Reducing Corn Yield Variability and Enhancing Yield Increases Through the Use of Corn-Specific Growth Models.

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ABSTRACT

Crop simulation models (CSMs) are used to evaluate management and environmental scenarios on crop growth and yields. Two corn (*Zea Mays* L.) crop growth simulation models, Hybrid-Maize, and CERES-Maize were calibrated and validated under Virginia conditions with the goal of better understanding corn response to variable environmental conditions and decreasing temporal yield variation. Calibration data were generated from small plot studies conducted at five site-years. Main plots were plant density (4.9, 6.2, 7.4, and 8.6 plants m^{-2}); subplots were hybrids of differing relative maturity (RM) [early = Pioneer® Brand ‘34B97’ (108 day RM); medium = Pioneer® Brand ‘33M54’ (114 day RM); and late = Pioneer® Brand ‘31G66’ (118 day RM)]. Model validation was generated from large scale, replicated strip plot trials conducted at various locations across Virginia in 2005 and 2006. Prior to model adjustments based on calibration data both CSMs under predicted corn grain yield in calibration and validation studies. CERES-Maize grain yield prediction error was consistent across the range of tested plant density while accuracy of Hybrid-Maize varied with plant density. Hybrid-Maize-estimated biomass production was highly accurate. Greater leaf area index (LAI) and biomass production were measured than was predicted by the CERES-Maize CSM. Both CSMs were modified based on calibration data sets and validated. Validation results of the calibrated CSMs showed improved accuracy in simulating planting date and environmental effects on a range of corn hybrids grown throughout Virginia over two years. We expect that both modified models can be used for strategic research and management decisions in mid-Atlantic corn production.

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INTRODUCTION

Since 1984, the annual average corn (*Zea Mays* L.) grain yield in Virginia has differed from the long-term average grain yield by more than 0.27 Mg ha^{-1} in nine years compared to the state of Iowa where this has occurred only twice in the same 20-yr period. Lack of consistent profitability is a major concern for Virginia corn growers and in our current agricultural system; profitability is directly tied to final grain yield. Years with low yields are seldom profitable. Based on Virginia Cooperative Extension budgets compiled for corn grain, no-till corn yielding 0.90 Mg ha^{-1} has a breakeven cost of $134 Mg^{-1} while no-till corn yielding 1.36 Mg ha^{-1} has a breakeven price of $100 Mg^{-1}. The need to stabilize corn yields across years and to avoid very low yields whenever possible is apparent.

Identification and evaluation of the factors contributing to year-to-year fluctuation in crop yields could provide a basis for the assessment of production risk and for adjustments in management practices to reduce risk. The ideal balance of yield building and yield protection factors is required to maximize grain production in a given environment; however this ideal varies as frequently as environment.

Weather, and particularly rainfall during the growing season, is the major determinant of corn grain yield in the mid-Atlantic, but management activities can be planned to maximize yields in a particular environment. Identification of optimum growing season length, optimum times for planting and silking, and avoidance of historic drought times will be important. Optimum plant population varies with site and year depending on yield potential but generally increases with increasing yield.

Corn growth simulation models enable an almost unlimited number of soil and climatic combinations to be tested for influence on yield. These models also enable users to determine how changes in management, i.e. planting date, affects the yield under the selected environmental conditions.

Corn growth simulation models are mathematical representations of plant growth processes as influenced by genotype, environment, and crop management. They are used by crop managers, researchers, and policy makers. Previously, crop models for corn development were of two main types, one group was not crop specific and relied heavily on photosynthesis and respiration information that was applicable to all warm-season grasses, the other group of models was highly specific for corn, required a large amount of data input and featured simplified environmental drivers for plant physiological events. Newly developed models, such as Hybrid-Maize incorporate portions of both generic and crop-specific models. Increased availability of online long-term weather data and improved personal computer performance and capacity are creating new and emerging uses for crop growth simulation models. The confluence of greater data access and computing power with more accurate, validated corn-specific growth models led us to evaluate two corn growth models for potential use in Virginia. Small plot research studies were conducted in 2005 and 2006 to collect data to calibrate model parameters. Concurrently, data were collected from on-going hybrid performance trials conducted by a number of Virginia Cooperative Extension Agents for use in model validation.

LITERATURE REVIEW

Corn production and climate

Corn is mainly cultivated between 30°and 55° latitude with the bulk of production at latitudes below 47° because of a limited frost-free period in more northern areas (USDA-FAS). Significant corn production also occurs year-round at tropical latitudes from near sea level in winter to elevations of several thousand meters in summer.

Table 1.1 World corn production by country for the 10 largest-producing countries. USDA FAS.

Country	Production, 1000 Metric tons	% of Global Production
US	276525	40.3
China	132741	19.3
EU	57541	8.4
Brazil	42425	6.2
Mexico	21338	3.1
Argentina	18450	2.7
India	14713	2.1
Canada	9194	1.3
South Africa	8763	1.3
Ukraine	7300	1.1
Others	96462	14.2
Total	685451	

The cold tolerance (latitude) limit for corn is a combination of frost-free days and overall cool temperatures. Production is generally impractical where mean midsummer temperature is <19°C or where midsummer nighttime temperatures are below 13°C. Most production occurs in areas with mean summer temperatures between 21 and 27°C and a frost-free period greater than 120 days (Shaw, 1988) (Table 1.1).

Cool, but not cold, nighttime temperatures within this framework favor high yields.

Moisture

Corn generally requires 41 to 64 cm of water to product an acceptable crop yield (Hanway, 1966; Shaw, 1977) but others have reported normal yields with as little as 30 cm (Lamm et al., 1995; Robins and Rhodes, 1958). In the drier western portion of the Corn Belt, supplemental irrigation is necessary to produce corn when season rainfall is below 43 cm, but corn will respond to irrigation at much higher rainfall levels depending on soil moisture and rainfall distribution (Neild and Newman 1986). Excessive rainfall can be detrimental to corn production, especially with standing water or ponding, however corn is grown in areas that receive more than 500 cm annual rainfall (Shaw 1988). When corn is grown in drier areas, yields are highly variable depending on temporal rainfall unless the crop is irrigated (Follett et al., 1978).

Atmospheric demand for water drives the need for moisture above that required by the plant. The wide range in the reported water needs to produce a corn crop can be attributed to the variability of evapotranspiration (Devi and Rao, 2002). Atmospheric water demand is a function of solar radiation (energy), wind which moves the moisture away from the evaporating surface of the leaf, humidity, and air temperature. Air temperature is related to the temperature of the evaporating surface and also affects the dryness of the atmosphere by varying its capacity to hold water. Radiation is usually considered the major factor controlling atmospheric demand with greater radiation associated with greater water demand as well as plant growth (Lindquist et al., 2005).

Water for the corn crop may come from in-season rainfall, from moisture stored within the effective rooting depth of the soil profile, irrigation, or any combination of these. The influence of growing season rainfall on corn grain yield is dependent on the amount of plant available water held by the soil. In light textured soils with low water holding capacity, corn is mostly dependent on rainfall or irrigation to supply this water need while some soils may be able to provide at least half of this amount.

Water use varies with crop stage. In the early season, water use – or loss – is mostly associated with evaporation from soil with plant transpiration increasing in magnitude with increasing plant size. Shaw (1981) reported the evapotranspiration (ET) of corn to be 0.2 to 0.25 cm per day during early vegetative growth in Iowa. The factor increased to approximately 0.5 cm per day beginning just prior to silking and continued at this level for approximately 20 days. After this point, ET gradually decreases daily until the crop reaches physiological maturity.

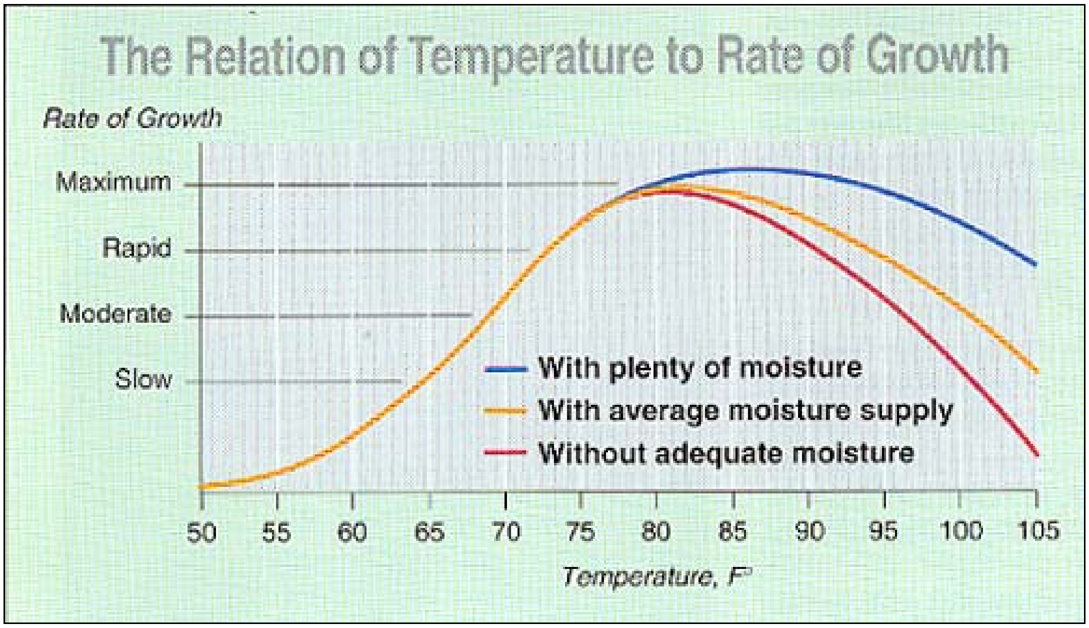
Moisture stress during early grain fill can result in significant grain yield decreases (Claassen and Shaw, 1970a). Generally, the later in the season the stress occurs post pollination, the less the impact on grain yield. During the late vegetative and early reproductive stages, corn water demand is highest and because this period generally occurs during mid-summer, it is also a period of high evaporation which results in a highly negative water balance unless large rainfall events occur.

Since plant water use influences total water use to such a large degree, plant population density impacts crop water use. Low plant density results in lower overall water use. As plant density increases, water use increases linearly to a maximum point and will remain there as long as water supply meets this demand. A point is reached at which higher plant density does not increase utilization of solar radiation per unit of ET (Kiniry et al., 2005). This point depends to a large degree on water holding capacity of the soil and rainfall patterns. Optimum use of available water on soils with relatively less available water requires lower plant density than on soils with greater available water (Liang et al., 1991; Norwood, 2001).

Temperature

The actual number of calendar days required to reach particular developmental points in the corn life cycle can vary widely from season to season. However, the rate of corn crop development is highly dependent on temperature. Corn growth proceeds at a slow level beginning at approximately 10°C and increases at a near-linear rate until temperatures approach 30°C (Cross and Zuber, 1972). As temperatures near this upper limit the rate of response of plant performance to increased temperature slows and may depend on overall water availability. Plants under water stress have a lower maximum threshold temperature (up to 4°C less) than plants under ideal water conditions (Figure 1.1).

Figure 1.1 Hypothetical corn growth rate in response to in-season temperature.



Authors: S.R. Aldrich, W.O. Scott, and R.G. Hoeft. April 1986.

This understanding of corn growth in response to temperature has lead to the concept of growing degree days (GDD) (Bonhomme et al., 1994). The GDD approach provides a more constant and uniform way of estimated corn growth in response to variable environmental conditions. One widely used, remainder-based index to calculate GDD is shown in equation 1, as proposed by Cross and Zuber (1972).

Equation 1.1

$GDD = (T_{max} + T_{min})/2 - T_{base}$

where T_{max} is maximum daily temperature and is set equal to 30°C when temperatures exceed this level

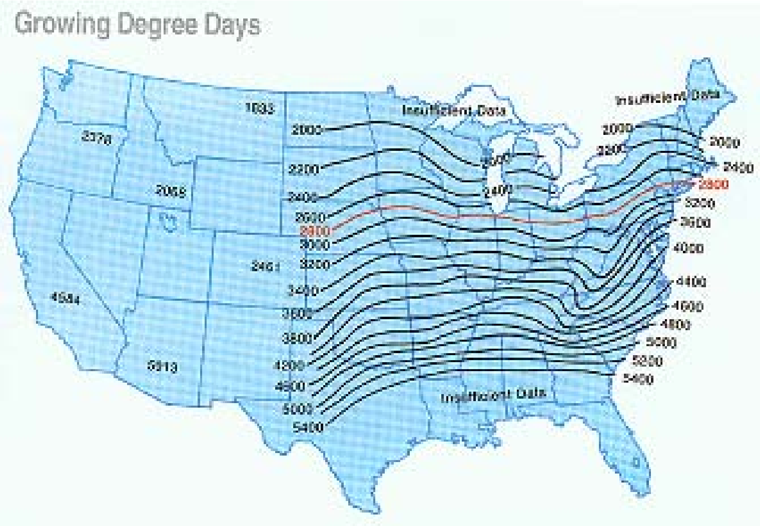
T_{min} is minimum daily temperature and is set equal to 10°C when temperatures fall this point

T_{base} is the base temperature for corn, 10°C

The average seasonal GDD accumulation for the corn growing areas of the US is shown in Figure 1.2. Areas with fewer than 2800 GDD cannot support the growth of full season hybrids due to the limited frost-free period.

The length of time necessary for corn to germinate and emerge after planting depends on soil temperature, moisture, aeration, and seed vigor. Air temperature only impacts corn development at this time indirectly and only as it applies to soil temperature. Prior to germination, seeds imbibe water and swell, triggering enzyme activity. Less water imbibition is required for seed germination with higher soil temperatures (Blacklow, 1972). Planting depth also influences the time to emergence (Alessi and Power, 1971) but is far less important than the effect of temperature.

Figure 1.2 Average growing season GDD accumulation for the continental US.



Authors: S.R. Aldrich, W.O. Scott, and R.G. Hoeft. April 1986.

Optimum planting date is largely dependent on temperature. Early plantings generally produce higher overall yields in northern areas by increasing the length of season prior to killing freeze (Begna et al., 2001) and in more southern latitudes due to avoidance of the highest seasonal temperatures (Bruns and Abbas, 2006). Optimum planting date is also heavily influenced by the coincidence of seasonal moisture trends with crop demand. Most agronomists recommend that planting begin when soil temperatures measured mid-morning average 10°C, however there has long been a trend toward earlier planting. This is due to many factors including larger farm size, seed with greater cold tolerance, and tillage/management schemes that enhance soil warming in the area of the planted seed. Baker and Swan (1966) found that air temperatures of 10°C closely approximated similar soil temperatures at planting depth. At higher air temperatures, the planting zone was similarly warmer. Under conventional tillage, soil is warmed by solar radiation, in many cases to temperatures above air temperatures because soil retains a greater degree of energy. This effect is reversed under high residue conditions and soil at planting depth may remain cooler than air temperature under no tillage conditions.

Cold, wet weather not only delays emergence of seed, but also favors development of pathogens. Seedling diseases and other early-season blights (especially *Pythium* spp.) are often more severe with unfavorable conditions (Broders et al., 2007). At least their impact is much greater when corn growth is slower. Insect pests are also influenced by early season temperatures. Normal planting dates in Virginia result in corn that is naturally protected from first generation European Corn Borer (ECB) (*Ostrinia nubialis*) because of the early developmental stage at the time of primary egg hatch (Youngman and Day, 1999). Later plantings are more susceptible at the time of hatch of the second generation of ECB larvae. Current insecticide seed treatments and the development of hybrids with genetically engineered resistance to ECB have decreased these threats and have further increased the acceptable corn planting window.

The time to silking for a particular hybrid depends heavily on in-season temperatures. Time to silking can vary as much as 20 days for the same hybrid when average temperatures increases from 20°C to 32°C during the growing season (Bonhomme et al., 1994). Numerous researchers have demonstrated that while the number of calendar days from emergence to silking varied considerably for the same hybrid, solar radiation requirement was similar over several evaluations (Allen et al., 1973; Boedhram et al., 2001; Howell et al., 1998)

Effects of Stress

Moisture stress impacting newly emerged seedlings results in decreased starch and chlorophyll (Maranville and Paulsen, 1970). However, dry weather in the weeks immediately after emergence prompts roots to explore deeper in the soil profile which may result in plants that are more able to tolerate later season drought conditions (Smit and Groenwold, 2005). Excess early-season moisture can also result in plant death or developmental delays during early vegetative growth.

Soil temperature controls corn root development to a great degree. Grobbelaar (1963) demonstrated that under constant light and air temperature conditions, soil temperature decreases from 20 to 5°C resulted in retarded development of crown roots. Once plants reached 20 days of age, soil and air temperatures appear to have similar and equal impacts on plant growth.

Young corn is tolerant of very cold temperatures, at least until the growing point moves above the soil surface. When the growing point is below the soil surface, (prior to V6) freezing temperatures may injure the aboveground portion of the plant but it will most likely regenerate and this damage usually results in only marginally diminished yields. Freezing temperatures that occur when corn is past the V6 stage usually result in major losses.

Moisture or nutritional stress that occurs in tandem with tasseling and silking can also result in severe yield loss because degree of ovule fertilization is affected by stress. High levels of stress can delay silking and since silking must coincide with pollen shed for fertilization to occur, anything than disrupts this timing will result in poor pollination and low yields. Claasen and Shaw (1970b) found that stress during early silking reduced yield by 3% per day, but that at 75% silking, this same level of stress resulted in yield loss of 7% per day.

The rate of increase in corn leaf area during early vegetative growth is most closely related to temperature (Ragland et al., 1965) for early plantings but later plantings were found to be related to solar radiation as much as temperature. The maximum rate of season long dry matter production of corn plants has been reported to occur at 27°C (Allmaras et al., 1964). Early season weather has little overall correlation with final grain yield (McCormick, 1980). This is likely due to the relatively small impact of moisture stress during early season compared with the much greater impact of stress that occurs near silking.

During late vegetative growth, there is a greater relationship between weather and final grain yield. In fact, Thompson (1986) found that corn grain yield in the corn belt states varied only slightly from the long term averages when growing season temperatures were near the long term average, yields were greater when July and August temperatures were lower than the long term average, and below average when July and August temperatures were higher than the long term average.

Modeling

Crop models simulate the effect of climate and management practices on the soil-plant ecosystem (Juang et al., 1989). Climate input variables are typically available daily, and so the time step of most functions occurs on a daily basis, however the time step for model validation is typically longer-term and driven by the time between major crop physiological events. Most crop models consist of separate programs or modules operating together that integrate a number of measureable variables (Jones et al., 2003). These variables, such as aboveground biomass or LAI, are chosen because they are reasonably easy to measure and accurately reflect the measured system productivity.

Many models simulate plant productive potential under nonlimiting conditions, however some allow the introduction of stress. Abiotic stress is generally defined as conditions that reduce plant processes or functions (Brisson et al., 2006). In models, stress is thus represented by reduction functions based on the limiting factor principle. These functions greatly simplify what occurs in plants in response to stress but they are generally accurate in reflecting the impact of a single stress on plant productivity. Interaction among multiple stress factors is a much more complicated process and is not well represented by simple reduction functions.

As noted in the previous section, a number of research breakthroughs in understanding plant physiological processes and functions occurred in the 1970’s. The first crop models were developed based on improved understanding of the linkage between photosynthesis and respiration (de Wit, 1978). Similarly other plant physiological processes were found to be related to plant growth functions, for example between LAI and gross photosynthesis (Duncan, 1971). The concept of radiation use efficiency as introduced by Spaeth and Sinclair (1985) was a major step in that it provided a simplified, universal function that approximated plant growth rate and was based on an easily measured input. Early models such as SUCROS (de Wit, 1978) were designed to further the understanding of plant response to environmental inputs specifically for teaching. Later models, including many crop specific ones such as the CERES group (Ritchie and Otter, 1984) and CROPGRO (Boote et al., 1998) placed much greater emphasis on agronomic outcomes and so focused much more heavily on management input effects on modeled crop performance. The EPIC growth model (Williams et al., 1984) diverged from this path and was created to investigate the impacts of ecosystem processes, such as soil erosion, on plant productivity. Over time, many of these models were improved through testing in a number of environments. Many also have received additional modules to deal more accurately with soil or environmental processes or with stress (Gabrielle et al., 1995). By virtue of importance and widespread culture, annual cash crops are where most modeling effort has been focused.

The crop growth models we evaluated estimate crop development through the season as a function of temperature and photoperiod. The effect of light and temperature is integrated through the use of GDD (Bonhomme et al., 1994). Leaf canopy development is described by the LAI at a given point in time, which is leaf surface area per unit area of measurement. Using the LAI approach bases the rate of intercepted photosynthetically active radiation on Beer’s Law which allows use of a relatively simple general calculation. CERES-Maize also employs the use of specific leaf area, which is the ratio of foliage area to mass. The approach is thought more effective in early season growth and it allows the integration of stress to slow leaf development. This model then successively uses temperature alone to drive leaf development (Jones and Kiniry, 1986). Radiation use efficiency is the slope of the linear increase in biomass and radiation intercepted. This relationship forms the basis for biomass accumulation in many corn-specific models including CERE-Maize, however Hybrid-Maize utilizes explicit functions for photosynthesis and respiration found in generic crop models combined with a simplified formulation for phenological development derived from CERES-Maize (Yang et al., 2004). In both cases, the potential supply of assimilate from the plants, the source, and the continuous demand of the grain for these assimilates (the sink) are combined to determine final grain yield. Sink size is calculated based on genetic parameters of the particular hybrid studied and depends on crop growth and environmental conditions prior to flowering.

Crop models are tools that can be used to evaluate agronomic practices prior to experimentation as well as other uses (Boote et al., 1996). They also provide teaching experiences in the ecophysical reactions of plants with the environment. Overall, models can provide a robust conceptual representation of crop performance. However, the overall system is much too complex to simulate all processes, so only specific, crop production relevant functions are generally addressed. These models assume that the unit to be simulated, for example the field, is homogenous in terms of soil, climate, and farming practices. This is rarely the case and these and other limitations should be kept in mind when interpreting or extrapolating modeled results.

PLANT DENSITY AND HYBRID IMPACTS ON CORN GRAIN AND BIOMASS YIELD AND NUTRIENT UPTAKE

ABSTRACT

Corn (*Zea mays L.*) production recommendations should be periodically evaluated to ensure that production practices remain in step with genetic improvements. Since most of the recent increases in corn grain yield are due to planting at higher densities and not to increased per-plant yield, this study was undertaken to measure the effects of plant density and hybrid on corn forage and grain yield and on nutrient uptake. Plant density (4.9, 6.2, 7.4, and 8.6 plants m^{-2}) and hybrid relative maturity (RM) [early (108 day RM); medium (114 day RM); and late (118 day RM)] combinations were evaluated over five site-years that included irrigated and non-irrigated conditions. There was no interaction of hybrid with plant density for grain, stem, or leaf biomass. The late RM hybrid out-yielded the medium and early hybrids by 550 and 1864 kg ha^{-1}, respectively. Grain yield was highest at 8.6 plants m^{-2}. Total stem yield was also greatest at the highest plant density but by only 340 kg ha^{-1} more than at 7.4 plants m^{-2}. Based on grain yield response over sites, the estimated optimum density was 7.6 plants m^{-2}, which is 0.7 plants m^{-2} higher than the current recommendation at this average yield level (11.5 Mg ha^{-1}). Grain nitrogen (N), phosphorus (P), and potassium (K) uptakes were highest for the medium RM hybrid. Nutrient uptake levels varied by planting density, with the lowest levels observed at the lowest and highest plant densities. At 4.9 plants m^{-2}, the reduced uptake is explained by lower biomass yields. At the 8.6 plants m^{-2} rate, N and K concentrations were lower, likely due to dilution.

INTRODUCTION

Recent increases in corn yields have been attributed to greater stress tolerance of modern hybrids, especially stress from interplant competition (Tokatlidis and Koutroubas, 2004). Most of the improvement has been the result of an increase in optimum plant density – not greater grain yield per plant. The ability to thrive at higher populations is presumably the result of more efficient capture and use of resources such as water, sunlight, and nutrients. Modern hybrids also have greater leaf longevity, more efficient root systems, and greater assimilate supply available for translocation to developing grain (Tollenaar and Wu, 1999).

While corn grain yields vary by environment, research has often produced maximum yields at or near the highest populations studied (Nafziger, 1994; Staggenborg et al., 1999; Stanger and Lauer, 2006; Thomison and Jordan, 1995; Widdicombe and Thelen, 2002) – not the parabolic relationship once commonly observed between density and yield (Alessi and Power, 1974; Karlen and Camp, 1985). On sandy, coastal plain soils, Karlen and Camp (1985) found two decades ago that increasing plant density from 7 to approximately 10 plants m^{-2} resulted in yield decreases unless supplemental irrigation was applied. But recent research in the mid-Atlantic evaluating the effect of row spacing and plant density found an interaction of these factors in only one of 28 instances (Kratochvil and Taylor, 2005); under relatively high-yielding conditions (9.5 Mg ha^{-1}), grain yields did not decrease in response to higher plant densities until the threshold of 10 plants m^{-2} was passed.

Total corn biomass, measured as silage yield, has been shown to be influenced by plant density in New York, USA, where maximum economic forage yield was calculated to occur at 9.8 plants m^{-2} (Cox et al., 1998).

South Carolina research with hybrids from the 1980s reported that leaf area index (LAI) averaged 4.3 at approximately 7 plants m^{-2}, and increased to 5.9 when density was increased to 10 plants m^{-2} (Karlen and Camp, 1985). These authors concluded that there was no net advantage to the higher LAI at the higher density, since the theoretical critical LAI of 3.5 to 4.5 (Eik and Hanway, 1966) was reached with the lower density.

The nutrient concentrations that develop in tissues are generally considered to be independent of plant density, whether for grain (Ottman and Welch, 1989; Overman et al., 2006) or forage (Hoff and Mederski, 1960). In instances where plant densities are insufficient to use all applied N, N concentrations in grain and forage may rise with increased N rates (i.e., luxury consumption); but at increased plant densities, higher N rates are used more effectively (Jordan et al., 1950; Stevens et al., 2005).

Nutrient concentrations are known to vary widely among corn hybrids and to be highly dependent on environment (Ferguson et al., 1991; Heckman et al., 2003; Schenk and Barber, 1980). The average nutrient concentration values reported for corn grain in well managed plot studies in Nebraska are 12.9, 3.8, and 4.8 g kg^{-1} of N, P, and K, respectively (Heckman et al., 2003).

In a corn forage study, Cox et al. (1998) studied eight hybrids with a range in RM of 100 to 112 days across a range of plant densities and found that, while there were yield differences among hybrids, interactions with density were infrequent. In row-spacing-by-plant-density studies in Indiana, hybrid RM differences had little effect on grain yield, but greater stalk breakage was noted at higher densities for one hybrid (Neilsen, 1988). Increased lodging is a major concern with higher plant densities. Nafziger (1994) also found no hybrid by plant density interactions for two hybrids. Similarly, in an eastern Corn Belt study of plant density and corn hybrid prolificacy, it was concluded that environment, genetics, and plant density main effects were more important to optimum grain yield than was the hybrid by density interaction (Thomison and Jordan, 1995). In eastern Nebraska, an 85 day RM hybrid was found to produce greater forage yield, while an earlier hybrid (68 day RM) had higher grain yield (Alessi and Power, 1974). Relative maturity and plant density did not interact for either forage or grain yield. Conversely, more recent Michigan research found significant interactions between plant density and hybrid for grain yield and moisture content at harvest of six hybrids (Widdicombe and Thelen, 2002). In spite of the fact that the majority of published studies report no, or only occasional, RM by plant density interactions, many growers and practitioners believe that a significant interaction routinely occurs and make changes in plant density because of this belief. The objectives of this research were to examine the effect of plant density and hybrids of different RM on corn silage and grain yields and nutrient uptake.

MATERIALS AND METHODS

Small-plot field studies were conducted in 2005 near Mt. Holly, VA (38° 5’ N, 76° 43’ W) (Site 1 = non-irrigated, Site 2 = irrigated) on a State fine sandy loam (fine loamy, mixed, semiactive, thermic, Typic Hapludalf) and Blacksburg, VA (37° 12’ N, 80° 34’ W) (Site 3) on a Hayter loam (fine loamy, mixed, active, mesic Ultic Hapludalf) and in 2006 at Mt. Holly (Site 4 = non-irrigated, Site 5 = irrigated). The experimental design was randomized complete block with a split-plot arrangement of treatments and four replications. Main plots were plant density (4.9, 6.2, 7.4, or 8.6 plants m^{-2}), and subplots were hybrids of differing RM [early = Pioneer® Brand '34B97' (108 day RM); medium = Pioneer® Brand '33M54' (114 day RM); or late = Pioneer® Brand '31G66' (118 day RM)]. Planting dates and agronomic information for the five site-years are listed in Table 2.1. Plots were planted with a Wintersteiger 2600 vacuum plot planter (Wintersteiger Inc., Salt Lake City, UT) and were four, 76-cm rows wide by 8 m long. The previous crop was soybean for all Mt. Holly trials and corn at the Blacksburg site. Starter fertilizer at a rate of 43 kg N ha^{-1} and 5 kg P ha^{-1} was applied 5 cm below and 5 cm to the side of the seed at planting. Total N rates in 2005 were 263, 190, and 170 kg N ha^{-1} at Mt. Holly irrigated, Mt. Holly non-irrigated, and Blacksburg, respectively. Total N applied in 2006 was 252 kg ha^{-1} at the irrigated Mt. Holly site and 180 kg N ha^{-1} for the non-irrigated site. Phosphorus and K were broadcast prior to planting at rates indicated by Virginia Tech soil test recommendations (Donohue and Heckendorn, 1994). Planting, emergence, and harvest dates as well as weather information were collected at all locations (Table 2.1). Weather information was gathered using Watchdog™ (Spectrum Technologies Inc. Plainfield, Illinois) weather stations at each site.

Aboveground biomass was hand-harvested from each plot at the R6 developmental stages (Ritchie et al., 1992). Also at the R6 stage, all plants in the center two rows of the plot were counted to generate a plant density value for each treatment. A total of five consecutive plants in the outer two rows were harvested at soil level. Total above-ground plant biomass as well as stem, leaf, and reproductive biomass fractions were determined by separating the components and drying them to a constant weight in a forced-air oven at 60° C. Biomass yield (kg ha^{-1}) was calculated as average plant weight times measured plant density.

Stems, leaves, and grain from the R6 samples were ground to pass a 1-mm screen. Total carbon (C) and N concentrations for each sample were determined via a LECO Tru-Spec® CHN dry combustion analyzer (LECO Corporation, St. Joseph, MI). Samples were digested using a $HNO_3/HClO_4$ acid solution. Phosphorus (P) concentrations were determined colorimetrically (Kuo, 1996), and K concentrations were determined by atomic absorption spectroscopy (Helmke and Sparks, 1996). Nitrogen, P, and K uptake values for grain and forage (leaf+stem) were calculated as the product of biomass yield of the respective plant components and nutrient concentration (kg nutrient per kg DM) within each component.

After field drying, grain was harvested from the center two rows of each plot using a Massey Ferguson 8XP plot combine. Plot yield, grain moisture, and test weight were determined using a Graingage™ system (Juniper Systems, Logan, UT). Grain yields from all trials are reported at a moisture content of 155 g kg^{-1}.

Statistical analyses were performed using the GLM procedure available from SAS (SAS Inst., 2004). The density effect was tested using the replication by density error term; and the RM effect and the interaction of density and RM were tested using the full error term. Interactions were detected for treatments across years and locations (Table 2.2); so data from each site year were analyzed – and are presented – separately. Mean comparisons using a protected LSD test were made to separate RM and plant density effects where F-tests indicated significant differences ($P<0.10$). Regression analyses were used to determine the relationship between plant density, grain and forage yield, and nutrient uptake across sites.

RESULTS AND DISCUSSION

Stem, Leaf, and Grain Yield

Stem biomass at R6 was significantly affected by plant density in two of five site years (Table 2.2). At Site 2, stem biomass was significantly greater at the two higher plant densities (average of 11,110 kg ha^{-1}) compared to the lower plant densities (average of 8817 kg ha^{-1}) (Table 2.3). The highest value (7818 kg ha^{-1}) was observed at the highest plant density at Site 4. Corn biomass yield increases with density up to the point at which interplant competition for resources creates a high level of stress (Kiniry et al., 2005). Grain production is usually more severely limited by reduced resources; so it is unsurprising that stem biomass was greatest at the highest plant density evaluated in these trials.

Relative maturity affected stem biomass at R6 in four of five site-years (Table 2.2). In all but one of these instances (Site 5) the late RM hybrid produced a higher stem biomass than the early RM hybrid (Table 2.3). At Site 5, the medium RM had the lowest stem biomass. Again, this is expected, since longer season hybrids generally have a greater portion of the growing season within which to accumulate vegetative biomass.

Leaf biomass was significantly impacted by both plant density and hybrid RM in all site-years (Table 2.2). The lowest plant density of 4.9 plants m^{-2} always resulted in the lowest leaf biomass with an average of 1978 kg ha^{-1} (Table 2.3). Similar to what was observed with stem biomass; the highest plant densities generally resulted in the highest leaf biomass. Other researchers have also reported corn biomass increases associated with plant densities above those required to reach optimum grain yields (Cox, 1997). The late-RM hybrid produced an average of 690 kg ha^{-1} more leaf biomass than the early hybrid across sites. In two site-years, the late-RM hybrid also produced more leaf biomass than the medium RM, but at Site 3, leaf biomass was highest for the medium-RM hybrid.

Plant density significantly affected grain yield in two site-years (Table 2.2). At Site 1, 8.6 plants m^{-2} resulted in grain yields that were significantly higher than the lowest plant density but not different from 6.2 or 7.4 plants m^{-2} (Table 2.3). The same result of lower grain yield at the lowest density was observed at Site 2 (Table 2.3). Modern corn hybrids are known to have little plasticity in leaf area per plant (Tetio-Kagho and Gardner, 1998a) and little capacity to develop secondary ears at low densities (Tetio-Kagho and Gardner, 1998b). Therefore low plant densities generally result in lower grain yields. Grain yield increased with increasing plant density (Figure 2.1), and while the rate of increase was declining, the yield was greatest at the highest plant density. The impact of plant density in these studies is similar to that reported by Kratochvil and Taylor (2005) and Widdicombe and Thelen (2002) (approximately 300 kg ha^{-1} increase for each seed m^{-2}) and more than that reported by some others (Farnham, 2001; Karlen and Camp, 1985). This may be due to the ability of the specific hybrids chosen to compensate with larger ears in response to less interplant competition. The growing environment was also favorable in all years of this study, and so plant-to-plant competition for water may have been less a factor than would be seen in some instances. Stem and leaf yield also generally increased with increasing plant density (Figure 2.1).

Hybrid RM influenced grain yield in three of five site-years (Table 2.2). At Sites 1 and 3, the medium and late hybrids yielded more than the early hybrid. At Site 2, grain yield of the late hybrid was equal to the medium and superior to the early hybrid (Table

2.3). Increased yield potential for later RM corn hybrids is commonly observed in this environment (Thomason et al., 2006). However, a number of acres are currently planted to early RM hybrids to facilitate harvest and potentially avoid silking during the hottest time of year.

Nutrient Uptake

There were significant interactions of plant density and RM for grain N uptake at Site 5 and for leaf+stem N uptake at Site 1 (Table 2.2). In both cases, the early hybrid had N uptake levels lower than the other two hybrids at low density but greater N uptake at high density. We observed a significant effect of plant density on grain N uptake at Site 3, grain P uptake at Sites 2, 3, 4, and 5, and grain K uptake at Sites 2, 4, and 5 (Table 2.2). At Site 3, grain N uptake was significantly lower at the highest plant density (Table 2.4). This was due to lower grain N concentration and may represent a dilution effect, similar to that described by Rehm et al. (1983) and Terman et al. (1977) Grain P uptake was lowest at 4.9 plants m^{-2} at Sites 2 and 5, at 6.2 plants m^{-2} at Site 4 and at 8.6 plants m^{-2} at Site 3. The differences in grain P concentration were quite small so grain yield heavily influenced these results. Grain K uptake was lowest in the lowest plant density at Sites 2 and 5 and lowest at 6.2 plants m^{-2} at Site 4. Again this appears to be mostly influenced by yield variations associated with optimum plant density in a particular site year. Plant density did not affect leaf+stem N or P uptake (Table 2.2). Leaf+stem K uptake at Site 3 was significantly higher at the 7.4 plants m^{-2} density (Table 2.3). Leaf yield was significantly higher at Site 3 at this density, and higher K uptake is likely a reflection of this.

Grain N uptake was influenced by RM in one occasion (Site 1) as was grain K uptake (Site 5) (Table 2.2). In both instances, the medium RM hybrid had greater nutrient uptake (Table 2.4). The results at Site 1 reflect both higher N concentration and high yield, while K uptake at Site 5 differed mainly due to concentration. Plant density affected leaf+stem N and P uptake at Site 5.

Grain N uptake increased incrementally up to 7.4 seeds m^{-2} but decreased at the highest density (Figure 2.2). This may be the result of nutrient dilution at these high plant densities since yield was still increased. This same trend was evident in leaf+stem N and K uptake (Figure 2.3). Grain P and K uptake were similar across the range of densities at 38 and 42 kg ha^{-1}, respectively. Leaf+stem P uptake was also essentially the same (17 kg P ha^{-1}) across plant densities (Figure 2.3).

CONCLUSIONS

Grain yield was highest at the highest plant density with a total advantage of 1141 kg ha^{-1} over the 4.9 plants m^{-2} planting rate. The late hybrid out-yielded the medium and early hybrids by 550 and 1864 kg ha^{-1}, respectively. Total stem yield was also greatest at the highest plant density but only 340 kg ha^{-1} more than at 7.4 plants m^{-2}. Overall results for leaf biomass were similar to those for stem biomass. Solving for the optimum population based on the quadratic model for grain yield resulted in an estimated optimum of 7.6 plants m^{-2}. This is slightly higher than the current recommendation of 6.9 plants m^{-2} that would be recommended for this average yield level (11.5 Mg ha^{-1}).

Grain N, P, and K uptake was highest for the medium RM hybrid. Grain yield was not highest for this hybrid, so the uptake values result from greater nutrient concentrations in the grain, especially compared to the late hybrid. Overall leaf+stem N uptake for the medium RM hybrid was the lowest of the three, but K uptake was highest. Nutrient uptake levels varied by density, with the lowest levels observed at the lowest and highest plant densities. At 4.9 plants m^{-2}, lower nutrient uptake is explained by generally lower grain and biomass yield. At the 8.6 plants m^{-2} rate, N and K levels in grain and tissue may have been lower due the dilution effect associated with higher biomass. However, all grain nutrient uptake values fall within the range reported by Heckman et al. (2003) for corn grown in the mid-Atlantic.

While numerous studies over the years have investigated the effect of plant density and hybrid characteristics on yield, recent increases in corn hybrid stress tolerance and standability make revisiting these basic studies worthwhile. Based on results from these studies, plant density recommendations at these high yield levels should be revised upwards.

Table 2.1 Production practices, sampling dates, and environmental conditions, Site 1 = Mt. Holly non-irrigated, 2005, Site 2 = Mt. Holly irrigated, 2005, Site 3 = Blacksburg, 2005, Site 4 = Mt. Holly non-irrigated, 2006, Site 5 = Mt. Holly irrigated, 2006.

Experiment	Planting Date	Emergence Date	Total N applied	R6 Biomass Sampling Date	GDD Planting to Sampling[†]	Rainfall Planting to Sampling	30 yr-mean Rainfall, Planting to Sampling Period	Grain Harvest
Site	---date---	---date---	---kg ha^{-1}---	---date---	----°C----	----mm----	----mm----	---date---
1	04/13/2005	04/20/2005	190	09/01/2005	1689	493	455	09/19/2005
2	04/19/2005	04/25/2005	263	09/01/2005	1688	490	455	09/20/2005
3	05/09/2005	05/14/2005	170	09/20/2005	1484	394	452	10/05/2005
4	04/28/2006	05/04/2006	180	08/29/2006	1658	409	456	09/22/2006
5	04/26/2006	05/03/2006	252	08/30/2006	1665	410	456	09/20/2006

[†] GDD = Growing Degree Days at base 10°C.

Table 2.2 Analysis of variance and mean values for stem, leaf and grain biomass, and N, P and K uptake in response to plant density and relative maturity by site and year.

		Source of					-------N uptake-------		------P uptake-------		-------K uptake-------	
Year	Site	Variation	df	Stem Yield	Leaf Yield	Grain Yield	Grain	Leaf+Stem	Grain	Leaf+Stem	Grain	Leaf+Stem
				--Pr>F--								
2005	1	Block	3	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Density	3	ns	**	***	ns	ns	ns	ns	ns	ns
		Block*Density	9	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Relative Maturity (RM)	2	**	***	**	*	ns	ns	ns	ns	ns
		Density*RM	6	ns	ns	ns	ns	*	ns	ns	ns	ns
		Block*Density*RM	24	-------	-------	-------	-------	-------	-------	-------	-------	-------
	2	Block	3	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Density	3	**	***	***	ns	ns	**	ns	**	ns
		Block*Density	9	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Relative Maturity (RM)	2	**	***	**	ns	ns	ns	ns	ns	ns
		Density*RM	6	ns	ns	ns	ns	ns	ns	ns	ns	ns
		Block*Density*RM	24	-------	-------	-------	-------	-------	-------	-------	-------	-------
	3	Block	3	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Density	3	ns	***	ns	*	ns	*	ns	ns	**
		Block*Density	9	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Relative Maturity (RM)	2	ns	***	*	ns	ns	ns	ns	ns	ns
		Density*RM	6	ns	ns	ns	ns	ns	ns	ns	ns	ns
		Block*Density*RM	24	-------	-------	-------	-------	-------	-------	-------	-------	-------
2006	4	Block	3	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Density	3	*	***	ns	ns	ns	**	ns	**	ns
		Block*Density	9	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Relative Maturity (RM)	2	**	***	ns	ns	ns	ns	ns	ns	ns
		Density*RM	6	ns	ns	ns	ns	ns	ns	ns	ns	ns
		Block*Density*RM	24	-------	-------	-------	-------	-------	-------	-------	-------	-------
	5	Block	3	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Density	3	ns	**	ns	**	ns	*	ns	**	ns
		Block*Density	9	-------	-------	-------	-------	-------	-------	-------	-------	-------
		Relative Maturity (RM)	2	**	***	ns	ns	**	ns	**	*	ns
		Density*RM	6	ns	ns	ns	**	ns	ns	ns	ns	ns
		Block*Density*RM	24	-------	-------	-------	-------	-------	-------	-------	-------	-------

*, **, *** - significant at the 0.10, 0.05, and .0.01 level, respectively
1,4 - Mt Holly non-irrigated
2,5 - Mt. Holly irrigated
3 - Blacksburg

Table 2.3 Treatment mean and LSD values from stem, leaf, and grain biomass by site and year.

Year	Site	Density	Stem Yield	Leaf Yield	Grain Yield
		---plants m^{-2}---	---	kg ha^{-1}	---
2005	1	4.9	6339	1675	11988
		6.2	7903	2161	12451
		7.4	8452	2637	13123
		8.6	8008	2302	13909
		LSD	ns[†]	601	1868
		RM			
		Early	6463	1734	11321
		Medium	8342	2401	13643
		Late	8222	2446	13639
		LSD	1388	363	2266
2005	2	4.9	8842	2614	13713
		6.2	8791	2763	15149
		7.4	11482	3692	14887
		8.6	10738	3530	15090
		LSD	1789	322	1376
		Early	9241	2699	13267
		Medium	9939	3216	14727
		Late	10709	3536	16134
		LSD	1142	329	1733
2005	3	4.9	4281	855	11129
		6.2	4678	1061	11593
		7.4	5845	1381	12295
		8.6	4899	1126	12018
		LSD	ns	191	ns
		Early	4525	969	9776
		Medium	5030	1300	12399
		Late	5222	1048	13103
		LSD	ns	163	1616
2006	4	4.9	6135	2190	7794
		6.2	6150	2203	7001
		7.4	7329	2579	8143
		8.6	7818	3332	8025
		LSD	1645	392	ns
		Early	6891	2197	7517
		Medium	6676	2547	7839
		Late	8551	2961	7867
		LSD	1044	305	ns
2006	5	4.9	7295	2558	9754
		6.2	7377	3022	11256
		7.4	7487	3091	10664
		8.6	7838	3432	11041
		LSD	ns	551	ns
		Early	7208	2580	10577
		Medium	6834	3009	10422
		Late	8506	3489	11038
		LSD	1301	316	ns

[†] - not significant at the 0.10 level

Table 2.4 Treatment means and LSD values from grain and leaf+stem, N, P, and K uptake.

			--------N uptake--------		-------P uptake--------		--------K uptake--------	
Year	Site	Density	Grain	Leaf+Stem	Grain	Leaf+Stem	Grain	Leaf+Stem
		--plants m^{-2}--	-------------------------------------kg ha^{-1}--					
2005	1	4.9	171	57	42	20	44	126
		6.2	193	99	46	24	46	210
		7.4	185	88	46	21	46	203
		8.6	198	75	50	23	50	182
		LSD	ns[†]	ns	ns	ns	ns	ns
		RM						
		Early	173	79	43	23	43	163
		Medium	204	78	47	23	49	204
		Late	183	82	48	20	48	174
		LSD	23	ns	ns	ns	ns	ns
2005	2	4.9	220	130	46	28	48	215
		6.2	242	137	53	29	55	235
		7.4	234	149	52	31	54	281
		8.6	232	137	53	27	55	242
		LSD	ns	ns	8	ns	6	ns
		Early	214	144	47	29	47	236
		Medium	277	137	55	31	58	266
		Late	206	135	51	26	53	228
		LSD	ns	ns	ns	ns	ns	ns
2005	3	4.9	170	46	36	10	36	105
		6.2	177	45	37	9	37	110
		7.4	181	51	41	10	41	144
		8.6	130	45	29	10	47	111
		LSD	43	ns	11	ns	ns	20
		Early	149	44	32	10	32	111
		Medium	173	48	39	10	45	132
		Late	171	48	37	9	44	109
		LSD	ns	ns	ns	ns	ns	ns
2006	4	4.9	99	50	24	12	32	154
		6.2	88	38	21	7	29	148
		7.4	103	44	25	11	34	175
		8.6	109	41	25	11	31	188
		LSD	ns	ns	4	ns	2	ns
		Early	101	44	24	11	32	160
		Medium	98	36	23	9	33	169
		Late	100	52	24	10	30	164
		LSD	ns	ns	ns	ns	ns	ns
2006	5	4.9	150	95	29	17	35	197
		6.2	151	52	36	14	43	162
		7.4	154	87	35	14	41	196
		8.6	138	55	34	12	45	180
		LSD	10	ns	4	ns	4	ns
		Early	156	74	34	14	39	175
		Medium	154	59	34	13	44	176
		Late	135	84	32	15	40	201
		LSD	9	15	2	3	3	ns

[†] - not significant at the 0.10 level

Figure 2.1 Average grain, stem, and leaf biomass as affected by plant density.

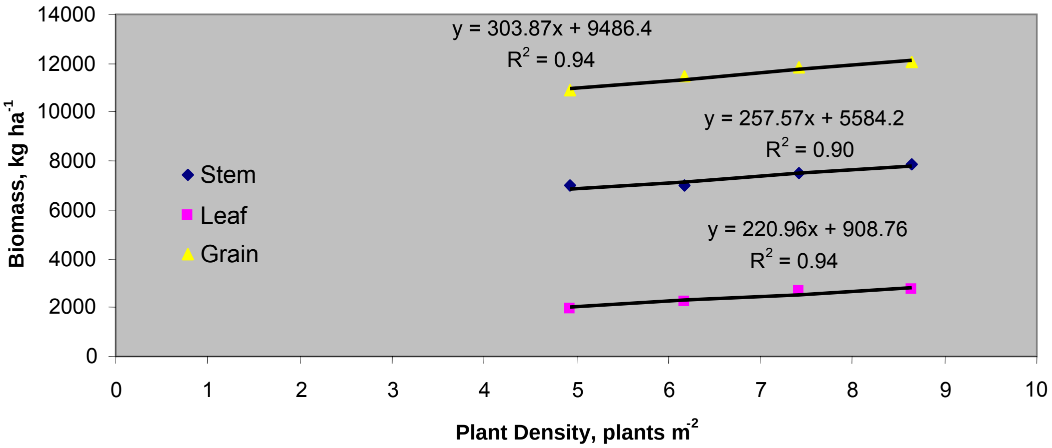


Figure 2.2 Grain N, P, and K uptake as affected by plant density.

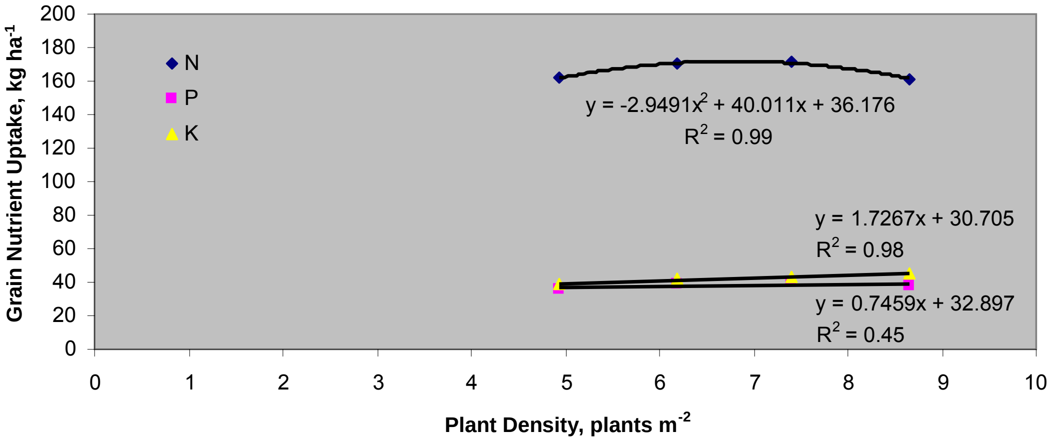
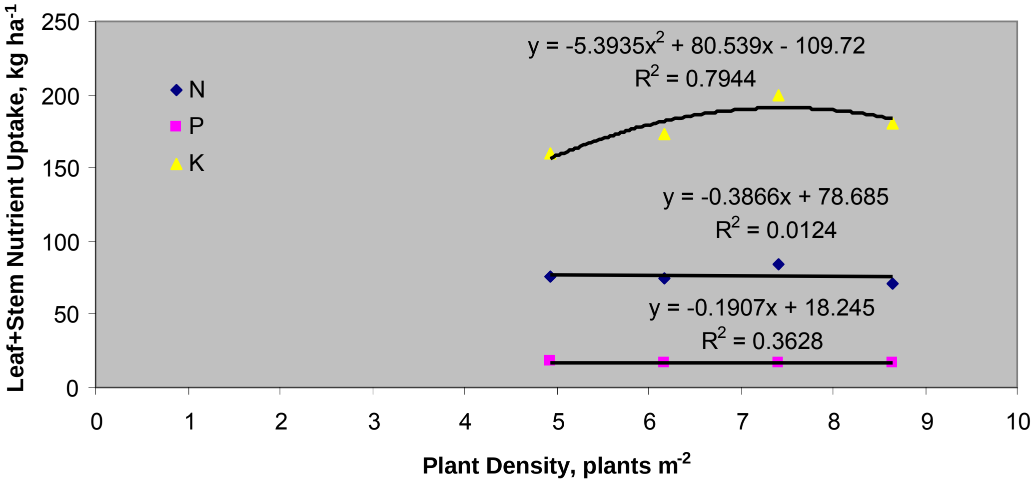


Figure 2.3 Leaf+stem N, P, and K uptake as affected by plant density.



CORN GROWTH MODEL CALIBRATION AND VALIDATION FOR THE MID-ATLANTIC USA

ABSTRACT

Crop simulation models (CSMs) offer the opportunity to evaluate a range of management and environmental scenarios on crop growth and yields. Simulation models must first be calibrated and validated under local conditions before they can be confidently applied for decision support. Two corn CSMs, Hybrid-Maize and CERES-Maize were calibrated and validated under Virginia conditions with the goal of better understanding corn response to variable environmental conditions and developing management programs that decrease temporal yield variation. Calibration data were generated from small plot studies conducted for five site-years. Main plots were plant density (4.9, 6.2, 7.4, and 8.6 plants m^{-2}) and subplots were hybrids of differing relative maturity (RM) [early = Pioneer® Brand '34B97' (108 day RM); medium = Pioneer® Brand '33M54' (114 day RM); and late = Pioneer® Brand '31G66' (118 day RM)]. Model validation was performed on data from large scale, replicated strip plot trials conducted at various locations across Virginia in 2005 and 2006. Prior to model adjustment both CSMs under predicted corn grain yield in calibration and cross validation studies. CERES-Maize grain yield prediction error was consistent across the range of tested plant density while accuracy of Hybrid-Maize varied with plant density. Hybrid-Maize-estimated biomass production was highly accurate. Greater leaf area index (LAI) and biomass production were measured than was predicted by the CERES-Maize CSM. Both CSMs were modified based on calibration data sets and cross validated. Validation results of the calibrated CSMs showed reasonable accuracy in simulating planting date and

environmental effects on a range of corn hybrids grown throughout Virginia over two years. We expect that both modified models can be used for strategic research and management decisions in mid-Atlantic corn production. Since each model has unique strengths and assessment modules, the CSM can be matched to the individual use.

INTRODUCTION

Crop simulation models are used to estimate plant, and particularly crop, productivity in response to environmental and management changes. They are based on numerous studies detailing the quantitative development of plants. Mathematical models designed to predict plant growth and development have existed for many years; however recent improvements in accuracy of models combining attributes specific to corn with general plant growth predictions across a range of environments offer new opportunities for research and management. In addition, crop simulation models provide data that are relevant to research, teaching, extension and decision support for identifying improved crop management options. Finally, increased availability of online long-term weather data and improved personal computer performance and capacity has greatly increased the potential for crop model use.

Crop simulation models have been applied to a number of environments to test the hypothetical impacts of different management practices (Lopez-Cedron et al., 2005) or cultivar characteristics (Boote et al., 2001) on production of biomass, biomass partitioning, and grain yield. Locally validated CSMs have been used in numerous instances to develop improved crop management strategies for irrigation, (Dogan et al., 2006; Hook, 1994) nitrogen management (Miao et al., 2006; Thorp et al., 2006) seeding dates (Carberry et al., 1989; Saseendran et al., 2005), and site-specific management

(Fraisse et al., 2001). Models have also been used to develop cultivar performance predictability when combined with geographic information systems, (Loffler et al., 2005) for evaluating the impacts of climate change on crop productivity, (Mati, 2000) and for policy development (Hammer et al., 2002).

There are currently several CSMs available specifically for corn. One of the most frequently used corn models is CERES-Maize, available in the DSSAT software package (Jones et al., 2003). There are over 200 published citations for the use of this CSM in various situations. Hybrid-Maize, developed at the University of Nebraska (Yang et al., 2004) is one of the newest corn models providing corn production management decision support. This software has yet to be extensively evaluated under conditions outside the Corn Belt.

CERES-Maize is a relatively simple, deterministic CSM that estimates corn growth, development, and yield (Jones and Kiniry, 1986). The CSM simulates daily biomass addition and partitioning among plant organs. Simulation processes are affected by environmental variables such as solar radiation, temperature and cultivar-specific factors and can include water and nitrogen stress when these options are chosen (Jones et al., 2003). CERES-Maize distinguishes five developmental stages; 1) emergence to the end of the juvenile period; 2) the end of the juvenile stage to tassel initiation; 3) tassel initiation to silking; 4) silking to the start of effective grain filling; and 5) start of effective grain filling to physiological maturity. Cultivar-specific growth parameters must be specified for each of these stages. This model is extremely sensitive to the timing of these stages and requires cultivar-specific input parameters for the growing degree day (GDD) interval necessary to reach each developmental stage. Plant component development is thus heavily influenced by temperature. Biomass production is calculated directly from the portion of absorbed solar radiation using a fixed value for radiation use efficiency which has been questioned by some researchers (Loomis and Amthor, 1999).

The Hybrid-Maize CSM combines the growth and development functions associated with the corn-specific CERES-Maize model with a more generic, mechanistic approach to the prediction of photosynthesis rate and respiration. This CSM is potentially more responsive to environmental conditions such as changes in solar radiation and temperature than other corn-specific models (Yang et al., 2004). Use of the Hybrid-Maize CSM is potentially more widespread outside research because it does not require the input of cultivar-specific data. It does request the user input seed brand and GDD to maturity for each simulation. Based on these inputs, the program accesses a database with regression coefficients for GDD total to relative maturity (RM) and GDD silking to GDD total to better approximate thermal time to physiological events by hybrid. Similar to other models, minimum weather inputs must include maximum and minimum temperature, solar radiation, precipitation, wind speed, and relative humidity.

Corn yield in the mid-Atlantic region is highly dependent on in-season rainfall which can vary significantly from year to year. It is not uncommon for the statewide average annual corn yield to differ by 2.2 Mg ha^{-1} or more over years. Accurate corn simulation models can help to better understand corn response to variable environmental conditions in the mid-Atlantic region and develop management strategies to decrease this temporal yield variability. To that end, we evaluated two corn crop growth simulation models, Hybrid-Maize, and CERES-Maize under Virginia conditions. Both models were modified based on observations from the calibration studies and validated against data from sites not utilized in the model calibrations.

MATERIALS AND METHODS

Small plot field calibration studies were conducted in 2005 near Mt Holly, VA (38° 5’ N, 76° 43’ W) (Site 1C = non-irrigated, Site 2C = irrigated) on a State fine sandy loam (fine loamy, mixed, semiactive, thermic, Typic Hapludalf) and near Blacksburg, VA (37° 12’ N, 80° 34’ W) (Site 3C) on a Hayter loam (fine loamy, mixed, active, mesic Ultic Hapludalf) and in 2006 at Mt. Holly (Site 4C = non-irrigated, Site 5C = irrigated). Experimental design was a randomized complete block with a split-plot arrangement of treatments and four replications. Main plots were plant density (4.9, 6.2, 7.4, and 8.6 plants m^{-2}) and subplots were hybrids of RM [early = Pioneer® Brand ‘34B97’ (108 day RM); medium = Pioneer® Brand ‘33M54’ (114 day RM); and late = Pioneer® Brand ‘31G66’ (118 day RM)]. Planting dates and agronomic information for the five site-years are listed in Table 3.1. Plots were planted with a Wintersteiger 2600 vacuum plot planter (Wintersteiger Inc., Salt Lake City, UT) and were four, 76-cm rows wide by 8 m long. At the V6 stage all plants from the center two rows of each plot for a length of 10 meters were counted to determine plant density. The average density for each population treatment by site was used as the model input population. The previous crop was soybean for sites 1C, 2C, 4C, and 5C and corn at site 3C. Starter fertilizer at a rate of 43 kg N ha^{-1} and 5 kg P ha^{-1} was applied 5 cm below and 5 cm to the side of the seed at planting. The remainder of the N was applied at sidedress as a surface band application. Total N rates in 2005 were 190, 263, and 170 kg N ha^{-1} at sites 1C, 2C, and 3C, respectively. Total N applied in 2006 was 180 kg N ha^{-1} at site 4C and 252 kg ha^{-1} at site

5C. Phosphorus and K were broadcast prior to planting at rates indicated by Virginia Tech soil test recommendations (Donohue and Heckendorn, 1994). Additional agronomic factors for these experiments are noted in Table 3.1.

In addition to the small plot studies, large, unreplicated strip plot validation trials consisting of 10 to 16 different corn hybrids (RM 108-112) were planted at five diverse locations in both 2005 (1V, Lancaster Co; 2V, Essex Co.; 3V, Middlesex Co.; 4V, Charles City Co.; and 5V, Chesapeake) and 2006 (6V, Charles City Co.; 7V, Chesapeake; 8V, Orange Co.; 9V, Gloucester Co.; and 10V, King and Queen Co.) in the Coastal Plain and Piedmont regions of Virginia. Plant population, plot number, nitrogen fertility, and other factors varied by site according to farmer practice (Table 3.2).

Hourly temperature and climatic information was gathered using Watchdog™ (Spectrum Technologies Inc. Plainfield, Illinois) weather stations at the small plot sites. Daily mean temperature and cumulative monthly rainfall for these experiments is presented in Figure 3.1. Climate data for the large strip plot studies were obtained from the nearest reporting station of the Southeast Regional Climate Center network (http://radar.meas.ncsu.edu/). Corn growing degree days (GDD) were calculated by determining the mean daily temperature and subtracting it from the base temperature needed for growth. The minimum temperature in the GDD calculation was set at 10°C since very little growth occurs below this temperature. Because corn growth rate slows rapidly above 30°C, this value was used as the maximum temperature. The GDD accumulation for one day is represented by equation 3.1:

Equation 3.1) $GDD = (T_{max} + T_{min})/2 - T_{base}$

where T_{max} is maximum daily temperature and is set equal to 30°C when temperatures exceed this level

T_{min} is minimum daily temperature and is set equal to 10°C when temperatures fall below this point

T_{base} is the base temperature for corn, 10°C

Daily GDD were summed over time to calculate the cumulative total from planting until a specific point in the growing season.

Leaf area index was measured for each plot at the V2-V4, V6-V9, V11-V14 and VT and R6 stages in the small plot trials and the V4 to V9 and R6 stage (Ritchie et al., 1992) for the large plot trials using the LAI 2000 (LI-COR, Lincoln, NE). The LAI-2000 allows wavelengths of light up to 490 nm to reach five silicon detectors arranged in concentric rings, measuring sky brightness at different zenith angles to estimate LAI (Welles and Norman, 1991). Measurements were taken near dawn or dusk, and a screen was held vertically to shade the plots from direct sun light when LAI estimates were taken. LAI was determined based on sampling methods prescribed by LI-COR (1991) for determining LAI in agricultural row plots with varied spacing or full canopies.

Aboveground biomass was hand harvested from each plot at the same time as LAI measurements were made. In the small plot trials, five consecutive plants in one of the outer two rows were harvested at soil level on each sampling date. Ten plants were similarly removed at each sampling from the large plot trials. Total plant biomass as well as stem, leaf, and reproductive biomass dry matter were determined by separating the components and drying them for five days in a forced-air oven at 60° C. Biomass yield (kg ha^{-1}) was calculated as the product of individual plant weight and plant population measured in each plot.

After maturity and field drying, grain was harvested from the center two rows from each plot in the small plot trials using a Massey Ferguson 8XP plot combine. Plot weight, grain moisture, and test weight were determined using a Graingage™ system (Juniper Systems, Logan, UT). Grain yields in the large plot trials were from the entire plot and were determined using commercial combines and weigh wagons. Grain yields from all trials are reported at 155 g kg^{-1} moisture.

Small plot trials (1C-5C) were analyzed as a split plot design using the GLM procedure available from SAS (SAS Inst., 2004)). Mean values of plant density effects averaged over hybrid RM were used to compare CSM output with observed grain, biomass, and LAI measurements. Data for the 10 to 16 hybrids studied at each validation site were averaged to generate one mean value for grain yield, biomass, and LAI per site. This was done because we did not generate genetic input coefficients for each hybrid in these studies. Also our overall goal was to evaluate these models for accuracy across a range of environments and hybrids, not to evaluate model performance for a specific hybrid in a specific field. The weather file associated with a particular validation site was then input into each CSM with the cultivar set as generic with the average genetic coefficients associated with this RM group used.

The CERES-Maize model was calibrated with data obtained from the small plot experiments, sites 1C-5C. For calibration, cultivar coefficients were measured at sites 1C-3C in 2005. These coefficients were obtained sequentially, beginning with the phenological developmental parameters associated with flowering and maturity dates, followed by the crop growth parameters related to kernel filling rate and yield (Hunt and Boote, 1998). An iterative process was used to select the most appropriate temperature increment value for each phenological and developmental parameter. For calibration of both CSMs, the simulated dates of emergence, flowering, and maturity (Table 3.3) as well as biomass and grain yield were compared with observed values.

The Hybrid-Maize model was similarly calibrated; however this CSM does not require input of cultivar coefficients. Instead, the brand of hybrid is input along with relative maturity information supplied by seed companies to better determine thermal time to major physiological events.

Model performance was evaluated based on accuracy of predicting LAI, aboveground biomass, and grain yield using comparison of the 1:1 line for observed and predicted values, and two statistical indices (root mean square error and scatter ratio). The root mean square error (RMSE) expressed in percent was used to estimate prediction error and was calculated according to Janssen and Heuberger (1995) using equation 3.2.

Equation 3.2) RMSE = $\sqrt{\frac{\Sigma_{i=1}^{N}(P_i - O_i)^2}{N}}$

where P_i and O_i refer to predicted and observed values for the studied variables, respectively, e.g., LAI, biomass, and yield. N is the number of observations within the dataset. The RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al., 1991). The scatter ratio relates model prediction (P_i) and field observations (O_i) to the mean of field observations ($\bar{O}$). Scatter ratio is calculated as shown in equation 3.3.

Equation 3.3) $$SR = \frac{[\sum_{i=1}^{N}(O_i-\bar{O})^2]}{[\sum_{i=1}^{N}(P_i-\bar{O})^2]}$$

where P_i and O_i refer to predicted and observed values for the studied variables, N is the number of observations within the dataset and $\bar{O}$ is the mean of O_i. This value relates the fraction of the overall scatter in the observations that is explained by the model, or predicted values. The optimum value is 1 and values decline as the predictive ability of the model declines (Janssen and Heuberger, 1995)

RESULTS AND DISCUSSION

Calibration Studies

Observed grain yield was higher than what was predicted by either model (Figure 3.2). The CERES-Maize CSM consistently under predicted grain yield across the range of population densities evaluated. The yield difference was, however, similar at each different density, approximately 1350 kg ha^{-1}. This interpretation matches the data corresponding to both LAI (Figure 3.3) and biomass (Figure 3.4). Observed LAI was greater than that predicted by CERES -Maize for almost every point and averaged nearly 0.5 units higher across the range with a RMSE of 20%. Biomass produced was similarly under predicted by CERES -Maize through the mid and late vegetative growth stages (Figure 3.4). This lower overall predicted production of biomass and grain could be explained by more efficient use of intercepted sunlight than is accounted for in the model. Lindquist et al. (2005) have reported that radiation use efficiency of maize under optimum conditions was as much as 0.4 to 0.5 g MJ^{-1} greater than the values currently accepted and used in most crop models. This greater interception and use of sunlight would result in greater daily and total productivity. A uniform increase of 4.25 kg ha^{-1} d^{-1}

in the modeled biomass production over the course of the growing season resulted in greater accuracy based on this calibration dataset (data not shown). Adjusting modeled LAI upward by 0.6 units at low plant density and 0.2 units at high plant density resulted in more accurate predictions throughout the season with a new RMSE of 12% (Data not shown). A resulting increase in modeled grain yield of 1350 kg ha^{-1} across the range of plant densities provided great improvement in the relationship of predicted and observed grain yield (Figure 3.5).

Differences measured between Hybrid-Maize-predicted and actual grain yield were more complex and varied with plant population (Figure 3.2). At the lowest density, actual yield was approximately 3000 kg ha^{-1} greater than predicted, while at the highest density, the difference was less than 1 Mg ha^{-1}. Otegui (1995) reports higher kernel numbers than the default of Hybrid-Maize and attributes most of this increase to contribution of subapical ears at plant densities below 6 plants m^{-2}.

Observed LAI did not exceed 4, even at the highest density, while the Hybrid-Maize model predicted much higher values. Other researchers have demonstrated that non-destructive LAI estimates are often below destructively measured LAI (Wilhelm et al., 2000), however published values generally do not differ by as much as was observed here. Leaf area index values used to develop the Hybrid-Maize CSM were frequently observed to be greater than 5, even at plant densities around 7 plants m^{-2} (Yang et al., 2004). These values are similar to those reported by (Jongschaap, 2007) but are greater than what has been reported by others in lower yield potential environments (Saseendran et al., 2005; Thomason et al., 2007). At 4.9 plants m^{-2}, modeled LAI matched observed measurements fairly closely, but the disagreement grew larger with each incremental increase in density (Figure 3.3) and resulted in a RMSE measure of 26%. Total biomass was predicted extremely well by the Hybrid-Maize model throughout the time course of the season across the evaluated range of plant densities as indicated by a RMSE of only 5% (Figure 3.4). Adjusting model parameters to allow greater kernel number per ear increased the accuracy of grain yield prediction (Figure 3.5). At 4.9 plants m^{-2}, the adjustment was 62 kernels ear^{-1}, (9.1 %) and 57 kernels ear^{-1} at 8.6 plants m^{-2}. This change resulted in an 11% decrease in RMSE associated with grain yield prediction.

The magnitude of grain yield response to plant density observed in these studies is less than is often observed in the Mid-West where the Hybrid-Maize CSM was developed. This is often the case in more southern areas of the US (Lee, 2006). In particular, relatively high grain yield was reached in these studies at low seeding density. In more northern areas, higher plant density has resulted in less thermal time to reach ½ maximum light interception and in greater total light interception by the canopy (Westgate et al., 1997). However in locations with a longer growing season, such as the mid-Atlantic region of the US, light is less of a limiting factor so plants at lower densities can produce competitive yields by producing more kernels per ear and/or multiple ears per plant. This fact may explain why the grain yield prediction error associated with Hybrid-Maize was greater at low plant density.

Validation Studies

Grain yield varied from 6100 to 12200 kg ha^{-1} across the large plot validation sites in 2005 and from 8400 to 12000 kg ha^{-1} in 2006 (Table 3.4). These ranges reflect the differences in site yield potential and rainfall received at various locations. Measured plant densities across the experimental sites varied from 5.4 to 7.7 plants m^{-2} which represents the typical range for plantings in the region. Similar to what was observed in the calibration studies, CERES-Maize under predicted grain yield in a majority of test locations. Other researchers have also reported modeled grain yield to be under predicted by CERES-Maize (Miao et al., 2006; Saseendran et al., 2005) and CERES-Sorghum (Staggenborg and Vanderlip, 2005) At site 10V, predicted yield was appreciably greater than the observed yield. This location had a high degree of plant stand variability, by hybrid, that negatively affected grain yield and so this location was not included in the grain analysis for the adjusted model comparison. Plots at the validation sites were sampled during early vegetative growth (V3 to V7) and at maturity. In 2005, biomass dry matter ranged from 150 to 3850 kg ha^{-1} depending on plant growth at individual sites (Table 3.4). Total biomass at R6 ranged from 10 to nearly 20 Mg ha^{-1} across the sampled sites. Similar early season production was observed in 2006; however average biomass across sites at R6 was 4900 kg ha^{-1} greater than in 2005. Root mean square error for CERES-Maize predicted biomass was 49% of a mean of 10300 kg ha^{-1}. Measured LAI at the first cutting ranged from 0.48 to 2.69 and from 0.22 to 1.81 in 2005 and 2006, respectively (Table 3.4).

Incorporating the modifications developed using the local calibration studies, the RMSE associated with CERES-Maize predicted grain yield decreased from 26% for the unmodified model output to 17% (Table 3.5). As shown in figure 3.6a and b, the relationship of predicted to observed grain yield, as compared to a slope of 1, was much improved over the unmodified Ceres-Maize results. The SR was also improved from 0.66 to 0.82 after adjustment, representing a major decrease in the amount of scatter in the data that was not explained by the models (Table 3.5).

The modified CERES-Maize model produced a biomass RMSE that was 27 % lower than that for the original model output. Scatter ratio improved from 0.36 to 0.78 (Table 3.5). Because Hybrid Maize accurately predicted plant biomass through the growing season, the vegetative production components of the model were not modified. Prior to adjustment, RMSE for CERES-Maize predicted LAI was 26% which would be termed fair. Leaf area index RMSE was improved from 26 to 11 % and the SR improved from 0.81 to 0.98 by increasing the daily growth rate predicted by CERES-Maize (Table 3.5).

The original RMSE for grain yield prediction of the Hybrid-Maize CSM across the 10 validation sites was 23%, which was slightly more accurate that the CERES-Maize results. The RMSE was decreased to 13% after adjusting based on location calibration results (Table 3.5). Similarly, scatter decreased from 0.58 to 0.83. Across the range of grain yields measured in these trials, the modified Hybrid Maize results reflected actual grain yield accurately in most instances with an estimated intercept of -122 kg ha^{-1} (Figure 3.6b). The Hybrid-Maize model adjustments did not specifically affect output values for biomass or leaf area.

CONCLUSIONS

Corn grain yield in these studies was under predicted by both non-calibrated CSMs. CERES-Maize error was consistently 1350 kg ha^{-1} across the range of tested plant density. We also measured generally greater LAI and biomass production than that predicted by the CERES-Maize CSM. CERES-Maize total daily growth rate output was increased to more closely match the measured variables. The adjusted model more accurately predicted dry biomass production during early season and at maturity (RMSE decrease of 27%). Error associated with CERES-Maize-predicted LAI was also decreased (15%). Grain yield prediction accuracy for the cross validation data set was much improved and the RMSE associated with the adjusted model output would be ranked as good, using the scale of Jamieson et al. (1991). The slope of the observed versus modified predicted grain yield trend was 0.98 indicating high accuracy.

Hybrid-Maize biomass prediction was highly accurate and adjustments made based on the calibration work did not affect modeled biomass output. Grain yield prediction RMSE for Hybrid-Maize varied by treatment with greater error (RMSE) at low plant density. Potential kernel number per ear was increased in order to more closely match observed grain yield and this increase was greater at low density. Similar to grain yield results for the CERES-Maize model, the modified Hybrid-Maize model applied to the cross validation data, resulted in a slope of 0.99 for the observed versus modified predicted grain yield trend. Modeled LAI was significantly higher than was observed in these experiments but we believe this to be an artifact of the difference in environment between our testing sites and where the model was developed. Because total biomass predictions were highly accurate without adjustments and because the model does not output separate leaf and stem values, we did not modify this variable.

Validation results of both calibrated CSMs showed reasonable accuracy in simulating planting date and environmental effects on a range of corn hybrids grown throughout Virginia over two years. We expect that both validated models can be used for strategic and management decisions in mid-Atlantic corn production. Since each model has unique strengths and assessment modules, the CSM can be matched to the particular use. Both modified models should be equally effective at predicting the effect of plant density and hybrid RM impacts as well as variable environmental conditions on plant productivity and grain yield.

Table 3.1 Production practices, sampling dates, and environmental conditions for calibration studies, sites 1-5, 2005-2006.

Experiment	Planting Date	Emergence Date	Total N applied	R6 Biomass Sampling Date	GDD Planting to Sampling†	Rainfall Planting to Sampling	30 yr-mean Rainfall, Planting to Sampling Period	Grain Harvest
Site	---date---	---date---	---kg ha^{-1}---	---date---	----°C----	----mm----	----mm----	---date---
1C	04/13/2005	04/20/2005	190	09/01/2005	1689	493	455	09/19/2005
2C	04/19/2005	04/25/2005	263	09/01/2005	1688	490	455	09/20/2005
3C	05/09/2005	05/14/2005	170	09/20/2005	1484	394	452	10/05/2005
4C	04/28/2006	05/04/2006	180	08/29/2006	1658	409	456	09/22/2006
5C	04/26/2006	05/03/2006	252	08/30/2006	1665	410	456	09/20/2006

†GDD = Growing Degree Days at base 10°C.

Table 3.2 Production practices, sampling dates, and environmental conditions for validation studies, 2005-2006.

Experiment	Planting Date	Emergence Date	Plant Population	Number of Plots	Total N applied	Vegetative Sampling	Growth Stage	Grain Harvest
			--plants ha^{-1}--		---kg ha^{-1}---			
1V	04/15/2005	04/22/2005	45,207-68,888	16	161	06/16/2005	V9	09/27/2005
2V	04/06/2005	04/16/2005	47,360-62,429	16	152	06/06/2005	V5	09/09/2005
3V	04/21/2005	04/27/2005	47,360-64,582	16	161	06/06/2005	V4	09/25/2005
4V	04/18/2005	04/24/2005	56,833-72,895	16	170	06/06/2005	V6	09/14/2005
5V	05/12/2005	05/17/2005	49,512-62,429	14	203	06/20/2005	V8	09/13/2005
6V	04/11/2006	04/20/2006	58,100-68,860	15	180	05/31/2006	V5	09/11/2006
7V	05/24/2006	04/24/2006	49,492-64,555	10	224	05/30/2006	V4	10/02/2006
8V	04/16/2006	04/26/2006	55,950-77,467	14	140	06/06/2006	V7	09/26/2006
8V	04/20/2006	04/26/2006	47,341-66,707	16	190	05/30/2006	V4	09/27/2006
10V	04/18/2006	04/25/2006	66,707-79,620	16	146	05/31/2006	V6	09/25/2006

Table 3.3 Observed and predicted dates of emergence, silking and physiological maturity for calibration sites 1C-3C.

Planted				--------Predicted--------	
13-Apr	Site 1C	Hybrid RM	Observed	CERES-Maize	Hybrid Maize
	Emergence Date	Early	22-Apr	03-May	21-Apr
		Mid	22-Apr	03-May	21-Apr
		Late	22-Apr	03-May	21-Apr
	Silking Date	Early	5-Jul	03-Jul	05-Jul
		Mid	6-Jul	07-Jul	09-Jul
		Late	7-Jul	09-Jul	10-Jul
	Physiological Maturity	Early	14-Aug	13-Aug	15-Aug
		Mid	25-Aug	25-Aug	21-Aug
		Late	28-Aug	28-Aug	24-Aug
19-Apr	Site 2C				
	Emergence Date	Early	26-Apr	03-May	23-Apr
		Mid	26-Apr	03-May	23-Apr
		Late	26-Apr	03-May	23-Apr
	Silking Date	Early	7-Jul	05-Jul	06-Jul
		Mid	8-Jul	09-Jul	09-Jul
		Late	9-Jul	11-Jul	10-Jul
	Physiological Maturity	Early	14-Aug	13-Aug	16-Aug
		Mid	24-Aug	26-Aug	22-Aug
		Late	29-Aug	29-Aug	24-Aug
09-May	Site 3C				
	Emergence Date	Early	16-May	17-May	12-May
		Mid	16-May	17-May	12-May
		Late	16-May	17-May	12-May
	Silking Date	Early	21-Jul	23-Jul	22-Jul
		Mid	24-Jul	30-Jul	25-Jul
		Late	26-Jul	31-Jul	26-Jul
	Physiological Maturity	Early	17-Sep	15-Sep	16-Sep
		Mid	28-Sep	30-Sep	24-Sep
		Late	2-Oct	02-Oct	25-Sep

Table 3.4 Biomass, LAI, and grain yield for validation sites 1V through 10V.

Year	Location	Cutting	Plant Density	Biomass	LAI	Grain Yield
			plants m^{-2}	kg ha^{-1}		kg ha^{-1}
2005	1V	1	.	3851	2.69	.
	2V	1	.	116	0.65	.
	3V	1	.	150	0.48	.
	4V	1	.	792	1.29	.
	5V	1	.	1767	2.21	.
	1V	2	5.7	17527	1.73	12262
	2V	2	5.4	17938	1.96	10026
	3V	2	5.3	16044	1.98	6179
	4V	2	6.7	16534	1.64	9628
	5V	2	5.5	17922	1.83	12170
2006	6V	1	.	614	.	.
	7V	1	.	199	0.80	.
	8V	1	.	1496	1.81	.
	9V	1	.	143	0.22	.
	10V	1	.	651	0.80	.
	6V	2	6.3	21579	1.54	11988
	7V	2	5.7	21979	1.77	9094
	8V	2	6.8	24689	1.79	10099
	9V	2	5.9	17279	1.56	8530
	10V	2	7.7	24416	1.80	8404

Table 3.5 Model evaluation measures for Ceres Maize and Hybrid Maize CSMs for validation data as output and modified based on calibration studies.

Product	CSM	Model Output	Adjusted Output
		--------------RMSE, %--------------	
Grain	CERES-Maize	26	17
	Hybrid Maize	23	13
		----------Ratio of Scatter----------	
	CERES-Maize	0.66	0.82
	Hybrid Maize	0.58	0.83
		--------------RMSE, %--------------	
Biomass	CERES-Maize	29	22
		----------Ratio of Scatter----------	
	CERES-Maize	0.36	0.78
		--------------RMSE, %--------------	
LAI	CERES-Maize	20	11
		----------Ratio of Scatter----------	
	CERES-Maize	0.81	0.98

Figure 3.1 Average daily temperature (lines) and monthly total rainfall (columns) for a) Sites 1C and 2C, b) Site 3C, and c) Sites 4C and 5C. Lined portion of columns represents supplemental irrigation at Sites 2C (a) and 5C (c).

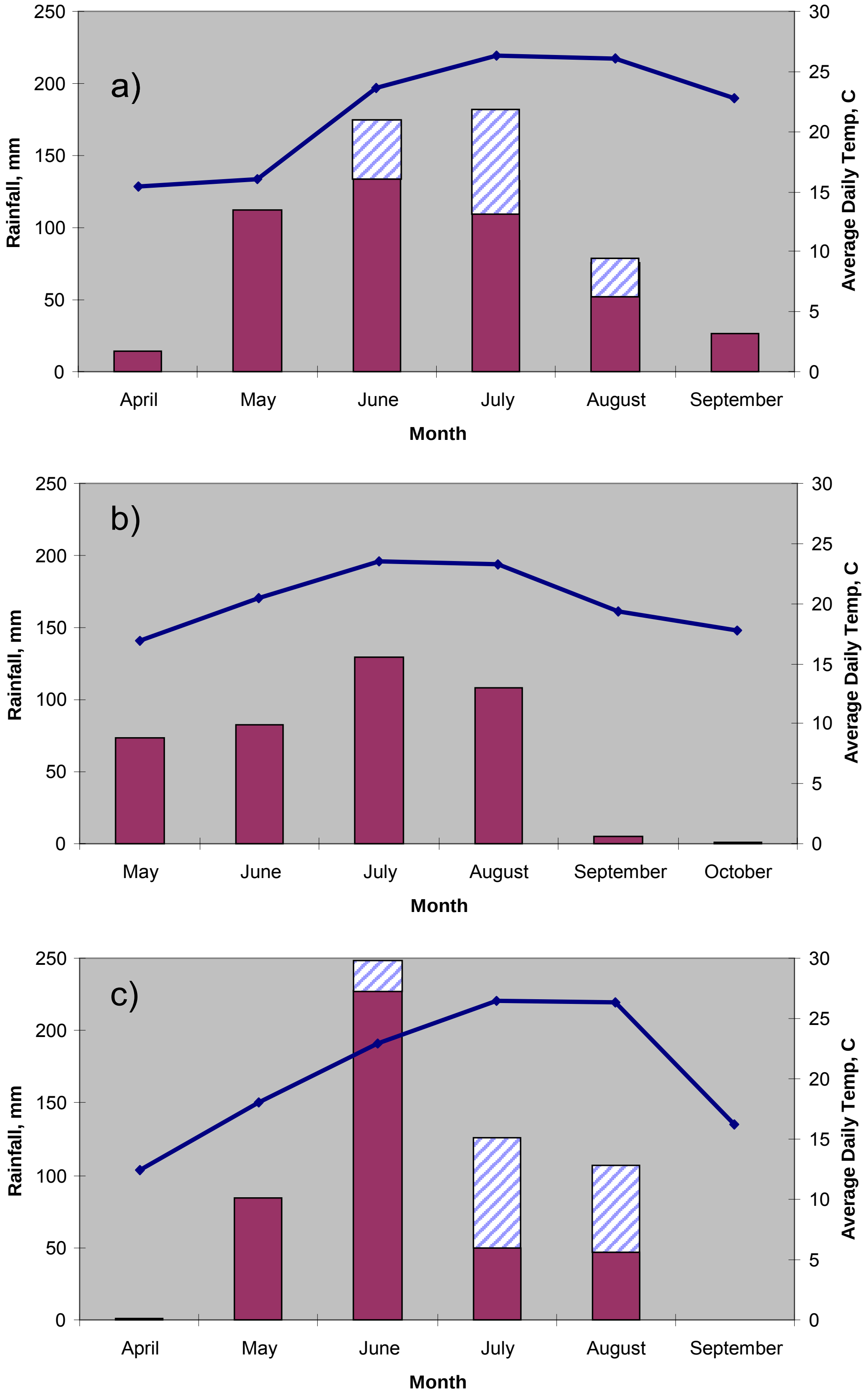


Figure 3.2 Observed and model-predicted grain yield from calibration sites as affected by plant density.

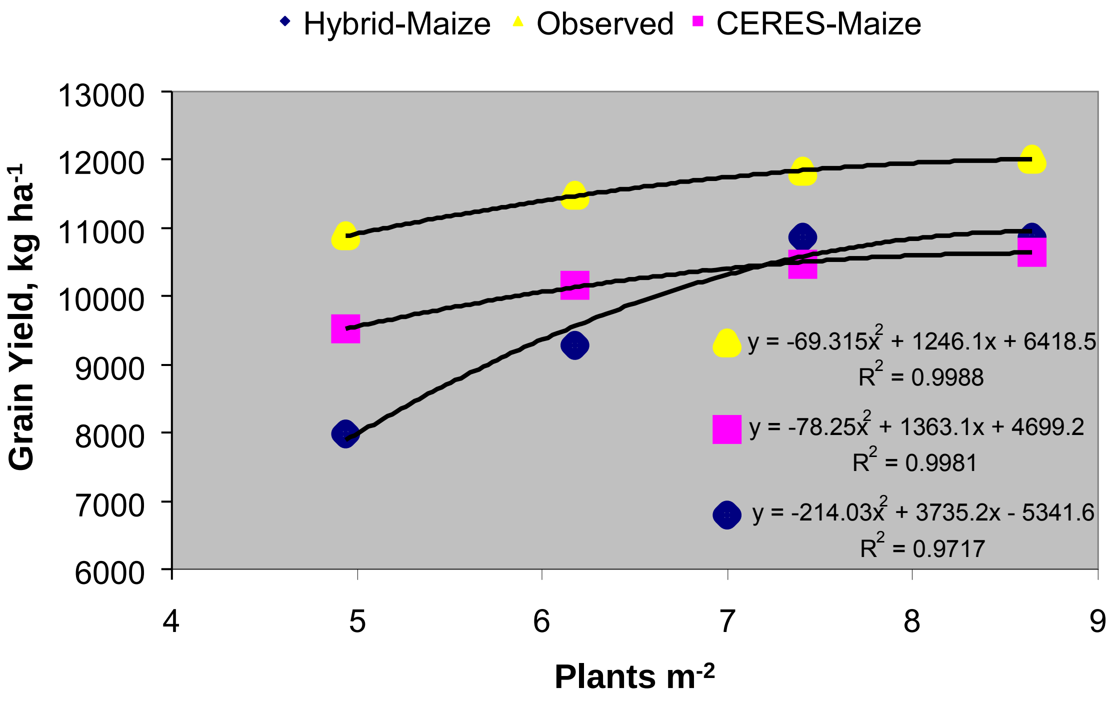


Figure 3.3 Comparison between observed and predicted values from calibration sites for LAI by plant density for a) Hybrid-Maize; and b) Ceres-Maize, calibration studies.

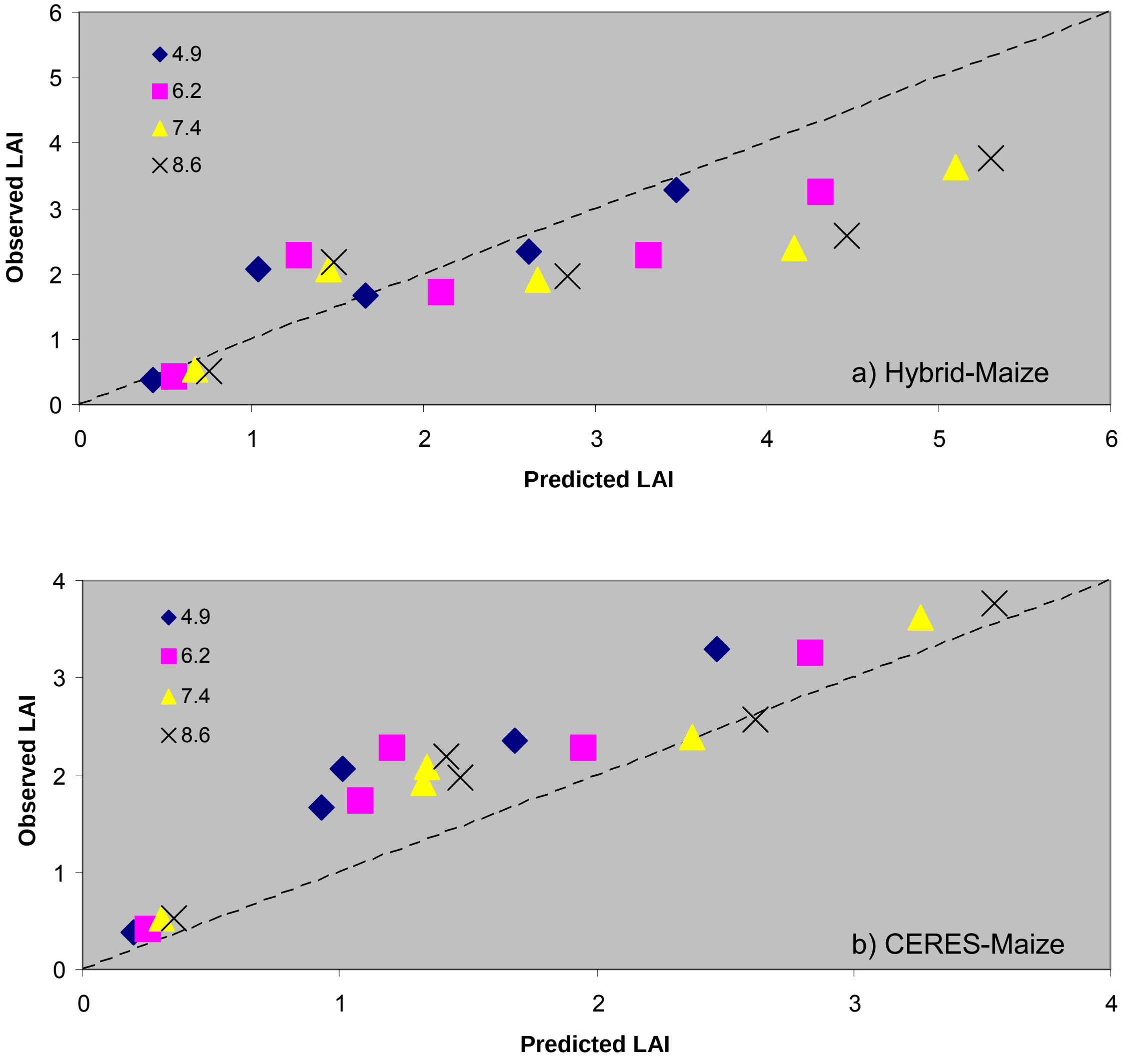
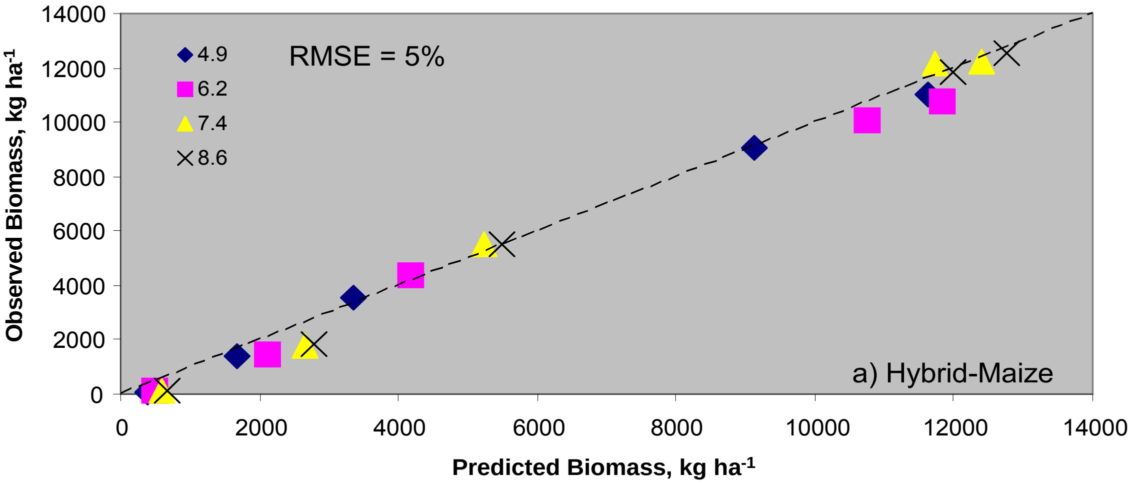


Figure 3.4 Comparison between observed and predicted values for stem+leaf biomass by plant density for a) Hybrid-Maize; and b) CERES-Maize, calibration studies.



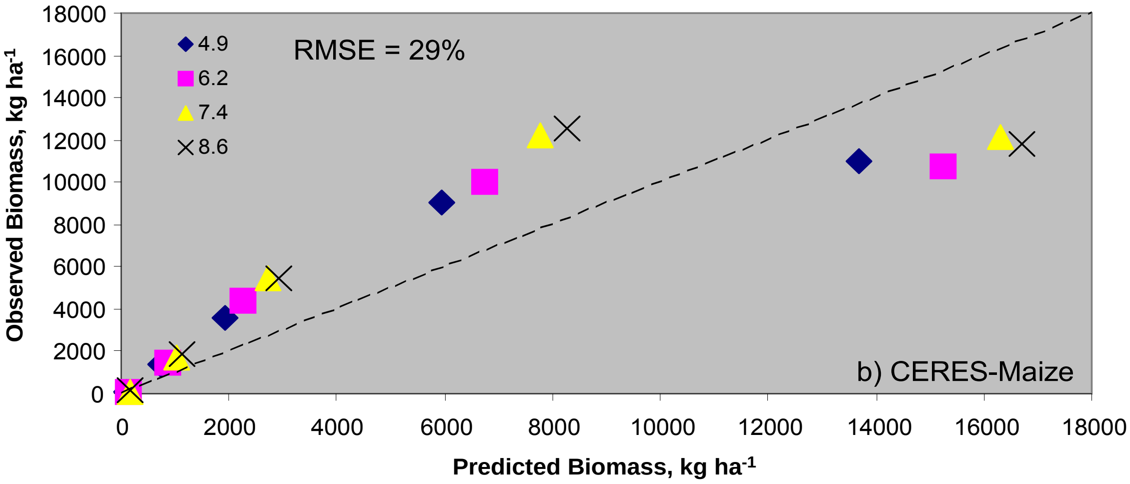


Figure 3.5 Comparison between observed and predicted values for grain yield by plant density a) as output and b) adjusted output, calibration studies.

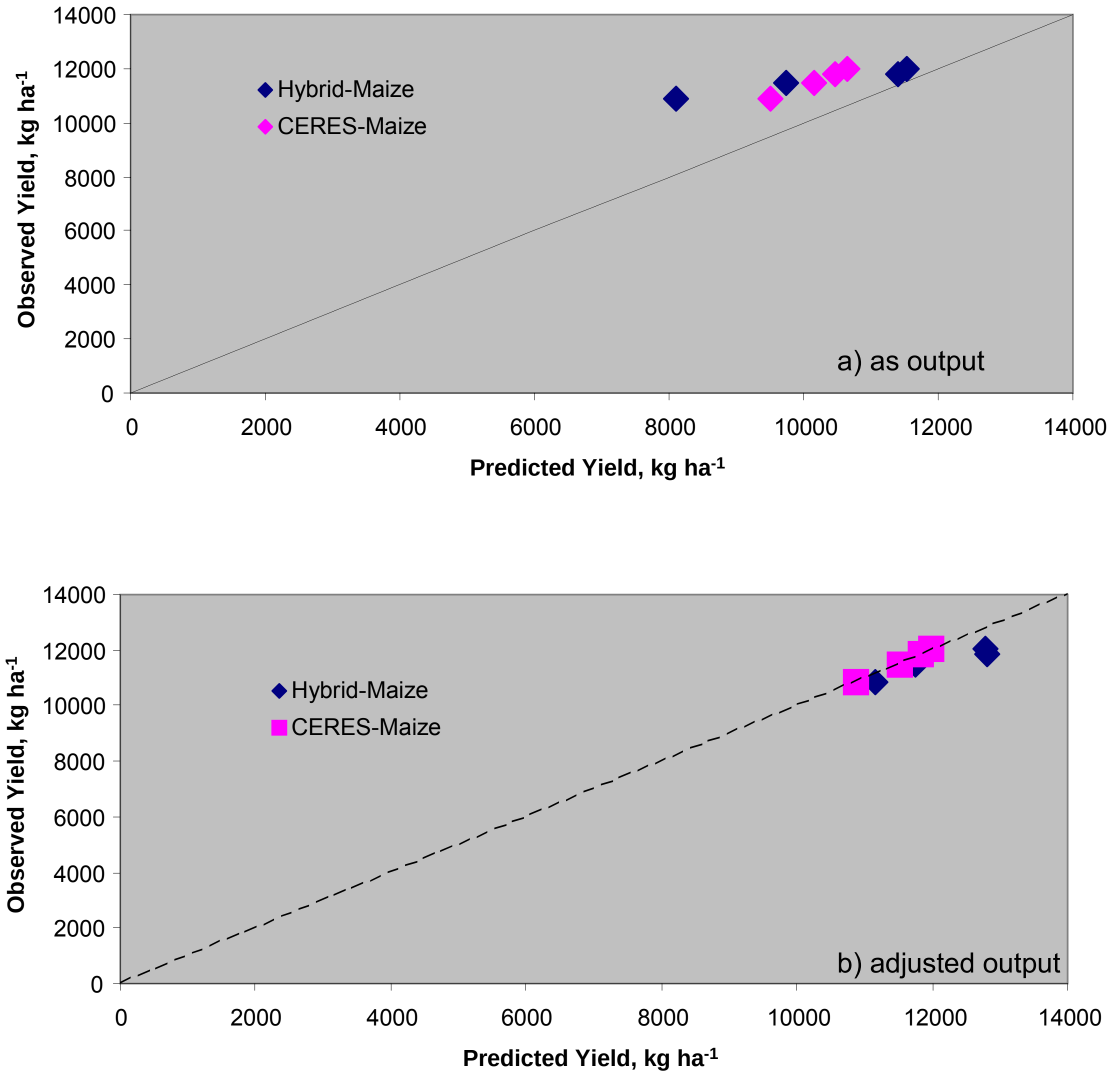
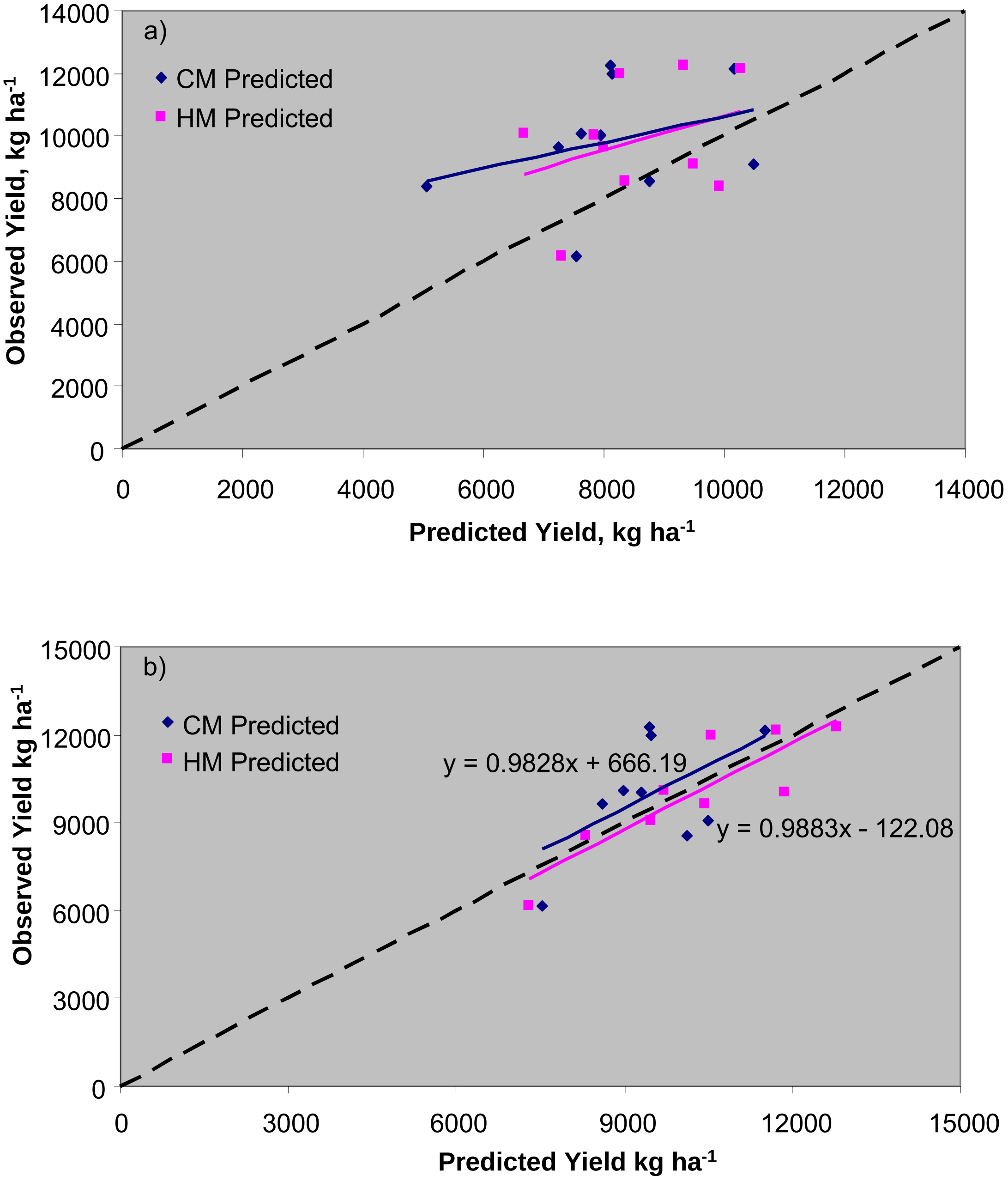


Figure 3.6 Grain yield predicted by CERES-Maize (CM) and Hybrid-Maize (HM) crop simulation models: a) as output, 10 sites; and b) modified output across 9 validation sites, 2005-2006.



SUMMARY AND CONCLUSIONS

Grain yield was highest at the highest evaluated plant density with a total advantage of 1141 kg ha^{-1} over the 4.9 seeds m^{-2} planting rate. The late hybrid out-yielded the medium and early hybrids by 550 and 1864 kg ha^{-1}, respectively. Total stem yield was also greatest at the highest plant density but only 340 kg ha^{-1} more than at 7.4 seeds m^{-2}. Overall results for leaf biomass were similar to those for stem biomass. Solving for the optimum density based on the quadratic model for grain yield resulted in an estimated optimum of 7.6 seeds m^{-2}. This is slightly higher than the current recommendation of 6.9 seeds m^{-2} that would be recommended for this average yield level (11.5 Mg ha^{-1}).

Grain N, P, and K uptake was highest for the medium RM hybrid. Grain yield was not highest for this hybrid, so the uptake values result from greater nutrient concentrations in the grain, especially compared to the late hybrid. Overall leaf+stem N uptake for the medium RM hybrid was the lowest of the three, but K uptake was highest. Nutrient uptake levels varied by density, with the lowest levels observed at the lowest and highest plant densities. At 4.9 seeds m^{-2}, lower nutrient uptake is explained by generally lower grain and biomass yield. At the 8.6 seeds m^{-2} rate, N and K levels in grain and tissue may have been lower due the dilution effect associated with higher biomass. However, all grain nutrient uptake values fall within the range reported by Heckman et al. (2003) for corn grown in the mid-Atlantic.

While numerous studies over the years have investigated the effect of plant density and hybrid characteristics on yield, recent increases in corn hybrid stress tolerance and standability make revisiting these basic studies worthwhile. Based on results from these studies, plant density recommendations at these high yield levels may need to be revised upwards.

When the evaluated corn growth models were compared to results observed from field testing reported in chapter one, corn grain yield was under predicted by both non-calibrated CSMs. CERES-Maize error was consistently 1350 kg ha^{-1} across the range of tested plant density. We also measured generally greater LAI and biomass production than that predicted by the CERES-Maize CSM. CERES-Maize total daily growth rate output was increased to more closely match the measured variables. The adjusted model more accurately predicted dry biomass production during early season and at maturity (RMSE decrease of 27%). Error associated with CERES-Maize-predicted LAI was also decreased (15%). Grain yield prediction accuracy for the cross validation data set was much improved and the RMSE associated with the adjusted model output would be ranked as good, using the scale of Jamieson et al. (1991). The slope of the observed versus modified predicted grain yield trend was 0.98 indicating high accuracy.

Hybrid-Maize biomass prediction was highly accurate and adjustments made based on the calibration work did not affect modeled biomass output. Grain yield prediction RMSE for Hybrid-Maize varied by treatment with greater error (RMSE) at low plant density. Potential kernel number per ear was increased in order to more closely match observed grain yield and this increase was greater at low density. Similar to grain yield results for the CERES-Maize model, the modified Hybrid-Maize model applied to the cross validation data, resulted in a slope of 0.99 for the observed versus modified predicted grain yield trend. Modeled LAI was significantly higher than was observed in these experiments but we believe this to be an artifact of the difference in environment between our testing sites and where the model was developed. Because total biomass predictions were highly accurate without adjustments and because the model does not output separate leaf and stem values, we did not modify this variable.

Validation results of both calibrated CSMs showed reasonable accuracy in simulating planting date and environmental effects on a range of corn hybrids grown throughout Virginia over two years. We expect that both validated models can be used for strategic and management decisions in mid-Atlantic corn production. Since each model has unique strengths and assessment modules, the CSM can be matched to the particular use. Both modified models should be equally effective at predicting the effect of plant density and hybrid RM impacts as well as variable environmental conditions on plant productivity and grain yield.

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APPENDIX A

LEAF, STEM AND TOTAL BIOMASS PRODUCTION BY SITE, CALIBRATION STUDIES, 2005-2006

Site 1C leaf, stem, and total biomass by cutting, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Cutting	RM	Plant Density	Leaf Biomass	Stem Biomass	Total Biomass
		plants m^{-2}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Early	4.9	3.84	8.15	10.14
	Early	6.2	5.94	14.10	23.31
	Early	7.4	7.29	13.37	18.33
	Early	8.6	1.99	5.60	5.11
	Mid	4.9	6.35	12.97	23.02
	Mid	6.2	12.61	29.17	45.31
	Mid	7.4	13.71	26.59	41.33
	Mid	8.6	19.12	29.06	43.90
	Late	4.9	11.90	23.09	40.70
	Late	6.2	10.69	22.68	30.50
	Late	7.4	10.87	26.12	37.96
	Late	8.6	9.71	10.37	20.39
2	Early	4.9	174.55	766.20	1078.89
	Early	6.2	361.30	1621.01	2136.51
	Early	7.4	330.45	1452.20	2122.41
	Early	8.6	236.26	1037.08	1258.78
	Mid	4.9	382.11	1498.31	2019.93
	Mid	6.2	445.08	1882.03	2344.91
	Mid	7.4	454.41	1917.55	2613.95
	Mid	8.6	478.63	1870.55	2469.81
	Late	4.9	426.06	2094.43	2511.63
	Late	6.2	471.63	2073.09	2634.58
	Late	7.4	326.50	1592.13	2128.03
	Late	8.6	322.73	1519.29	1928.69
3	Early	4.9	526.34	1529.34	2431.42
	Early	6.2	1110.45	2954.27	4625.87
	Early	7.4	1234.77	3033.21	5565.31
	Early	8.6	993.49	2314.19	3553.60
	Mid	4.9	934.47	2010.84	3611.97
	Mid	6.2	1397.13	4381.89	5222.48
	Mid	7.4	1183.65	3113.21	5544.61
	Mid	8.6	1288.59	3389.66	4900.12
	Late	4.9	1069.91	3146.58	4293.85
	Late	6.2	1138.80	3418.90	5448.68
	Late	7.4	1319.63	3143.35	5145.07
	Late	8.6	1209.30	3160.04	4373.01
4	Early	4.9	1255.76	7255.76	8511.52
	Early	6.2	2079.36	8079.36	10158.73
	Early	7.4	2943.33	8943.33	11886.66
	Early	8.6	1728.11	7728.11	9456.22

	Mid	4.9	2119.91	8119.91	10239.81
	Mid	6.2	3067.65	9067.65	12135.30
	Mid	7.4	3366.34	9366.34	12732.68
	Mid	8.6	3746.83	9746.83	13493.67
	Late	4.9	2351.86	8351.86	10703.73
	Late	6.2	2870.32	8870.32	11740.63
	Late	7.4	3524.75	9524.75	13049.49
	Late	8.6	3099.76	9099.76	12199.52
5	Early	4.9	1153.17	8153.17	9306.33
	Early	6.2	1865.09	7593.84	9458.93
	Early	7.4	2197.17	7196.19	9393.36
	Early	8.6	1721.22	6358.51	8079.73
	Mid	4.9	1720.05	6886.71	8606.76
	Mid	6.2	2364.94	8561.31	10926.25
	Mid	7.4	2620.06	8180.19	10800.25
	Mid	8.6	2899.52	9739.40	12638.92
	Late	4.9	2152.36	7426.44	9578.79
	Late	6.2	2252.48	7553.86	9806.33
	Late	7.4	3094.88	9980.97	13075.85
	Late	8.6	2283.96	7927.26	10211.23

Site 2C leaf, stem, and total biomass by cutting, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Cutting	RM	Plant Density	Leaf Biomass	Stem Biomass	Total Biomass
		plants m^{-2}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Early	4.9	3.11	8.54	10.18
	Early	6.2	2.90	10.79	11.71
	Early	7.4	4.24	15.50	9.76
	Early	8.6	4.16	13.36	14.38
	Mid	4.9	5.34	21.68	28.23
	Mid	6.2	7.64	19.11	21.53
	Mid	7.4	8.95	35.39	34.08
	Mid	8.6	10.31	27.32	30.43
	Late	4.9	6.55	16.47	18.39
	Late	6.2	5.71	18.62	22.61
	Late	7.4	8.93	24.43	28.60
	Late	8.6	9.62	25.02	32.28
2	Early	4.9	453.64	1343.81	2226.30
	Early	6.2	425.63	1363.79	1634.46
	Early	7.4	578.01	1921.41	2915.82
	Early	8.6	650.70	1854.69	2587.33
	Mid	4.9	411.63	1215.32	1816.27
	Mid	6.2	543.31	1670.50	2369.16
	Mid	7.4	493.07	1620.98	2258.23
	Mid	8.6	744.70	2259.63	2951.27
	Late	4.9	463.73	1475.09	1840.56
	Late	6.2	481.74	1434.52	1768.71
	Late	7.4	660.37	2009.13	2550.90
	Late	8.6	734.30	2229.67	2973.29
3	Early	4.9	1297.59	3550.93	4447.33
	Early	6.2	1266.80	2750.02	4081.06
	Early	7.4	1652.27	4268.96	5961.72
	Early	8.6	1819.07	3982.02	5970.70
	Mid	4.9	1223.66	2941.73	3664.04
	Mid	6.2	1425.77	2838.67	4947.44
	Mid	7.4	1846.46	3832.21	6251.47
	Mid	8.6	1800.54	4995.34	6347.65
	Late	4.9	1118.44	2526.08	3552.56
	Late	6.2	1372.64	3136.83	4326.63
	Late	7.4	1569.91	3796.49	6134.54
	Late	8.6	1862.21	3448.28	5954.61
4	Early	4.9	2039.30	9048.64	11087.93
	Early	6.2	2060.82	9355.40	11416.22
	Early	7.4	3053.85	11196.14	14249.99
	Early	8.6	2932.36	12005.67	14938.02

	Mid	4.9	2440.73	9038.19	11478.92
	Mid	6.2	2364.13	9223.87	11588.00
	Mid	7.4	3647.30	13927.24	17574.54
	Mid	8.6	3467.12	12936.29	16403.42
	Late	4.9	2423.23	9388.38	11811.60
	Late	6.2	2591.05	10412.64	13003.69
	Late	7.4	3382.18	13992.32	17374.51
	Late	8.6	3337.81	12879.14	16216.95
5	Early	4.9	2405.15	8583.85	10988.99
	Early	6.2	2294.88	8156.22	10451.10
	Early	7.4	3067.28	10495.80	13563.08
	Early	8.6	3028.26	9731.31	12759.57
	Mid	4.9	2596.21	8730.07	11326.28
	Mid	6.2	2963.10	8696.79	11659.89
	Mid	7.4	3884.61	11586.73	15471.34
	Mid	8.6	3418.34	10741.80	14160.14
	Late	4.9	2842.39	9211.20	12053.60
	Late	6.2	3030.76	9521.60	12552.37
	Late	7.4	4124.70	12363.79	16488.48
	Late	8.6	4145.28	11741.42	15886.69

Site 3C leaf, stem, and total biomass by cutting, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Cutting	RM	Plant Density	Leaf Biomass	Stem Biomass	Total Biomass
		plants m^{-2}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Early	4.9	6.80	15.97	29.62
	Early	6.2	11.57	27.41	45.00
	Early	7.4	7.05	22.86	40.18
	Early	8.6	10.01	24.02	41.20
	Mid	4.9	14.24	36.67	60.37
	Mid	6.2	16.78	25.01	44.67
	Mid	7.4	21.90	44.37	78.58
	Mid	8.6	25.01	45.62	76.60
	Late	4.9	10.03	22.77	45.80
	Late	6.2	14.42	27.68	48.62
	Late	7.4	21.87	54.97	85.59
	Late	8.6	19.57	36.31	70.91
2	Early	4.9	59.02	242.72	308.66
	Early	6.2	102.80	374.94	491.06
	Early	7.4	94.36	432.52	669.73
	Early	8.6	69.25	285.60	396.80
	Mid	4.9	135.08	440.24	607.19
	Mid	6.2	107.64	327.94	479.67
	Mid	7.4	206.84	764.58	1017.53
	Mid	8.6	189.09	590.21	876.28
	Late	4.9	110.69	410.82	570.36
	Late	6.2	107.82	367.04	529.92
	Late	7.4	156.79	527.78	740.59
	Late	8.6	113.20	430.19	631.31
3	Early	4.9	209.00	722.24	1056.92
	Early	6.2	290.26	1164.63	1461.02
	Early	7.4	514.32	1708.37	2218.37
	Early	8.6	416.91	1378.47	1751.40
	Mid	4.9	471.81	1519.83	1967.60
	Mid	6.2	356.10	1067.40	1524.32
	Mid	7.4	698.56	1974.78	2561.40
	Mid	8.6	449.03	1419.01	2103.86
	Late	4.9	364.17	1299.00	1639.77
	Late	6.2	294.21	1015.20	1376.44
	Late	7.4	560.79	1802.20	2290.21
	Late	8.6	465.89	1368.60	1756.77
4	Early	4.9	1321.96	5588.02	6909.98
	Early	6.2	1920.60	7774.77	9695.37
	Early	7.4	2145.74	8402.73	10548.47
	Early	8.6	2028.06	8213.94	10242.00

	Mid	4.9	2098.20	8057.45	10155.65
	Mid	6.2	2048.51	8735.75	10784.25
	Mid	7.4	2873.54	11058.24	13931.78
	Mid	8.6	2676.39	10198.26	12874.65
	Late	4.9	2018.73	7536.57	9555.29
	Late	6.2	2116.86	7980.08	10096.94
	Late	7.4	2439.95	9961.21	12401.15
	Late	8.6	2548.12	10681.34	13229.46
5	Early	4.9	777.35	3760.36	4537.71
	Early	6.2	1008.29	4777.70	5786.00
	Early	7.4	1169.30	5244.64	6413.94
	Early	8.6	920.98	4317.57	5238.56
	Mid	4.9	914.13	4463.97	5378.09
	Mid	6.2	1178.06	4704.92	5882.99
	Mid	7.4	1681.45	5913.40	7594.85
	Mid	8.6	1424.56	5038.24	6462.80
	Late	4.9	873.54	4618.00	5491.55
	Late	6.2	995.33	4552.06	5547.38
	Late	7.4	1291.71	6376.76	7668.47
	Late	8.6	1033.19	5340.61	6373.80

Site 4C leaf, stem, and total biomass by cutting, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Cutting	RM	Plant Density	Leaf Biomass	Stem Biomass	Total Biomass
		plants m^{-2}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Early	4.9	60.28	21.10	81.38
	Early	6.2	60.30	18.06	78.36
	Early	7.4	98.07	33.97	132.04
	Early	8.6	123.70	51.12	174.82
	Mid	4.9	51.94	18.17	70.11
	Mid	6.2	67.25	22.89	90.14
	Mid	7.4	129.45	40.65	170.09
	Mid	8.6	156.89	59.16	216.05
	Late	4.9	85.57	28.41	113.98
	Late	6.2	75.83	34.11	109.94
	Late	7.4	148.69	50.49	199.18
	Late	8.6	138.97	59.29	198.26
2	Early	4.9	504.79	192.77	633.96
	Early	6.2	568.09	235.99	532.56
	Early	7.4	761.76	301.26	855.70
	Early	8.6	989.50	422.84	1143.07
	Mid	4.9	494.57	196.18	560.45
	Mid	6.2	553.03	256.79	719.64
	Mid	7.4	1035.05	389.85	1246.64
	Mid	8.6	927.63	387.16	1066.75
	Late	4.9	685.91	264.86	920.18
	Late	6.2	606.11	228.46	645.79
	Late	7.4	927.27	376.04	1132.65
	Late	8.6	1273.37	439.16	1445.04
3	Early	4.9	1565.39	499.79	5039.39
	Early	6.2	1680.19	461.79	5785.10
	Early	7.4	2227.93	685.51	8307.15
	Early	8.6	3064.33	925.95	9480.39
	Mid	4.9	1595.14	1662.71	4939.63
	Mid	6.2	1448.05	456.25	6670.83
	Mid	7.4	2822.47	807.24	8847.52
	Mid	8.6	2850.95	994.41	9583.25
	Late	4.9	1423.26	533.25	5754.71
	Late	6.2	1476.65	480.69	6214.87
	Late	7.4	2411.32	796.87	8508.19
	Late	8.6	3405.59	1041.20	9672.83
4	Early	4.9	5113.03	2025.69	9106.61
	Early	6.2	7061.74	2569.00	8386.26
	Early	7.4	8195.68	2855.68	8017.56
	Early	8.6	6602.22	3122.52	12537.70

	Mid	4.9	6602.64	1945.64	6020.21
	Mid	6.2	5470.19	2222.48	7441.97
	Mid	7.4	7564.32	3347.98	12291.42
	Mid	8.6	6570.68	3341.72	11579.62
	Late	4.9	5294.63	2316.45	8312.76
	Late	6.2	7194.13	2534.64	6599.06
	Late	7.4	7257.55	2961.92	10698.60
	Late	8.6	9489.62	3476.71	10160.76
5	Early	4.9	12844.05	1915.75	14759.80
	Early	6.2	8673.11	1863.97	10537.08
	Early	7.4	9688.45	2032.67	11721.12
	Early	8.6	8938.92	2972.73	11911.65
	Mid	4.9	10049.60	1864.30	11913.91
	Mid	6.2	7984.86	2104.00	10088.86
	Mid	7.4	9363.75	2859.92	12223.66
	Mid	8.6	10229.43	3360.29	13589.72
	Late	4.9	14906.17	2788.92	17695.10
	Late	6.2	10380.55	2642.39	13022.94
	Late	7.4	9236.46	2845.49	12081.95
	Late	8.6	10174.70	3772.89	13947.59

Site 5C leaf, stem, and total biomass by cutting, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Cutting	RM	Plant Density	Leaf Biomass	Stem Biomass	Total Biomass
		plants m^{-2}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Early	4.9	175.29	53.47	228.76
	Early	6.2	226.95	60.68	287.63
	Early	7.4	241.74	51.44	293.18
	Early	8.6	336.50	71.36	407.86
	Mid	4.9	217.48	54.17	271.65
	Mid	6.2	212.18	65.54	277.72
	Mid	7.4	252.75	74.71	327.46
	Mid	8.6	292.42	85.69	378.11
	Late	4.9	184.81	58.75	243.57
	Late	6.2	290.50	81.21	371.71
	Late	7.4	237.90	78.31	316.20
	Late	8.6	357.99	121.70	479.69
2	Early	4.9	1526.27	395.58	2487.49
	Early	6.2	1457.96	417.82	1803.30
	Early	7.4	1648.87	404.73	1547.06
	Early	8.6	2140.10	677.12	2750.24
	Mid	4.9	1328.39	434.14	2000.39
	Mid	6.2	1807.92	483.81	1865.86
	Mid	7.4	1870.15	644.30	2405.20
	Mid	8.6	2116.72	648.43	2238.80
	Late	4.9	1156.47	395.94	1776.49
	Late	6.2	1452.88	424.81	1841.57
	Late	7.4	1600.48	472.33	1980.78
	Late	8.6	2362.39	664.93	2969.97
3	Early	4.9	2874.74	820.09	3694.84
	Early	6.2	3019.74	957.02	3976.76
	Early	7.4	3831.75	995.38	4827.13
	Early	8.6	4286.37	1308.35	5594.72
	Mid	4.9	2951.52	817.33	3768.85
	Mid	6.2	3815.80	976.75	4792.55
	Mid	7.4	3682.01	1130.16	4812.17
	Mid	8.6	4508.70	1472.86	5981.56
	Late	4.9	2538.63	772.50	3311.13
	Late	6.2	3929.16	1008.17	4937.32
	Late	7.4	4211.16	1192.56	5403.72
	Late	8.6	4004.51	1246.14	5250.65
4	Early	4.9	4296.82	2069.38	6366.19
	Early	6.2	5827.87	2873.19	8701.06
	Early	7.4	5295.16	2560.68	7855.84
	Early	8.6	7216.22	3618.74	10834.95

	Mid	4.9	4673.97	2522.68	7196.66
	Mid	6.2	6077.10	3217.66	9294.76
	Mid	7.4	6877.30	3498.05	10375.36
	Mid	8.6	7681.85	3965.11	11646.97
	Late	4.9	5232.02	2770.88	8002.90
	Late	6.2	6312.89	3426.99	9739.87
	Late	7.4	6520.01	3515.79	10035.79
	Late	8.6	7828.77	4373.20	12201.97
5	Early	4.9	11241.12	2022.11	13263.22
	Early	6.2	11187.58	2495.89	13683.48
	Early	7.4	12043.72	2585.70	14629.42
	Early	8.6	14498.30	3215.58	17713.89
	Mid	4.9	11470.75	2762.32	14233.07
	Mid	6.2	11726.15	2910.07	14636.23
	Mid	7.4	11463.53	2919.40	14382.93
	Mid	8.6	10205.33	3444.91	13650.24
	Late	4.9	13088.94	2890.44	15979.37
	Late	6.2	13974.38	3661.10	17635.48
	Late	7.4	13089.99	3768.38	16858.37
	Late	8.6	11308.87	3634.54	14943.41

APPENDIX B

CALIBRATION STUDY GRAIN YIELDS, 2005-2006

Grain Yield by location, calibration studies, Early RM = Pioneer Brand 34B96; Mid RM = Pioneer Brand 33M54; Late RM = Pioneer Brand 31G66.

Location	RM	Plant Density	Grain Yield (15.5% Moisture)
		plants m^{-2}	kg ha^{-1}
1C	Early	4.9	7204
	Early	6.2	13581
	Early	7.4	12415
	Early	8.6	12083
	Mid	4.9	13260
	Mid	6.2	12435
	Mid	7.4	13697
	Mid	8.6	15180
	Late	4.9	15500
	Late	6.2	11336
	Late	7.4	13256
	Late	8.6	14465
2C	Early	4.9	11558
	Early	6.2	16627
	Early	7.4	12370
	Early	8.6	12513
	Mid	4.9	13332
	Mid	6.2	13594
	Mid	7.4	15518
	Mid	8.6	16465
	Late	4.9	16246
	Late	6.2	15224
	Late	7.4	16773
	Late	8.6	16291
3C	Early	4.9	8691
	Early	6.2	10785
	Early	7.4	10256
	Early	8.6	9371
	Mid	4.9	11785
	Mid	6.2	11693
	Mid	7.4	12433
	Mid	8.6	13683
	Late	4.9	12912
	Late	6.2	12301
	Late	7.4	14197

	Late	8.6	13001
4C	Early	4.9	7467
	Early	6.2	6655
	Early	7.4	8289
	Early	8.6	7657
	Mid	4.9	7888
	Mid	6.2	7298
	Mid	7.4	8484
	Mid	8.6	7688
	Late	4.9	8029
	Late	6.2	7050
	Late	7.4	7658
	Late	8.6	8733
5C	Early	4.9	9069
	Early	6.2	10928
	Early	7.4	11035
	Early	8.6	11278
	Mid	4.9	10359
	Mid	6.2	10879
	Mid	7.4	10211
	Mid	8.6	10240
	Late	4.9	9837
	Late	6.2	11961
	Late	7.4	10797
	Late	8.6	11607