## 4.4. Sensitivity Analysis and Model Validation

So far, validation of Hybrid-Maize has mainly been conducted for maize grown under irrigated and favorable rainfed conditions in North America. Validations on rainfed maize grown in areas with more severe drought stress have been limited. No validation of the soil water component has been conducted for soils found in subtropical or tropical regions.

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 ($\varepsilon$), 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 ±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 ($\varepsilon$) (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 $\varepsilon$, 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.

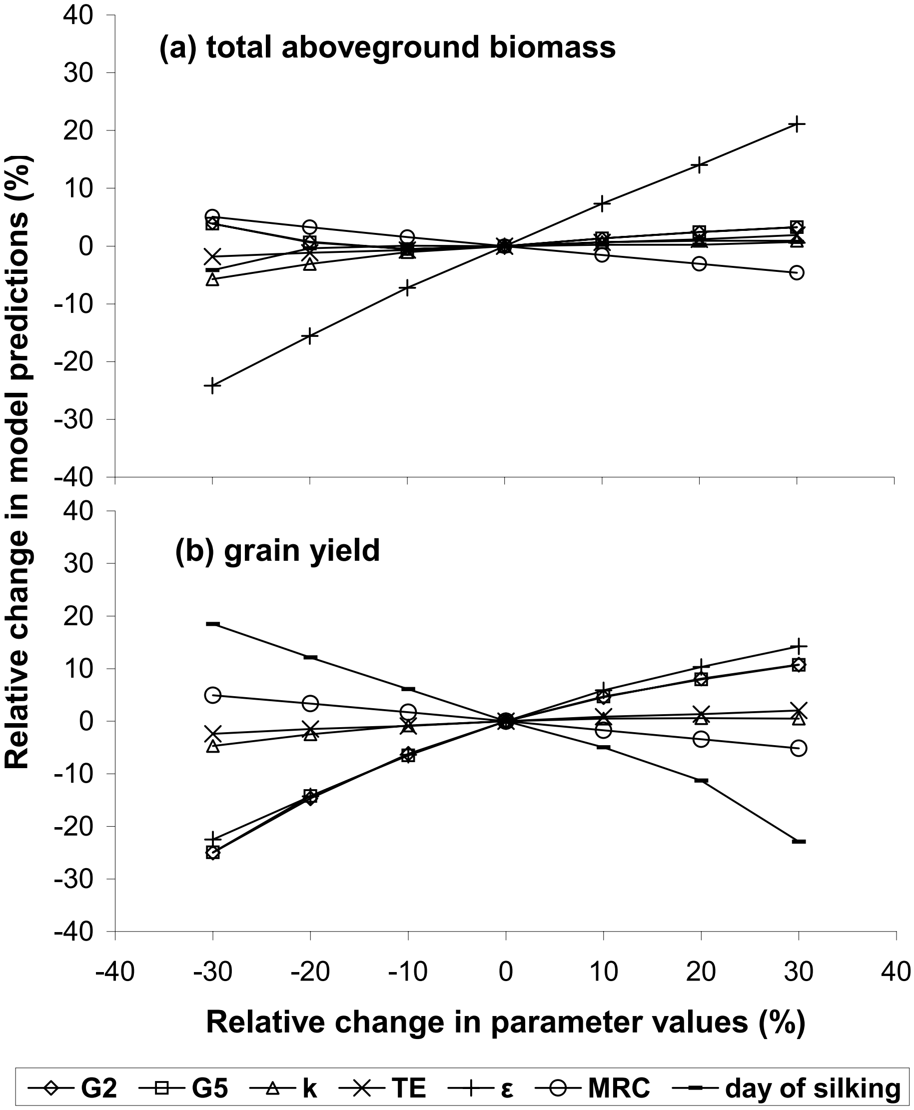

**Figure 4.3.** Sensitivity analysis of the Hybrid-Maize model using weather data for Lincoln, NE (from: Yang et al., 2004).

### *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.

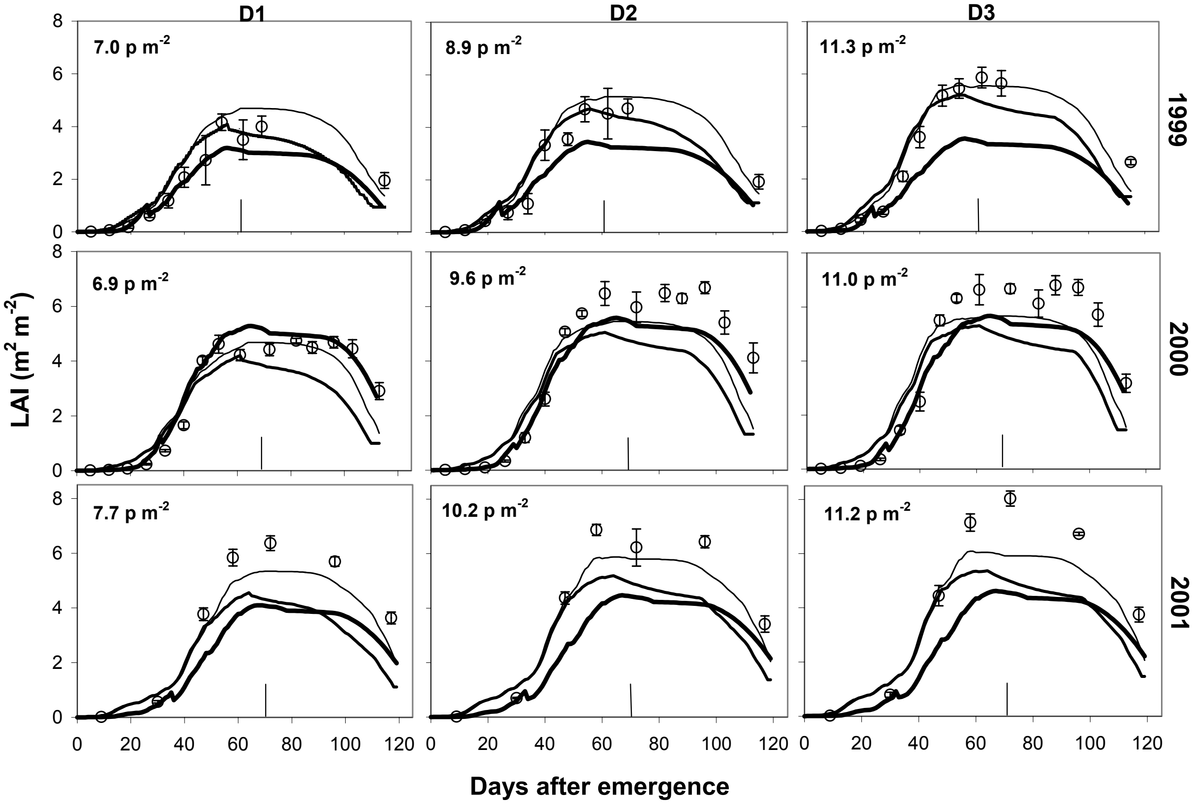

**Figure 4.4.** Observed (symbols and error bars = mean and SE) leaf area index (LAI) of maize and LAI predicted by Hybrid-Maize (fine line), CERES-Maize (medium line), and INTERCOM (thick line) for three plant density treatments (D1, D2, and D3) at Lincoln during 1999 to 2001. Actual plant densities 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.

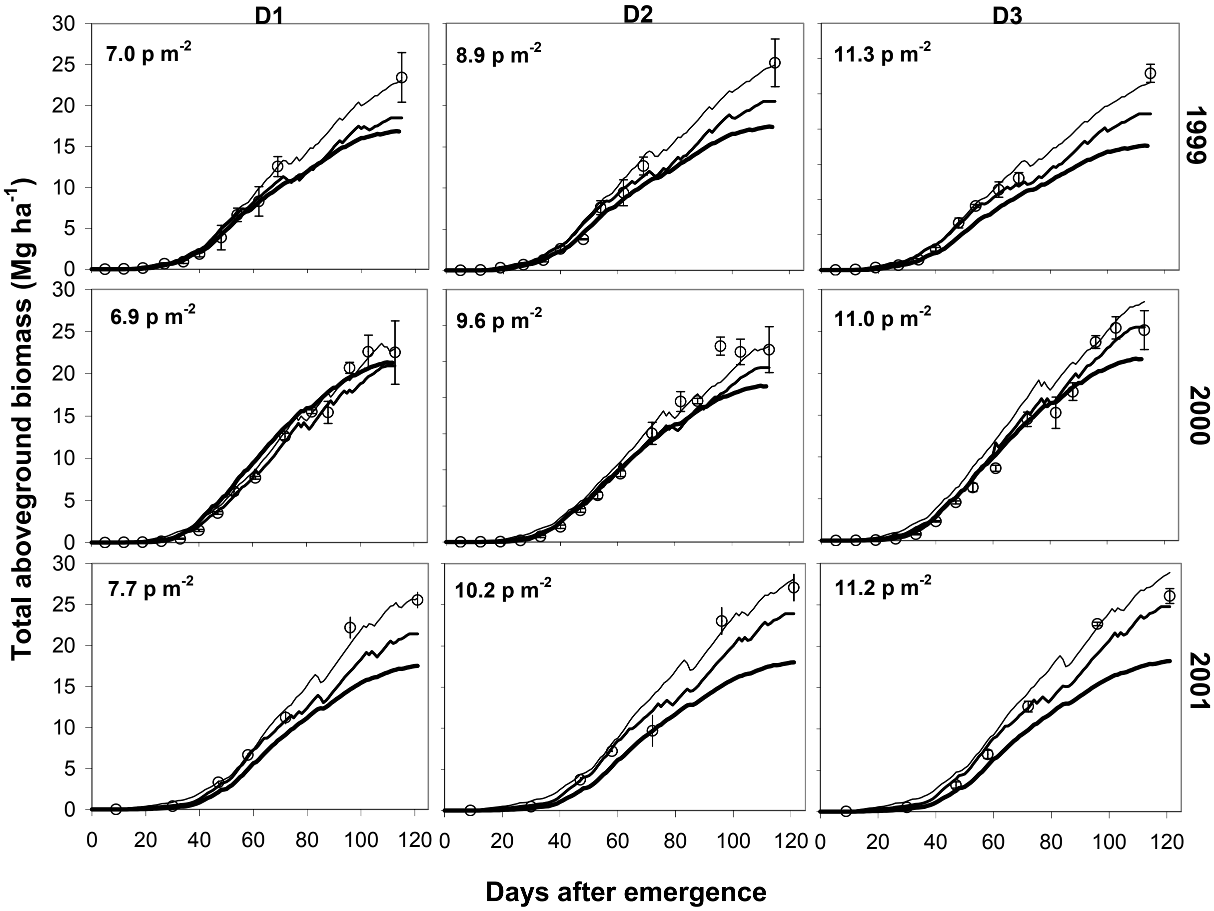

**Figure 4.5.** Observed (symbols and error bars = mean and SE) total aboveground biomass of maize and biomass predicted by Hybrid-Maize (fine line), CERES-Maize (medium line) and INTERCOM (thick line) models for three plant density treatments (D1, D2, and D3) at Lincoln during the 1999 to 2001 cropping 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 plants m$^{-2}$), 14.0 Mg ha$^{-1}$ in 2000 (in a plot with 9.8 plants m$^{-2}$), and 14.5 Mg ha$^{-1}$ in 2001 (in a plot with 11.2 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 ½ 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.

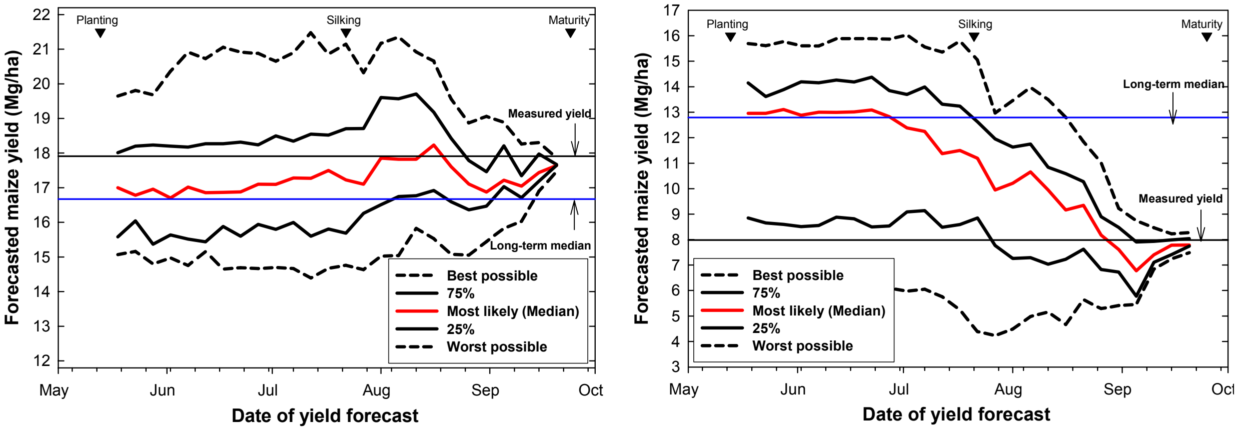

**Figure 4.6.** In-season forecasting of maize yields in two fields in Nebraska, 2003. LEFT: Irrigated maize at Lincoln. RIGHT: Rainfed maize grown at Mead.

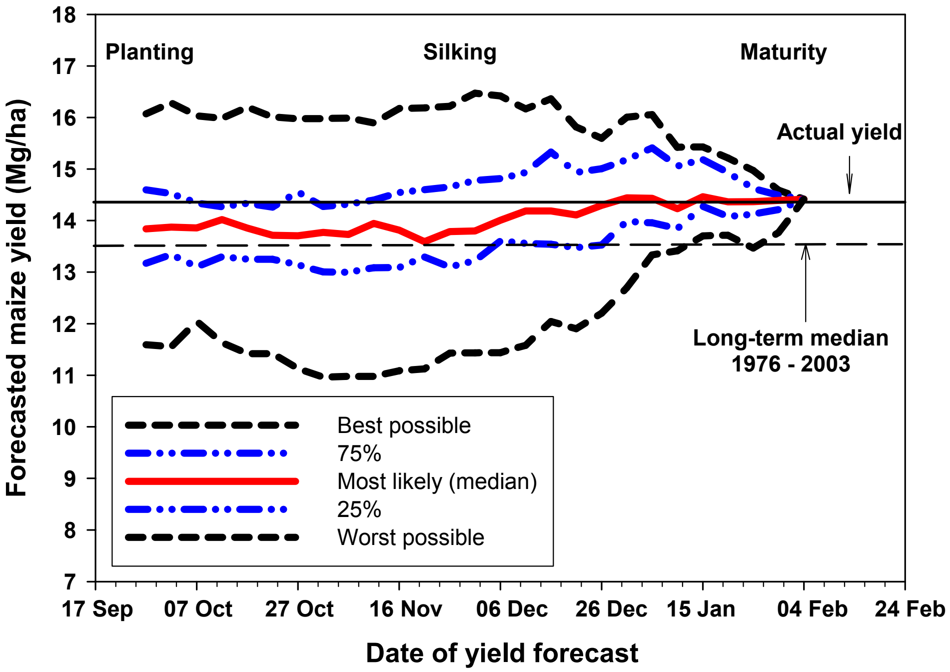

**Figure 4.7.** In-season forecasting of irrigated maize yield at Oliveros, Agrentina, 2003-2004 growing season (data provided by Fernando Salvagiotti, INTA).

### 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 degreed of local model adaptation. Major known issues are:

- Under yield potential 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 25,000 to 45,000 plants/acre (60,000 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 high plant density (>90,000 plants/ha) may occur in years with high temperature stress at silking or higher than normal temperatures during grain filling (Table 4.1.). The interactive effects of plant density and temperature on silking, kernels set, kernel survival, gross assimilation and assimilate loss from maintenance respiration are apparently not well accounted for.

- Hybrid-Maize does not allow simulating interactive effects of varying row spacing and plant population on growth and yield. All development and validation research was done with maize planted at 30” row spacing (76 cm), although the model has also been applied in narrow-row maize (38-50 cm)

- Hybrid-Maize has mainly been validated with 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 very 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.

- Hybrid-Maize simulates maize growth and yields under optimal water regime (yield potential) as well as water-limited conditions. Most of the model validation so far has 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. Simulation results under water-limited conditions must be interpreted and used with caution, particularly in areas that are prone to severe drought stress at different growth stages of maize because the model has not been rigorously validated under such conditions.
- 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.
- 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 $\text{GDD}_{10\text{silking}}$ and $\text{GDD}_{10\text{total}}$ 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 cultivars bred for two ears per plant. Those may require adjustment of the genetic coefficients under **Settings → Parameter settings → Crop growth**.
    - Default soil physical parameters for different soil texture classes under **Settings → Parameter settings → Soil** may differ for sub-tropical and tropical soils because of different clay mineralogy.

Future model improvement will focus on (i) addressing some of the uncertainties listed above, (ii) adding a nitrogen module to make decisions on N use, (iii) adding a module for estimating total N, P, and K fertilizer requirements, and (iv) adding a module for simulating carbon and nitrogen turnover from crop residues and the soil organic carbon and nitrogen balance.

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