of the genetic coefficients under **Settings → Parameter settings → Crop growth**.
 - Default soil physical properties and drainage classes under **Settings → Parameter settings → Soil** may differ for sub-tropical and tropical soils because of different clay mineralogy.

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6. Appendix

6.1. User-modifiable Parameters Describing Crop Growth and Development

Parameter	Default value	Reference
Potential number of kernels per ear (G2). The default value is for high yielding maize hybrids in the U.S. Corn Belt	676 kernels ear ⁻¹	Mean of maize cultivars in Nebraska, Iowa, Illinois and Indiana, Jones and Kiniry (1986)
Potential kernel filling rate (G5). The default value is for high yielding maize hybrids in the U.S. Corn Belt	8.7 mg kernel ⁻¹ d ⁻¹	Mean of maize cultivars in Nebraska, Iowa, Illinois and Indiana, Jones and Kiniry (1986)
Light extinction coefficient (k). The default value is for modern maize hybrids.	0.55	Lizaso et al. (2003b), Maddonni et al. (2001), and Yang et al. (2004).
Fraction of leaf mass that can be translocated to grain per day if leaf mass remains above minimum.	0.005 d ⁻¹	Jones and Kiniry (1986)
Minimum fraction of leaf mass below which no translocation of carbohydrate from leaf to grain is allowed.	0.85	Jones and Kiniry (1986)
Growth respiration coefficient of leaf	0.47 g CH ₂ O g ⁻¹ dry matter	Kropff and van Laar (1993)
Growth respiration coefficient of stem	0.52 g CH ₂ O g ⁻¹ dry matter	Kropff and van Laar (1993)
Growth respiration coefficient of root	0.45 g CH ₂ O g ⁻¹ dry matter	Kropff and van Laar (1993)
Growth respiration coefficient of grain	0.49 g CH ₂ O g ⁻¹ dry matter	Kropff and van Laar (1993)
Maintenance respiration coefficient for leaf	0.01 g CH ₂ O g ⁻¹ dry matter d ⁻¹	Through calibration of data collected in Nebraska
Maintenance respiration coefficient for stem	0.006 g CH ₂ O g ⁻¹ dry matter d ⁻¹	Through calibration of data collected in Nebraska
Maintenance respiration coefficient for root	0.005 g CH ₂ O g ⁻¹ dry matter d ⁻¹	Through calibration of data collected in Nebraska
Maintenance respiration coefficient for grain	0.005 g CH ₂ O g ⁻¹ dry matter d ⁻¹	Through calibration of data collected in Nebraska

Parameter	Default value	Reference
Efficiency of carbohydrate translocation	0.26	Kiniry et al. (1992)
Daily root death rate in fraction	0.005	Jones and Kiniry (1986)
Stay-green coefficient in Eq. (10)	4	Yang et al. (2004)
Fraction of dead leaf at maturity in maximum LAI achieved at silking	0.7	Yang et al. (2004)
Upper effective temperature for GDD accumulation	34 °C	Jones and Kiniry (1986)
Maximum (photosynthetic) assimilation rate at plateau (A_{max})	7.0 g CO ₂ m ⁻² leaf hr ⁻¹	Kropff and van Laar (1993)
Minimum temperature for assimilation	8 °C	Kropff and van Laar (1993)
Starting temperature for maximum assimilation	18 °C	Kropff and van Laar (1993)
Ending temperature for maximum assimilation	30 °C	Kropff and van Laar (1993)
Initial light use efficiency	12.5 g CO ₂ MJ ⁻¹ PAR	Kropff and van Laar (1993)
Upper effective temperature for maintenance respiration	30 °C	Kropff and van Laar (1993)
LAI above which stress due to light competition occurs	4	Jones and Kiniry (1986)
Biomass partitioning coefficient for root at emergence	0.35	Kropff and van Laar (1993)
Development stage (scale from 0 to 2 with silking as 1) when root growth stops	1.15	Kropff and van Laar (1993)
Potential root depth	150 cm	Dardanelli et al, 1997; Djaman and Irmak, 2012
Start of stage-2 soil evaporation as a fraction of total evaporable water (TEW)	0.7	Fig 38 of FAO Report 56. Allen et al (1998)
Offset for calculating GDD _{silking} from GDD _{total}	-50	Yang et al. (2004)

Threshold of water stress index above which canopy expansion stops	0.5	Morgan, 1984; Sadras and Milroy, 1996
Sensitivity of leaf senescence to full water stress after silking, in fraction of LAI per day	0.5	Morgan, 1984; Sadras and Milroy, 1996
Start LAI for adjusting ET reference for full canopy	3.5	Allen et al, 1998
Level-off LAI (i.e., full canopy) for adjust ET reference	4.5	Allen et al, 1998

6.2. Default Soil Physical Properties for Different Soil Texture Classes

Texture	Porosity	GAM cm ⁻²	PSI _{max} cm	K _{sat} cm d ⁻¹	alfa cm ⁻¹	AK cm ^{-2.4} d ⁻¹
loamy sand	0.44	0.033	200	26.5	0.0398	16.4
silt loam	0.51	0.185	300	6.5	0.02	47.3
Loam	0.50	0.018	300	5.0	0.0231	14.4
sandy clay loam	0.43	0.0096	200	23.5	0.0353	33.6
silty clay loam	0.45	0.0105	300	1.5	0.0237	36.0
clay loam	0.45	0.0058	300	0.98	0.0248	1.69
light clay	0.51	0.0085	300	3.5	0.0274	2.77
silty clay	0.51	0.0065	50	1.3	0.048	28.2
clay	0.54	0.0042	80	0.22	0.038	4.86

Adapted from Driessen and Konijn (1992).

6.3. Guideline for estimating ground coverage of corn and soybean residues. From Nebraska Extension publication G95-1134-A.

Corn residues

Soybean residues



Table 6.4a* Default Curve Numbers (CN) for different field slopes and drainage classes.

Field slope (%)	Drainage class		
	Excellent	Good	Poor
<2	61	73	84
2-5	64	76	87
5-10	68	80	91
>10	71	83	94

Table 6.4b* Description of soil drainage classes

Drainage class	Description	Soil texture and depth
Excellent	Somewhat excessively to excessively drained	<ul style="list-style-type: none">• Deep sandy soils (>1.5m; loamy sand or sandy loam)
Good	Moderate to moderately well drained	<ul style="list-style-type: none">• Shallow sandy soils (<1.5 m; loamy sand or sandy loam)• Soils with intermediate textures (any depth; loam, silt loam)• Deep soils with light clay textures (depth >1.5 m; silty clay, silty clay loam or clay loam).
Poor	Somewhat poorly to very poorly drained	<ul style="list-style-type: none">• Heavy clay soils (any depth; clay)• Shallow soils with light clay textures (<0.8 m; clay, silty clay, silty clay loam or clay loam)

*Adapted from Ritchie *et al.* (1990) and Gijsman *et al.* (2007).

6.5. Simulation of Major Processes in Different Models

Processes	CERES-Maize	INTERCOM	Hybrid-Maize
Photosynthesis computation	Constant RUE used to directly convert absorbed PAR into DM, adjusted for T; daily time-step for PAR interception without regard to solar angle.	Total intercepted PAR is split into direct and diffuse parts; solar angle considered; integrated over LAI distribution; adjusted for T.	Simplified version of INTERCOM routine, but without splitting total intercepted PAR into direct and diffuse parts and intra-day changes in solar angle.
Maintenance respiration	Not simulated but implicitly 'discounted' in the constant RUE value.	Based on live biomass and coefficients of 0.03, 0.015, 0.01 & 0.01 g CH ₂ O respired per g DM per day for leaf, stem, root & grain respectively, at 25°C; Q ₁₀ of 2.	Similar to INTERCOM, but with lower coefficients: 0.011, 0.006, 0.006 & 0.005 g CH ₂ O per g DM per day for leaf, stem, root and grain, respectively.
Leaf area expansion and senescence	Driven by T as a function of leaf number and assimilate availability; senescence driven by T.	Driven by assimilate availability, DM partitioning coefficients, and SLA; partitioning coefficients change with growth stage; senescence driven by T.	Similar to CERES-Maize until silking with SLA limited to ≤ 400 cm ² g ⁻¹ ; leaf senescence after silking modified.
DM accumulation	Driven by T as a function of phenology, limited by assimilate availability; excess assimilate partitioned to roots.	Driven by assimilate supply and regulated by DM partitioning to all organs; partitioning coefficients change with growth stage.	Similar to CERES-Maize but with modification in dry matter partitioning to root; SLA limited to ≤ 400 cm ² g ⁻¹ .
Date of silking	Input parameter, hybrid specific.	Input parameter, hybrid specific.	Either as input parameter or estimated by: $GDD_{\text{silking}} = 100 + 0.4451 GDD_{\text{total}} - 50$
Cob growth	Driven by T as a fixed proportion of daily assimilation from silking until GDD=170 after silking.	Simulates mass of whole reproductive organ, including seed and cob.	Similar to CERES-Maize but DM partitioning to cob reduced by 60%.
Grain filling and translocation	Filling rate driven by T, assimilate supply and potential filling rate; potential filling rate is hybrid specific; limited translocation from stem and leaf reserves occurs when source < sink with a translocation efficiency of 26%.	Filling driven by assimilate supply; amount of translocated assimilate is a fixed proportion of 'live' DM loss from stem and leaf senescence.	Translocation and grain filling similar to CERES-Maize, actual grain filling rate is adjusted by plant density.

Abbreviations: RUE = radiation use efficiency; DM = dry matter; T = temperature; PAR = photosynthetically active radiation; LAI = leaf area index; SLA = specific leaf area; GDD = growing degree days; GDD_{silking} = GDD from emergence to silking; GDD_{total} = GDD from emergence to maturity.