

**A CONCEPTUAL MODEL TO ESTIMATE THE NITROGEN REQUIREMENT
OF CORN (*Zea mays* L.)**

A Dissertation

by

CATALINO JORGE LOPEZ COLLADO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2005

Major Subject: Soil Science

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Major Subject: Soil Science

ABSTRACT

A Conceptual Model to Estimate the Nitrogen Requirement of Corn (*Zea mays* L.). (December 2005)

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The objectives of this work were to evaluate the vegetative parameters used to estimate crop N demand and to estimate the accuracy and precision of the conceptual model of fertilization using an error propagation method. Corn plants were collected throughout the entire crop life cycle to determine the fresh and dry weight of the aboveground biomass and roots, root index, plant height, and corn grain yield.

Three experiments were conducted, two under field conditions and one under greenhouse conditions. In the first field experiment in 2002, three sites were selected. The first site was the Texas A&M University (TAMU) Agricultural Experiment Station Research Farm in which a Ships clay soil was used. The second site was a cooperative farmer's land on a Weswood silt loam soil in Burleson County. These first two sites used Pioneer 32R25 as the corn hybrid. The third site was also a Ships soil in the TAMU Farm, but Dekalb 687 was the corn variety. In 2003, the second experiment was on a Ships soil in the field of TAMU Farm, and the third experiment was conducted in a greenhouse using Ships and Weswood soil.

No differences in the root index and harvest index were observed, even when the Dekalb 687 hybrid was included. Variations in plant N concentration, moisture content, and yield were noted, but followed predictable patterns with time over the season. These

parameters were consistent throughout the entire life cycle of the crop. The linear relationship between the fresh weight of aboveground biomass and fresh weight of roots was $R^2 = 0.92$, the moisture content of corn plants over time was fit to a second grade polynomial with $R^2 = 0.98$, and plant N content had a close linear relationship ($R^2=0.90$) with the total plant dry weight, including roots, at harvest. The accuracy of the conceptual model was low under field conditions (55%), but high under greenhouse conditions (90%). Precision of the conceptual model was low both in the field (194%) and the greenhouse (115%) conditions.

This dissertation is dedicated to

My Son

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1. INTRODUCTION

Since ancient times, people that grew fruit trees, grasses, and annual crops have had a major concern: how to determine the optimal amounts of nutrients to add to soil in order to obtain the highest yield of the highest quality crops. There are several ways to determine the optimal application rate of a nutrient. Mathematical models, binary relationships, statistical analysis of experimental rate studies, chemical analysis of the soil and plants, computer programs and conceptual models have all been used.

Conceptual models of fertilization are based on theory, and have all been created within the last 30 years. One tenet of many conceptual models of fertilization is that the rate of fertilization should equal crop nutrient demand minus the quantity of available nutrient in the soil. This term is then divided by the efficiency factor of fertilizer uptake by the crop.

Although models have been used to predict the requirements of nutrients, behavior of nutrients in soils and plants, and soil-plant-water-environment relations, have not been tested for accuracy and precision under different conditions. Both characteristics are important to decide the use of a model.

The balance sheet model was proposed by George Stanford in 1966, and has been a matter of study since then. Today, different algorithms have been proposed and used to estimate the nutrient demand by crops, nutrient supply by soil, and fertilizer use efficiency.

This dissertation follows the style of the Soil Science Society of America Journal.

2. LITERATURE REVIEW

Estimating crop fertilization requirement may appear simple, but this usually is not the case. Since Justus Von Liebig showed in 1850 the necessity to add nutrients to crops, many research studies have been conducted to determine crop nutrient requirements and soil and plant nutrient deficiencies. The most widely used method to estimate the requirement for fertilizer is to conduct experiments where rates of nutrients are applied and plant growth responses are measured. Although this way to estimate the fertilizer requirement is relatively easy to carry out, a disadvantage is that the results are often difficult to extrapolate to other areas due to differences in soil properties, climate, and fertilizer requirements of each crop. These differences vary from site to site and from year to year because of variations in soil, seasonal growing conditions, agricultural practices, etc. (Colwell, 1994). These types of experiments use the soil as a “black box”, where fertilizers are introduced as an input, and yield is the only output. One disadvantage of this approach is that improved knowledge about interaction of the soil-crop-environment is reduced (Cooke, 1982).

Fertilizer rate studies have been important in generalizing crop nutrient requirements but have not been useful at the soil process level. Conceptual models have been used to explain what happens to soil-plant-environment relationships when fertilizers are added. Previous models theorized that crop nutrient requirements must be equal to the nutrients removed from soil. This is a basic logical first step. Some recent work has included transformations that occur in soils, in plants, and even included soil energy balances, but their use has been restricted to biological purposes and hasn't introduced crop yield, a principal factor for agricultural use (Müller, 2000).

Laws in agriculture

There are few laws in agriculture. One is the Law of the Minimum of Liebig (van de Ploeg et al., 1999), Stoke's Law (Gee and Bauder, 1986), Darcy's Law, and the Increases-Decreases Law, which came from economic theory. The first law explains that higher yield is restricted by the most deficient nutrient. The second one is about the sedimentation of soil particles in liquid media. The particles settle proportionally to their diameter and inversely proportional to the fluid viscosity. Darcy's Law is a generalized relationship for flow in porous media. It shows that volumetric flow rate is a function of the flow area, elevation, fluid pressure and a proportionality constant. It may be stated in several different forms depending on the flow conditions. Since its discovery, it has been found valid for any Newtonian fluid. Likewise, while it was established under saturated flow conditions, it may be adjusted to account for unsaturated and multiphase flow. This law is important for several fields of study including ground-water hydrology, soil physics, and petroleum engineering (Brown, 2003). The fourth law explains that increases in yield eventually decrease in relation to increased fertilizer application.

Models

Models are theoretical representations that show how systems function. They are useful for predicting changes. Models should be precise and exact, and have a high probability that a phenomenon that occurs in a theoretical model will also occur in real life (Peitgen et al., 1992). For non-biological phenomenon, models are more precise and exact than for biological phenomenon, and those in turn are more feasible than social, economic and psychological models. At higher levels of relationship and structure, consequences are often more difficult to predict, and adequate models are more difficult to develop. This is because small changes in a process may result in large changes in intermediate or final responses (Peitgen et al., 1992).

The first system science or modeling work in soil science was that of Hans Jenny (Jenny, 1930). This work related soil nitrogen and organic matter functions with different environments and factors:

Nitrogen = f(climate>vegetation>topography(relief)>parent material>age)

Agriculture has developed with the knowledge of the essentiality of nutrients to plants (Mengel and Kirby, 1978; Marschner, 1995), as well as the development of the chemical analysis of soil-water-plants-atmosphere, and organic and inorganic compounds (Parnes, 1986). It has also been improved with methods to produce synthetic fertilizers (The British Sulfur Corporation Limited and Arab Federation of Chemical Fertilizer Producer, 1982), pesticides, herbicides, and improved management of crops, along with the use of mechanical traction, and knowledge about soil-water-crop-atmosphere-biota relationship (Stevenson and Cole, 1999). In this last case, the culture, education, psychology, economy, and political relationships of farmers are important factors to consider.

Agriculture, more specifically crop yield, depends on a variety of factors, both controllable and uncontrollable. In Mexico and other countries of the world, chemical, physical and biological factors control crop production, but the determination of what and how much to produce are the economic and political factors.

Models in agriculture

Agriculture has developed models to explain a broad variety of processes, for example, derivation of soil properties through a land inference model (Zhu et al., 1997), and modeling of nutrient uptake by plant roots growing in soil. This objective mechanistic model accurately describes equations for the nutrient-uptake process and plant growth. A mechanistic model differs from a regression model, in which coefficients are obtained statistically for unknown processes occurring between “black boxes”. The first ones

were called deterministic models; the second ones were called probabilistic or stochastic models (Barber, 1984; Barber, 1995). Once a model has been developed and verified, it may be useful for predicting the consequences of changing characteristics of soil and plant parameters with respect to nutrient uptake by plants (Barber and Cushman, 1981). However, one question to answer for future generations is what might occur if a deterministic model were evaluated with probabilistic procedures (Vogel, 1999).

In relation to root nutrient absorption, some experiments have been developed to validate simulation models (Reginato et al., 2002) for the growth and P (phosphorus) uptake of rape (*Brassica napus*) in soils at a range of P concentrations (Grant and Heaney, 1997). This kind of work has been carried out to evaluate the possibility of predicting solute uptake and plant growth response from independently measured soils and plant characteristics (Barber and Cushman, 1981). A mechanistic model was used to predict P and K (potassium) uptake in corn (*Zea mays* L.) (Chen and Barber, 1990), and soybean (*Glycine max*) (Silberbush and Barber, 1983; Silberbush and Barber, 1984), and how soil bulk density and P addition affect K uptake in soybeans (Silberbush et al., 1983). Actually, models have been used to help explain processes in soils, and soil-plant-atmosphere relationships and are referred to as soil-environment models.

Most models have been developed over the last 30 years. Some of them explain C/N (carbon/nitrogen) transformations, e.g. ROTHC, CENTURY, DAYSI, VVN, DNDC, HURLEY PASTURE MODEL and ECOSYS (Powlson et al., 1996). ROTHC is a carbon turnover model developed at Rothamsted Experimental Station (Coleman and Jenkinson, 1996). CENTURY is a turnover model developed for predicting long-term changes of carbon and nitrogen (Porton, 1996). DAYSI is a C/N turnover model (Mueller et al., 1996). VVN is a C/N turnover model developed in the early 1980's (Gunnewiek, 1996). DNDC is a C/N turnover model with the emphasis of predicting gaseous N emission developed by Li and colleagues (Li, 1996). HURLEY PASTURE MODEL is an ecosystem model with a soil and litter submodel (Thornley, 1998).

ECOSYS is an ecosystem model which includes a submodel dealing with C and N transformations (Grant et al., 1993).

MODEL MAKER is a computer program where soil-atmosphere processes are shown as conceptual ideas and they are transformed into a mathematical model (Müller, 2000). This is a new tool for understanding the soil-biosphere relationship. But, it doesn't explain specific effects on crops and yields, nor does it include nutrient interaction effects.

CRoPMan is a production-risk management model designed to help agricultural practitioners optimize crop management, maximize production and profit, identify limitations to crop yield, assist growers with replant decisions, and identify best management practices that minimize the impact of agriculture on soil erosion and water quality. It is a WindowsTM-based application of EPIC (Environmental Policy Integrated Climate model) originally developed by the USDA-ARS that simulates the interaction of natural resources (soil, water, climate) and crop management practices to estimate impacts on products harvested.

CRoPS is the Crop Rotation Planning System for Whole-farm Planning. CRoPS is a computer program that selects crop rotations for fields on individual farms, ensuring that the combined crop rotations, i.e. the whole-farm plan, meet the production and financial needs of farmers, while implementing sound environmental practices (Stone et al., 1999).

CropSyst is a crop simulation model like CERES and EPIC, but with higher process detail (Stockle et al., 1994, Stockle, 2003). The CERES approach (Jones and Kiniry, 1986) calculates crop water uptake as the minimum of attainable crop water uptake, and could predict the corn yield and nitrogen uptake under semiarid conditions (Pang et al., 1997).

EPIC is the abbreviation of Erosion Productivity Impact Calculator or Environmental Policy Integrated Climate (current). It is used to assess effects of soil erosion on crop productivity, and predicts effects of management decisions on soil, water, nutrient, and pesticide movement and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management. The model components are weather, surface runoff, return flow, percolation, evapotranspiration (ET), lateral subsurface flow and snow melt, water erosion, wind erosion, N and P loss in runoff, N leaching; organic N and P transport by sediment, N and P mineralization, immobilization and uptake, denitrification; mineral P cycling, N fixation, pesticide fate and transport, soil temperature, crop growth and yield for over 80 crops, crop rotation, tillage, plant environment, drainage, irrigation, fertilization, furrow diking, liming, economic accounting, and waste management from feed yards dairies with or without lagoons (Williams and Meinardus, 2004).

APEX is the abbreviation for Agricultural Policy or Environmental eXtender. The objective of this software is to provide a tool for managing whole farms or small watersheds to obtain maximum production efficiency while maintaining environmental quality. APEX uses a component of the EPIC program. The components of the model focus on hydrology, soil erosion produced by water and wind, N and P cycling, pesticide fate, soil temperature, plant growth, tillage-plant-environmental controls, and economics, and also overland flow, subsurface flow, channels, and flood plains, water, sediment, nutrients, and pesticides (Williams and Meinardus, 2004).

NutMan is a program that helps nutrient management planners develop crop nutrient management plans. Nutrient management involves the allocation of nutrients to crop fields and pastures so that plants receive adequate nutrient levels at appropriate times, manure is allocated efficiently, and both costs and environmental risks are minimized (Stone et al., 2003).

PLMS is the Pasture Land Management System, a practical and portable computer decision aid supporting private land-use decisions related to pasture land management. The program helps livestock farmers compare different strategies for managing their land and livestock. The basic idea is to bring the balance of forage produced on the farm and forage demanded by the livestock into a seasonal balance. Using PLMS, a farmer can explore intensive grazing, manipulating stocking rates, and modifying forage species to improve productivity and profit, while also benefiting the environment. PLMS provides nearly instant feedback on how user-generated alternative grazing systems affect critical variables like farm profit, milk production, and pounds of beef to market. It also estimates the environmental consequences of alternative plans, from effects on soil erosion to influences on greenhouse gases (Stone et al., 2005).

NuMaSS is the Nutrient Management Support System. It is a computer program to diagnose soil constraints and selects the appropriate management practices, based on agronomic, economic and environmental criteria, for location-specific conditions. It is focused on soil acidity and N and P applications. Its central algorithm for nutrient requirement is based on the balance sheet model (Smyth et al., 2004).

Ways to estimate the nutrient requirement of crops

There are different ways to estimate crop nutrient requirements, e.g. binary relationships, diagnostic recommendation integrated systems (Beaufils, 1971; Beaufils, 1973), plant chemical or biochemical analysis (Martin-Prevel, 1974), analysis of photosynthates, ranges of sufficiency, Kenworthy indices (Kenworthy, 1961), soil analysis, visual analysis (Davidescu and Davidescu, 1982), factorial experiments with increasing rates of fertilizer, or mathematical and statistical models (Buwalda and Smith, 1988). The last one includes multiple regression and factorial designs.

Rational, conceptual, and mechanistic model

Rational or conceptual models are models which come from studying the processes, transformations, and relationships of the entire system (Pickett, 2000). In agriculture, the system includes the crop-soil-environment (Rodriguez, 1990). Mechanistic models are models that primarily explain phenomena by reference to physical or biological causes (Barber, 1995).

Conceptual model of fertilization

A conceptual model is a mental conceptualization where processes are explained using diagrams, flow charts and theories. These models are important because they clarify ideas of how, where, what, and why processes work (Tanji et al., 1979). These ways of describing the world were created parallel to the development of systems theory, which explains how to study the process and systems. In agriculture and agroecosystems terms such as input, output, transformations, feedback, adiabatic, open and closed systems, resilience, independence, equality, sustainability, stability, autonomy, and productivity are used (Prasad and Power, 1997; Gliessman, 1998).

Agriculture and the specific case of fertilizer recommendations should consider ideas from chaos theory to help explain the randomness of processes, how many are random and how many contribute to randomness to make fertilizer recommendations unpredictable. In this case, use of non-linear models, elaboration of computer programs, use of conceptual ideas, and statistical deterministic models could help to explain relationships within the soil and environment. This environment is constituted by meteorological conditions (rain, temperature, and radiation), crops and vegetation (savanna, forest, tropical forest, desert, grassland, and swamps), landscape (slopes), soil conditions, and biological activities (pest and diseases).

The balance method, or balance-sheet method (Stanford, 1966; Black, 1993), is a conceptual model of fertilization which states that the rate of fertilization should be equal to the plant demand for nutrients minus the source of nutrients by soil. This result is then divided by the efficiency of fertilizer uptake, either using organic or inorganic compounds (Stanford, 1966; Stanford, 1973). Mathematically the model is as follows:

$$\text{Requirement of nutrient} = \frac{\text{Nutrient demand of the crop} - \text{Supply of nutrient by the soil}}{\text{Efficiency of fertilizer uptake}} \quad \dots\dots\dots(1)$$

Nutrient demand of the corn crop. A simplistic formula has been developed to help estimate crop nutrient demand. The development of this formula goes from partitioning particular vegetative parts of the crop to general vegetative parameters using mathematic algorithms. The demand of nutrients by any crop comes from the sum of each one of the requirements of its parts. It can be mathematically expressed as:

$$\text{N.D.} = \text{RB} \times \text{IRNu}_r \times (1 - \%H_r) + \text{SB} \times \text{IRNu}_s \times (1 - \%H_s) + \text{LB} \times \text{IRNu}_l \times (1 - \%H_l) + \text{YB} \times \text{IRNu}_y \times (1 - \%H_y) \quad \dots\dots\dots(2)$$

Where:

N.D. = Nutrient demand (kg ha^{-1})

RB = Root biomass (kg)

IRNu = Internal requirement of nutrients for each plant component: $_r$: roots, $_s$: stem, $_l$: leaves, $_y$: yield (%)

$(1 - \%H)$ = Algorithm to change from wet-biomass basis to dry-biomass basis, where $\%H$ is the moisture content of the plant tissue (%)

SB = Stem biomass (kg)

LB = Leaf biomass (kg)

YB = Yield biomass (kg ha^{-1}).

In this formula, the moisture content (1-%H) and the IRNu could be established as a common factor, but it requires that %H to be a weighted average.

So, the formula is simplified as follow:

$$\text{N.D.} = \text{IRNu} \times (\text{RB} + \text{SB} + \text{LB} + \text{YB}) \times (1 - \%H) \dots\dots\dots(3)$$

SB, LB, and YB are considered to be the total aboveground biomass (TAGB). If we multiply equation 3 by the term $\left(\frac{\text{TAGB}}{\text{TAGB}}\right)$, or 1, the formula becomes as follows:

$$\text{N.D.} = \text{IRNu} \times \left(\left(\frac{\text{RB}}{1} \right) + \left(\frac{\text{TAGB}}{1} \right) \right) \times \left(\frac{\text{TAGB}}{\text{TAGB}} \right) \times (1 - \%H) \dots\dots\dots(4)$$

The root biomass (RB) can be changed to root index (R.I.), which is more constant and can be obtained for each crop and variety.

The root index (R.I.) is the proportion between the weight of roots and the total weight of aboveground biomass (Aung, 1974). Some authors consider total aboveground biomass as the biomass of leaves (usually petioles are included in leaves), stems, branches, and yield biomass (Aung, 1974; Etchevers and Galvis, 1995, Sinclair, 1998, Bindi et al., 1999, Hebert et al., 2001). Others consider biomass as leaves, stems, and branches only, without including yield biomass (Hay, 1995). In our case, the yield biomass will be included.

$$\text{R.I.} = \frac{\text{root biomass}}{\text{total above ground biomass}} = \frac{\text{RB}}{\text{TAGB}}$$

$$N.D. = IRNu \times \left(\left(\left(\frac{RB}{TAGB} \right) \times \left(\frac{TAGB}{1} \right) \right) + \left(\left(\frac{TAGB}{1} \right) \times \left(\frac{TAGB}{TAGB} \right) \right) \right) \times (1-\%H) \dots\dots\dots(5)$$

Following mathematic substitution, the equation can be simplified as follows:

$$N.D. = IRNu \times ((R.I. \times TAGB) + TAGB) \times (1-\%H) \dots\dots\dots(6)$$

$$N.D. = IRNu \times (R.I. + 1) \times TAGB \times (1-\%H) \dots\dots\dots(7)$$

If we add the parameter $\left(\frac{Yield}{Yield} \right)$ to equation 6, it changes to:

$$N.D. = IRNu \times (R.I. + 1) \times TAGB \times (1-\%H) \times \left(\frac{Yield}{Yield} \right) \dots\dots\dots(8)$$

But $\left(\frac{TAGB}{Yield} \right) = \left(\frac{1}{H.I.} \right)$, where H.I. is the Harvest Index, so the formula

changes to:

$$N.D. = \frac{IRNu \times (R.I. + 1) \times (1 - \%H) \times Yield}{H.I.} \dots\dots\dots(9)$$

This equation implies the use of constants for each crop and variety. During the last 50 years, scientific studies have established the values for H.I., R.I., %H, and IRNu for some crops. In those cases, only yield needs to be estimated to calculate the crop nutrient demand. Crop yield can be estimated using multiple regression techniques (Runge and Benci, 1971), farmers' census data, agroecological zonification methods, which include

the use of meteorological and soils conditions, direct interviews with farmers, or using experimental data from experimental stations.

Estimating crop nutrient requirements doesn't guarantee the estimated yield, because yield depends on other uncontrolled conditions such as rainfall amount and distribution, temperature, radiation, disease, pests, and management (Wallace and Bressman, 1979). This model could calculate the requirement of nutrients necessary to attain the most probable potential yield under the most probable environmental conditions. After years of research, it becomes reasonable that crop nutrient demand can be established as:

$$N.D. = \frac{IRNu \times (R.I. + 1) \times (1 - \%H) \times Y}{H.I.} \dots\dots\dots(10)$$

Where:

N.D. = Nutrient demand (kg/ha).

IRNu = Internal requirement of nutrients, with its unit being in percentage form, e.g. a nitrogen concentration of 1.5% means 0.015 in the formula. The I.R.Nu. refers to nutrient concentrations inside the whole plant. It could be considered as a constant, taking into account the optimal or maximum yield under an optimal nutrient concentration and under different environments (Loué, 1987). Its interval ranges from >0 to <1. For N, the interval could range from >0.00% to 4.00% considering the total N in the entire plant on a dry-weight basis. In decimal expression, it ranges from >0.000 to 0.0400.

R.I. = Root index. The units are grams of roots over grams of aboveground biomass or could be expressed as percentage, e.g. 15% means 0.15 in the formula. At present, it is well known that there is a close relationship between the weight of the aboveground plant and the weight of the roots. This relationship can be written as follows:

$$R.I. = \frac{\text{weight of roots}}{\text{weight of aboveground biomass}} \dots\dots\dots(11)$$

This relationship is constant for specific conditions. The weight of aboveground biomass is the total amount of dry matter that a plant or crop produces above the soil surface. The interval of root index ranges from >0 to <1 .

- 1 = The number one in the expression $(R.I. + 1)$ comes from the formula derivation and expresses the total aboveground biomass.
- 1 = The number one in the expression $(1 - \%H)$ is a factor of conversion. It is used to convert fresh weight to dry weight (1 meaning 100%). It is used together with $\%H$.
- $\%H$ = Percentage moisture content of plants. This percentage is expressed in decimal form, e.g. 95% means 0.95 in the formula. The expression $(1 - \%H)$ changes the values from moisture-based weight to dry-based weight. Its interval ranges from >0 to <1 .
- Y = Yield in kg ha^{-1} or ton ha^{-1} on a physiological or commercial basis. This is the yield that it is estimated for the following year; this yield is called the expected yield of grain or target yield or goal yield (Black, 1993). This yield can be estimated based on experimental yields obtained in similar areas with similar soil conditions, or with potential yield studies considering climatologic and soil conditions. Its interval could range from >0 to $<300,000 \text{ kg ha}^{-1}$. For corn a range from >0 to $12,000 \text{ kg ha}^{-1}$ is possible.
- H.I. = Harvest index in percentage, e.g. 45% must be changed to 0.45 in the formula. The harvest index is the relationship between the whole weight of the plant and the weight of the commercial product. It could be fruits, grains, forages, legumes, or grass. This term could be considered as a constant. Its interval ranges from >0 to <1 .

Internal requirement of nitrogen. On average, the N concentration of whole corn plants under optimum conditions is 1.25% (Larson and Hanway, 1977; Loué, 1987). Stanford (1966) estimated that the N content of the above-ground portions of the mature corn plant should contain from 1.2 to 1.3% N. A $10,000 \text{ kg ha}^{-1}$ corn crop will contain at least 200 kg of N in the grain and stover. Only the most fertile soils will supply this N, unless corn follows a legume meadow in the cropping system or N has been applied as manure or inorganic fertilizer (Larson and Hanway, 1977).

Root index. Root index is the relationship between the roots and the aboveground biomass, expressed as the root:aboveground biomass ratio. In some literature, it is referred to as the shoot:root ratio. Some authors mention that the shoot:root ratio is not constant for corn. However, their studies were carried out only at early phases of corn development (Aung, 1974). It is necessary that researchers define what root index means, how they are using the concept, and the physical and biological limits of shoot, root, and aboveground biomass.

Costa et al. (2000, 2002) found a close relationship between root fresh weight and root length for corn (*Zea mays* L.) genotypes of leafy reduced stature (LRS), leafy normal stature (LNS), and conventional commercial hybrid Pioneer 3905 (P3905). Because root mass is easier to measure than root length or surface area, root mass could be used to estimate root length. The leafy type had the highest proportion of very fine roots. In another experiment, it was found that at 80 days after emergence (silking stage), the root:shoot ratio for maize was 0.135, 0.170 and 0.095 for 0, 127 and 255 kg N ha⁻¹, respectively. The root dry mass was higher for treatments receiving 127 kg N ha⁻¹ compared to 0 and 255 kg N ha⁻¹. Total root length was linearly and positively correlated to the total root dry mass for pooled data of the three genotypes. However the specific relationship varied among genotypes (Murphy and Smucker, 1995, Costa et al., 2002). Their findings indicate that one could obtain reasonable estimates of total length by simply measuring root weight (Costa et al., 2002).

One study found that the mean corn root diameter is greater in the absence of N application than at rates of 127 or 255 kg N ha⁻¹ (Costa et al., 2002). This contradicts the general observation that finer-diameter roots are formed under low N regimes (Fitter, 1996). In another greenhouse experiment, water stress reduced the number of order 5 corn roots (roots finer than 0.5 mm diameter) and increased the number of these roots under N stress (Lopez Collado, 1992, unpublished data).

A measure of the shoot:root (S:R) ratio may provide an index for the performance of each organ in a certain growth environment. For example, if the situation favors shoot growth at the expense of root growth, the plant will exhibit a relatively high S:R value. Conversely, if root growth is favored over shoot growth, the plant will have a lower S:R value. The S:R ratios may be used to ascertain how environmental and chemical factors affect and modify the growth of the shoot and root. The S:R ratios of plant species differ, and for a particular species the S:R value may vary with chronological age and stage of morphological development. It may also be dependent on environmental conditions (Aung, 1974).

In wheat (*Triticum aestivum* L.) and peas (*Pisum sativum* L.) during the first 3 days of growth, the radicle grew faster than the plumule, which was reflected by a low S:R ratio (Aung, 1974). Subsequently, the radicle grew slower than the plumule, and there was a corresponding increase in the S:R ratio. This work was carried out in nutrient culture for 15 days. The growth of the root is synchronized with the morphological stage of the shoot. In the vegetative phase, shoot and root growth proceed concurrently in linear relations, but with the shoot growing at a faster rate. With the advent of flowering and fruiting, however, root growth slows or ceases abruptly due to a shortage of photosynthates from the shoot. The productive shoot diverts and monopolizes the available assimilates at the expense of the root (Foth, 1962). A sharp decline in root development has been found with the time of fruit development (Aung, 1974). Also, during maturation of modified storage structures, such as the onion bulb, a marked decrease was found in both root weight and number as bulbing proceeded. Consequently, S:R ratios were higher at the postbulbing stage than at the prebulbing stage (Copper, 1955).

Both physical and chemical factors can alter the S:R ratios of plants. Soil type influences the growth of shoots and roots of crops. Plant growth on a sandy soil had a lower S:R ratio than similar plants grown on a loamy soil. While the physical structure of the soil

can affect S:R ratios of these plants, the chemical fertility factor was not clearly delineated. Changes in S:R ratios have been observed in wheat, rice (*Oryza sativa* L.) and bean (*Phaseolus vulgaris* L.) plants by exposing them to different oxygen concentrations. The S:R ratio of wheat decreased as O₂ concentrations dropped from 21% to 1.5%, whereas rice showed higher S:R ratios with decreasing O₂ concentrations (Aung, 1974).

Temperature can change the S:R ratio. In tomato plants, the S:R ratio was lower for plants growing at 17°C than at 27°C, and also at 15°C compared with 25°C. The reduction of shoot growth at lower temperature was not due to a deficiency of mineral nutrients or water supply, but rather to endogenous mechanisms, which was hormonal (Aung, 1974).

Much of the variability of crop response is related to soil properties that affect water availability. Effective soil rooting depth is one such property. It has been reported that a higher correlation exists between corn grain yield and soil depth during years of low rainfall than years with greater rainfall, in which plant rooting depth is limited by a fragipan or duripan. This response indicates a contribution of soil water-holding capacity and availability. Other properties that also influence yield as topsoil depth decreases are soil bulk density and chemical properties (Frye et al., 1983; Gantzer and McCarty, 1987; Swan et al., 1987; Boyer et al., 1990; Thompson et al., 1991).

Pruning, soil moisture content, and light modify the S:R ratio. Heavy pruning of fruit trees increased the S:R ratio due to a reduction in root development. In corn, the S:R ratio was increased from 2.47 to 3.40 by increasing the soil moisture content from 7.5-15.5% to 21% respectively. In radishes (*Raphanus sativus*), the S:R ratio decreased with long photoperiods due to development of the taproot over the shoot. In corn hybrids and barley (*Hordeum vulgare* L.), the S:R ratio is higher with increasing applications of N and P. This behavior was attributed to greater carbohydrate utilization by shoots at the

expense of roots. In lettuce (*Lactuca sativa* L.), the S:R ratio was increased with increasing amounts of $\text{Ca}(\text{NO}_3)_2$. In sweet potato, the S:R ratio was increased with N applications (Aung, 1974).

Moisture content. The plant corn moisture content at maturity harvest is variable (Ritchie et al., 1997; Osborne et al., 2002). However, the standard moisture content of shelled corn at harvest is around of 15.5% or 155 g of water per kg^{-1} of dry matter, on a wet basis. This means that each kilogram of shelled corn will actually consist of 845 g of dry matter and 155 g of water (Buffington, 2003). The water content in corn is important in cost production and equitable price for corn silage (Lauer, 2005). For corn silage, the term grain equivalent per ton of silage is used (kg of grain per ton of corn silage). It could be used to estimate the corn grain weight per ton of corn silage at 15.5% of moisture content. However, it is not always reliable. The relationship using the grain yield equivalent to estimate the grain weight at 15.5% of moisture content ranged from $R^2 = 0.40$ to $R^2 = 0.78$ from 1997 to 2004 experiments (Lauer, 2005).

Remote sensing is becoming a valuable tool that has the potential to assess corn crop chlorophyll and relative water content due to N and water stress over a large area in a short amount of time (Osborne et al., 2002). Schlemmer et al. (2005) found in a greenhouse experiment that chlorophyll had a stronger correlation than relative water content (RWC). This physiological parameter had a low correlation with various regions of the spectral reflectance curves, in the range from 400 to 1000 nanometer of wavelength. A short-duration acute water stress had little or no effect on the leaf chlorophyll content. However, an estimate of the water content of corn crop could be more through the visible and near infrared reflectance of the whole canopy level. In this study, there were no significant differences between treatments with N fertilizer over the relative water content; however, the supply of water presented a clear difference. It ranged from a high of approximately 90% for well watered treatments to a low of 65% for low-water treatments, averaged across all N rates (56, 112 and 168 kg N ha^{-1}). In this

experiment, the corn plants were harvested at the V6 and V7 growth stages, (Ritchie et al., 1997). In a similar experiment, but in the field, the use of hyperspectral remote sensing could not detect significant differences in water stress in irrigated corn, however, the presence of water stress influenced the wavelength used to estimating plant N content. The hyperspectral imagery predicted chlorophyll meter readings with an R^2 greater than 0.82, and estimated the N content, biomass, and grain yield (Osborne et al., 2002).

A field study showed that the water stress in corn is variable over short distances even lower than 10 meters, and it is related with the soil water content; although this variance in the field couldn't be explained (Sadler et al., 2000). This corn water stress was measured using the difference between the temperature of canopy and air using an infrared thermometer (Sadler et al., 2000). On the other hand, there were no significant differences in corn grain yield, grain N uptake, and grain water use efficiency, using strip-tillage, chisel plow, and no-tillage in a two field years experiment (Licht and Al-Kaisi, 2005). The moisture content of corn grain showed in most of the cases no significant differences between densities of population (59000, 69000, 79000 and 89000 plants ha^{-1}), six kinds of hybrids (Novartis seeds: MAX23, 4242Bt, MAX21, 4640Bt, MAX454, and 6800Bt), using two row spacing (38 and 76 cm) during a three year field experiment. The ranges for corn grain moisture content were from 161 to 196 g kg^{-1} for hybrids x row spacing, and from 159 to 162 g kg^{-1} for plant density x row spacing (Farnham, 2001).

Corn yield. The grain yield for hybrid Pioneer 32R25 under different conditions ranged from 5.1 to 13.4 Mg ha^{-1} (Table 1); (Mislevy, 2001; Wright et al., 2002; A. Nelson, personal communication, 2002; J. Betran, personal communication, 2003).

Table 1. Corn Pioneer 32R25 yields under different conditions.

| Yield t ha ⁻¹ | Place | Conditions and observations |
|-----------------------------|--|--|
| 11.2 | College Station, Experiment Station. | Under irrigation, summer 2002. † |
| 12.6 | College Station, Experiment Station. | Dryland, 2002. ‡ |
| 11.4 | College Station, Experiment Station. | Dryland, 2002. ‡ |
| 7.7 | College Station, Experiment Station. | It yield was calculated with base in a Yield Calculator. ‡ |
| 5.1 | College Station, Experiment Station. | Dryland, 2002.§ |
| 8.2 | Farmer | Dryland ‡ |
| 11.4 | Farmer | Dryland ‡ |
| 6.6 | Weslaco. | Under irrigation, summer 2002. † |
| 8.6 | Bardwell (blacklands) | Dryland (rainfed), summer 2002. † |
| 12.8 | Dumas (highplains) | Under irrigation, summer 2002. † |
| 11.9 | Ona, Florida. The University of Georgia. 2001 Corn Performance Test. | Yield was calculated at 15.5% moisture. Planted: march 22, harvested July 9, 2001. Plant population: 28000 plants/acre. 50 lb N, 80 lb P ₂ O ₅ , and 160 lb K ₂ O/acre as preplant; 200 lb N/acre as sidedress. Irrigated 20 inches. ¶ |
| 9.8 | North Florida Research and Education Center (NFREC). University of Florida. | # |
| 6.7 | Edisto Research and education Center, Blackville, SC. | Means adjusted by Lattice Procedure. Corn Hybrid performance, irrigated trial, Coastal Plain. 2002 data. ¶ |
| 9.6 | Pee Dee Research and Education Center, Florence, SC. | Irrigated trial-coastal plain. Harvest moisture 14.1%, husk coverage 3.2%. Days to mid-silk (days) 78. |
| 8.6 | Pee Dee Research and Education Center, Florence, SC. | Irrigated trial-Coastal plain; Mean adjusted by Lattice Procedure. 2002 data. ¶ |
| 7.6 | Blackville and Florence, SC. | Irrigated trials-2 location averages. Harvest moisture 15.0%, Husk coverage 2.3%, test weight (lb/bu) 60. 2002 data. ¶ |
| 12.7 | Calhoun Field Laboratory, Clemson, SC. | Corn Hybrid performance. Dryland-Piedmont bottomland. Harvest moisture 15.7%, husk coverage 2.7%.¶ |
| 11.7 | Calhoun Field Laboratory, Clemson, SC. | Dryland-Piedmont bottomland; Harvest moisture 16.5%, husk coverage 2.7%, test weight (lb/bu) 60. 2002 data. ¶ |
| 11.9 | Calhoun Field Laboratory, Clemson, SC. | Dryland-Piedmont bottomland. ¶ |
| 12.1 | Jasper, Florida. | Farmer Debra E. Adams. 1 st . Place 2002 corn yield contest state winners. A no till/Strip till Non-irrigated class. ¶ |
| 13.2 | Oklahoma | Farmer Brenda Schulz. 2 nd . Place 2002 corn yield contest state winners. A no till/Strip till Non-irrigated class. ¶ |
| 7.8 | Lodge, South Carolina | Farmer Marion Rizer. 2nd. Place. 2002. Corn yield contest state winners. A no till/Strip till Non-irrigated class. ¶ |
| 10.4 | Columbia, Alabama | Farmer John & Joy Pitchford. 3rd. Place. No till/strip till irrigated class. ¶ |
| 13.4 | Winnsboro, Louisiana. | Farmer Wesley Moroni. 1 st place.¶ |

† The yield of Pioneer 32R25 is variable, but under optimum conditions it can reach higher than 12 t ha⁻¹ (Dr. Javier Betran, Texas A&M University. Soil and Crops Department. College Station. Personal communication).

‡ Pioneer™. 2005. Corn Yield Calculator. Use this corn yield calculator to determine what the potential yield might be for the corn hybrids planted on your farming operation. (available on November 22, 2005). http://www.pioneer.com/growingpoint/decision_tools/corn_yield.jsp

§ M.Sc. Alfred Nelson. 2002. Personal communication.

¶ Mislevy P., A. E. Coy, J. LaDon-Day and P. A. Rose (Ed.). 2001. Corn Performance Tests. The Georgia Agricultural Experiment Station. University of Georgia. Research Report Number 675. November 2001. Department of Crop and Soil Sciences, Coastal Plain Experiment Station, Tifton, GA. <http://www.ces.uga.edu/ES-pubs/RR675-silage-Ona.htm> and <http://www.ces.uga.edu/ES-pubs/RR675-contents.htm> (available on November 22, 2005).

D. L. Wright, B. Kidd, P. J. Wiatrak, J. J. Marois. 2002. North Florida Research and Education Center, Quincy FL. Florida Cooperative Extension Service, University of Florida, Gainesville.

Different methodologies can be used to predict corn grain yield. Some of them use the water available for the crop (Timlin et al., 2001), annual precipitation and other parameters using multiple regressions (Runge and Benci, 1971), soil fertility levels, temperature, precipitation and evapotranspiration using regression models and agro-ecological zones methods (Kassam, 1977; Derby et al, 2004), soil physical characteristics and crop radiance (Chang et al, 2003), root zone water quality and weather conditions using simulation models like RZWQ and CERES (Anapalli et al., 2005).

One method to estimate corn yield is that proposed by Timlin (Timlin et al., 2001). This method uses the following formulas to estimate yield or relative yield:

$$Y = Y_P - (A)(S_S) \dots\dots\dots(12)$$

In order to be able to represent results from different sites on a more general basis, equation 2 will become a relative yield equation by dividing equation 1 by potential yield (Y_P). The result is:

$$Y_R = 1 - (A_R)(S_S) \dots\dots\dots(13)$$

Solving equation 2, the result is:

$$Y_R = 1 - (0.027)(S_S) \dots\dots\dots(14)$$

This formula was found to estimate the relative corn yield trend with reasonable accuracy.

Where:

Y : yield of corn grain (kg ha^{-1}).

Y_P : the potential yield when water is not limiting.

Y_R : the relative yield. It is $Y_R = Y/Y_P$.

A_R : the relative water stress response coefficient. It is estimated as $A_R = A/Y_P$. Its value was 0.027.

A : the change in corn grain yield in kg ha^{-1} per unit of seasonal water stress.

S_S : seasonal water stress index. It is defined by:

$$S_S = \sum_{i=1}^n (S_{di})(W_i) \dots\dots\dots (15)$$

Where:

S_{di} : The daily stress index for Day i , calculated as $S_{di} = 1 - T_a / T_p$, where T_a is the actual transpiration and T_p is the potential transpiration

n : the number of days from planting to harvest

W_i : weighting factor that accounts for the sensitivity of grain yield to water stress on that day. The value for W_i varies with respect to the growth stage.

The potential yield (Y_P) and relative water stress response coefficient (A_R) were calculated using Ontario Corn Heat Units (OCHU), mean irrigated yield, and regressing yield measured over a range in soil depth on calculated seasonal stress indices (Timlin et al., 2001).

Harvest index. Yield is assumed to be a set fraction of the crop's aboveground biomass. For corn, the harvest index (H.I.) has been calculated as 0.5. As the biomass varies spatially, so does the yield. Timing of weather events, particularly precipitation,

temperature, and varying soil conditions, can have a great effect on the H.I. (Norman, 2003). The H.I. has been taken as a measure of success in partitioning assimilated photosynthate into harvestable product. The dramatic increases in corn grain yield in the past 50 years have resulted from a number of factors, but increased H.I. is commonly considered one of the most important. According to Donald and Hamblin (1976), Beaven in 1914 was the first to consider the ratio of grain weight to total plant weight and called this ratio the “migration coefficient”. The “migration coefficient” concept was largely ignored until relatively recent times. In 1962, Donald suggested the term “harvest index” and recommended it as an important reference to assess progress in germplasm development toward improved yield potential. The implication was that increased H.I. indicated progress in partitioning crop photosynthate to the harvestable component (Sinclair, 1998). H.I. did not become an important feature of crop assessment until after the publication of a review on H.I. by Donald and Hamblin in 1976 (Hay, 1995).

Comparing the years of release of wheat cultivars, it was shown that H.I. increased with time, ranging from 0.35 to 0.50 from 1908 to modern advanced breeding lines, even when grown in sites with low and high fertility (Austin et al., 1980). In Australia, H.I. of wheat cultivars increased from 0.30 for old varieties to 0.37 for recent varieties (Perry and D’Antuono, 1989). Similar increases in H.I. have been found for barley in the United Kingdom where most of the grain yield increase for cultivars grown in 1880 compared to cultivars released in 1980 was associated with an H.I. increase from 0.36 to 0.48 (Riggs et al., 1981). In rice, the dwarfing genes increased H.I. from 0.30 to 0.50. On the other hand, increases in the H.I. of maize have been modest, from 0.45 in the 1930’s to 0.50 in the 1980’s, and much of the maize yield increase resulted from an increase in total crop mass (Russell, 1985).

The H.I. can be defined as the ratio of seed mass or yield to total aboveground plant mass (Sinclair, 1998, Bindi et al., 1999). Total plant mass consists of the total weight of aboveground biomass, including stems, leaves, and grain. Instead of the seed growth rate

(SGR), the change in harvest index with respect to time is considered the best parameter to use to characterize seed growth. Changes of H.I. are linear and stable over a range of growth conditions, including variations in sowing date, irrigation treatment, and N levels. This behavior is well documented for wheat, pea (*Pisum sativum* L.), sunflower (*Helianthus annuus* L.), and soybean (*Glycine max* (L.) Merr.) (Bindi et al., 1999). Although the H.I. of Avalon wheat changed during reproductive growth, at least during the last 10 days before harvest, the H.I. was constant before the crop reached its maximum growth (Bindi et al., 1999).

In a peanut experiment, H.I. was expressed as the pod harvest index (P.H.I.), which was defined as the ratio of pod to total dry weight, including the roots. Seed harvest index (S.H.I.) is the ratio of seed to total dry weight. In the Craufurd et al. experiment (2002), they used a factor of 2.33 to describe the high energy cost of synthesis of kernels with high oil and protein contents. Weights of roots, leaves, stems, pegs, pods, and seed per plant were recorded after oven-drying these components to a constant weight for 3 days at 80°C. The high temperature tolerant varieties of peanut had the same H.I. 90 days after planting. However, temperature susceptible genotypes had reduced H.I. at 30°C compared to 25°C. The relationship between the days after planting and S.H.I. was linear from 41 to 90 days after planting ($R^2 > 0.94$).

In an experiment with 15 maize cultivars, significant relationships were found between H.I., grain yield (G.Y.), and stem biomass (S.B.). A strong positive relationship was detected between H.I. and grain yield under drought. High H.I. under drought was associated with rapid early ear growth and suggested that an increase in partitioning to ears was responsible for increases in H.I. under all water regimes (Edmeades et al., 1999). Stem biomass varied inversely with HI across all entries, as well as among entries comprising a selection series. Selection reduced S.B. under drought (Edmeades et al., 1999). In the same experiment, H.I. under drought was 0.167 with a standard deviation (std. dev.) of 0.0618 and a coefficient of variation (CV) of 36.8; under irrigation H.I. was

0.393 with a std. dev. of 0.0212 and a CV of 5.3. The gain in H.I. for corn under dry conditions was 0.025 and under irrigation was 0.005 (Edmeades et al., 1999).

Yang et al. (2004) found that in a 3-year field experiment using 33A14 and 33P67 Pioneer® maize hybrids, there were no significant differences in the H.I. through different years (1999, 2000, and 2001) using three different population densities (7.2, 9.6 and 11.2 plant m⁻²). The overall mean H.I. was 0.51.

The H.I. has a defined behavior, starting with a lag phase followed by a linear increase, then a cessation of the linear increase (Bange et al., 1998). This behavior is shown in Fig. 1 (Chapman et al., 1993, Bange et al., 1998) and is also similar for taro (*Colocasia esculenta* L.) (Lu et al., 2001), wheat (2 cultivars), sunflowers (3 cultivars), peas (4 cultivars), soybean (3 cultivars) (Bange et al., 1998; Bindi et al., 1999), and maize (Muchow, 1990).

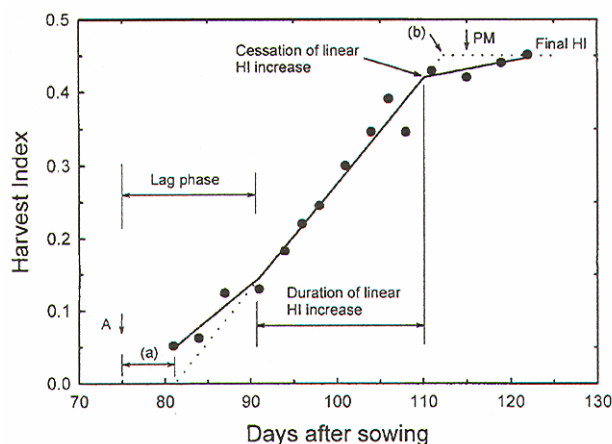


Fig. 1. A three phase linear function fitted to measurements taken from sunflower genotype 8640, showing the linear increase in harvest index, lag phase, and the time when the linear harvest index increase ceases. The graph also shows (dotted line) how Chapman et al. (1993) defined the lag phase (a) and cessation of linear harvest index increase (b). H.I., harvest index; A, first anthesis; P.M., physiological maturity.

One term related with H.I. is the nitrogen harvest index (NHI); this term is closely related with H.I. and more specifically with the N content of grain. The NHI is defined as the ratio between grain N content (GNC) and stover N content (SNC) (Sinclair, 1998).

Comment about the harvest index. It is necessary that researchers and authors of papers clarify the exact meaning of H.I. as used in their experiments. It is necessary to explain what they consider as the commercial product or the amount assigned in the numerator of the mathematic relation, and explains what constitutes the denominator. The denominator always contains an estimate of total biomass. Total biomass should be explained, given that the expression could be on a fresh or dry weight basis. Sometimes, the grains or roots weight are considered in the aboveground biomass or the generic term of shoot is described ambiguously. Shoot is a young stem, but it doesn't necessary imply that one should consider the leaves, tassel, or another part of the plant. On the other hand, it is important to mention at what physiological time period samples were taken. The term maturity can be ambiguous given that there are commercial and physiological maturities, even the number of days to maturity or days after planting is different for the same hybrid, depending on environment conditions. An option could be to mention the usual number of days to complete the physiological or commercial maturity of the crop under given environmental conditions, or the parameters used to establish that phase. An example of ambiguity of information is found in a paper that stated that "90 days after planting the ICGV 86015 genotype of peanuts was harvested and the harvest index was measured". Questions are: Is 90 days enough to complete physiological maturity or to complete filling pods under that environment and is it enough for that genotype?. The moisture content or percentage of oil might be a better parameter to measure the maturity of the crop, in conjunction with the number of days after planting.

Soil nitrogen supply. After decades of searching for a rapid method to estimate the N mineralization capacity of soil, there is still no consistent recommendation. For this reason, it is legitimate to examine the causes for the often conflicting results in literature. Gross N mineralization and consumption during waterlogged and aerobic incubation were estimated in a wide range of soils (Wang et al., 2001). It was found that 17 to 90 and 23 to 59% of the mineralized N was consumed during waterlogged and aerobic incubations, respectively. As net N production rate represents the balance between N-producing and N-consuming processes, it appears difficult to find a simple method that could be used to predict the net effect of several concurrent processes. Total organic N, water soluble organic N, alkali-hydrolyzable N, acid-hydrolyzable N, hot salt-hydrolyzable N and N in the light organic matter fraction were assessed against this reference criterion. All indices except light fraction N were significantly related to gross N mineralization. Water-soluble organic N had the highest correlation of all the indices tested. None of the chemically hydrolyzed N fractions consistently showed closer relationships with N mineralization than total organic N, suggesting that these chemical methods are ineffective in extracting a biologically labile fraction of soil organic N (Wang et al., 2001).

The procedure to estimate the supply of nutrients from soils is different for each type of nutrient, and different methods may be used to estimate the nutrient concentration. One method was proposed by Etchevers and Galvis-Spinola (1995) to estimate N supply using different kinds of soils with variations in organic matter content. They found a regression equation using the soil organic matter concentration in a series of soils. The overall formula was as follows:

$$\text{Nitrogen supply} = (\text{NO}_3\text{-N})_{\text{initial}} + \text{organic N reserve} \dots\dots\dots(16)$$

$$\text{The organic N reserve} = 25.9 + 17.9 (\text{soil organic matter percentage}) \dots\dots\dots(17)$$

On the other hand, the nitrogen supply from soil may also be estimated by the total N content in the tops and roots of the crop without N fertilization (Østergaard et al., 1985, Smyth et al., 2004). In natural conditions without fertilizer, the supply of nutrients is the same as plant demand. Other procedures to estimate soil N supply can be used, provided that supply is expressed as actual kilograms of N absorbed per hectare. In natural conditions, without fertilizer and for some conditions of population density, the supply of nutrients is assumed to be the same that the plant demands (Smyth et al., 2004), but it is not always the case that plant demand equals the supply of nutrient by the soil. The maximum supply of nutrient from the soil limits the maximum content of nutrient in the plant. This is the maximum amount of nutrient demanded by the crop under that soil condition. But this statement does not imply that under better or worse soil or environmental conditions the demand of nutrient by the crop could be either higher or lower for the same type and variety of crop.

An experiment with corn was carried out to compare N supply from soils differing in N-fertilizer responsiveness (Mulvaney et al., 2001). Hydrolysis with 6 M HCl was performed on composite soil samples. The concentrations of amino sugar-N were 33 to 1000% greater ($p < 0.001$) for 11 nonresponsive than for seven responsive soils. No consistent differences were observed in their contents of total hydrolyzable N, hydrolyzable $\text{NH}_4\text{-N}$, or amino acid-N. Upon aerobic incubation for 3 months with biweekly leaching, production of $(\text{NH}_4 + \text{NO}_3 + \text{NO}_2)\text{-N}$ averaged 260% greater for three nonresponsive soils than for two responsive soils and was accompanied by a net decrease in amino sugar-N but not amino acid-N. Soil concentrations of amino sugar-N were highly correlated with check-plot yield ($r = 0.79^{***}$) and fertilizer-N response ($r = -0.82^{***}$). On the basis of amino sugar-N, all 18 soils were classified correctly as responsive ($< 200 \text{ mg kg}^{-1}$) or nonresponsive ($> 250 \text{ mg kg}^{-1}$) to N fertilization (Mulvaney et al., 2001).

Better estimates of soil mineralizable N are needed to determine crop needs for N fertilizer. An experiment was carried out to estimate net soil N mineralization in soil maintained in continuous corn, corn-soybean, and corn-soybean-wheat/alfalfa (*Medicago sativa* L.)-alfalfa rotations (Carpenter-Boggs et al., 2000). Cumulative net N mineralized in a 189-d field temperature incubation averaged $133 \pm 6 \text{ kg ha}^{-1}$ in continuous corn, $142 \pm 5 \text{ kg ha}^{-1}$ in corn-soybean, and $189 \pm 5 \text{ kg ha}^{-1}$ in corn-soybean-wheat-alfalfa. Across rotations, average net N mineralized was $166 \pm 9 \text{ kg ha}^{-1}$ in 0 N plots, $147 \pm 10 \text{ kg ha}^{-1}$ in low N plots, and $152 \pm 10 \text{ kg ha}^{-1}$ in high N plots. Inclusion of a legume, particularly alfalfa, in the rotation increased net N mineralized. Generally, more soil N was mineralized from plots receiving no fertilizer N than from soil with a history of N fertilization. Variable temperature incubation produced realistic time-series data with low sample variability.

The need to estimate mineralization has long been recognized in making N fertilizer recommendations, but little progress has generally been made in identifying a specific fraction of soil organic N that affects crop responsiveness to N fertilization (Mulvaney et al., 2001).

Efficiency of added fertilizer. The growth of all organisms can be limited by the amount of available nutrients. Plants are no exception. In natural conditions, climax vegetation that is established depends on soil fertility. Plants are in dynamic equilibrium with their environment. Nutrients are recycled in leaf and litter fall, and the supplies are slowly augmented by natural processes, notably the biological fixation of N and the weathering of soil minerals to release other nutrients. When farmers intervene and substitute their crops for natural vegetation, some of the nutrients are removed in the yields, thus diminishing soil fertility. Fertilizers allow one to raise soil fertility so that the yield of crops no longer need be limited by the amount of plant nutrients that the natural system can supply, and factors other than nutrition then set the limit to

productivity. Fertilizers are, therefore, essential to the future of our modern world where the population is increasing so rapidly (Cooke, 1982).

The principle of using simple chemical salts to supply the inorganic ions that are plant nutrients is straightforward, but the efficient use of fertilizer is a complicated subject. It involves first the correct choice of type and amount of fertilizer and then correct decisions on times and methods of application. These decisions must be made against the economic background of cost of fertilizers and the value of the extra yield to be produced. However, the weather, as a random factor, sometimes is what determines crop production (Cooke, 1982). It is clear that the efficiency of fertilizer depends on placement, timing, source of nutrient, kind of crop, soil water content, and environmental conditions.

Broadcast fertilization leads to stratification of soil P and K in the ridge-till system, which may reduce fertilizer use efficiency. In an experiment with corn, broadcast and deep-band (15- to 20 cm depth) placements were used to measure nutrient availability. No yield differences were observed between broadcasting and deep-band placement for P and K. Deep-banded K increased yield over broadcast K in four sites of fifteen, and deep-banded P increased yield over broadcast P in one of fifteen sites used (Borges and Mallarino, 2001). The source of nutrient can also affect the efficiency of fertilizer (Sharpley and Sisak, 1997). Fertilizer can be either chemical or organic compounds, and can include chemical fertilizers, manures, compost, foliar fertilizers, waste waters, green manure covers, and mulch. Their chemical composition and decomposition rate of organic material will affect their efficiency (Zhang and Mackenzie, 1997). Uptake depends of the ability of the crop root system to get nutrients from the soil (Delgado et al., 2000). The crop family, genera, species, and variety are related to the efficiency of fertilization. The management of the crop; no-tillage, conventional tillage, soil conservation structures, population density, insect and disease control, use of biological,

physical, or chemical agents, pesticides, fungicides, bactericides, and herbicides, all may impact crop field and nutrient demand (Sillanpää, 1982; Foth and Ellis, 1997).

The efficiency of nitrogen applied could be estimated as follow:

Efficiency = immobilization coefficient x denitrification coefficient x leaching coefficient(18)

However, when using this methodology, it is necessary to work with N^{-15} (Rodriguez, 1990; Jackson, 2000). N^{-15} have been used to estimate the efficiency and balance of N using others algorithms (Norman at al., 1997; Schindler and Knighton, 1999)

Alternative ways to determine the efficiency of added nutrients can be used. For example, previous experiments with fertilizers, where the rate, yield, and the relationship with a control have been recorded may be useful. Fertilizer efficiency can be measured comparing the increment of yield when one unit of fertilizer is add in relation with the same soil where no fertilizer was used.

Nitrogen efficiency can be measured using the following formulas. Each, however, is different and the researcher should be clear about the kind of efficiency that needs to be measured:

N use efficiency (NUE; kg kg^{-1}) as the ratio of grain yield to N supply, where N supply is the sum of soil NO_3^- -N at sowing, mineralized N and N fertilizer.(19)

N uptake efficiency (NU_pE ; kg kg^{-1}) as the ratio of total plant N uptake to N supply. (20)

N utilization efficiency (NU_tE ; kg kg^{-1}) as the ratio of grain yield to total plant uptake.(21)

N harvest index (NHI; %) as the ratio of N in grain to total plant N uptake.(22)

N physiological efficiency (NPE; kg kg^{-1}) as the ratio of (yield at N_x – yield at N_0) to (N uptake at N_x – N uptake at N_0), N_x and N_0 are treatments with and without N application, respectively.(23)

N agronomic efficiency (NAE; kg kg^{-1}) as the ratio of (yield at N_x – yield at N_0) to applied N at N_x , N_x and N_0 are treatments with and without N application, respectively.(24)

N apparent recovery fraction (NRF; %) as the ratio of (N uptake at N_x – N uptake at N_0) to applied N at N_x , N_x and N_0 are treatments with and without N application, respectively.(25)

Others terms used are AE_N , agronomic efficiency of applied N (kg grain yield increase kg^{-1} N applied), and RE_N , apparent recovery efficiency of applied N (kg N taken up kg^{-1} N applied):

$$AE_N = (GY_{+N} - GY_{0N})/N \dots\dots\dots(26)$$

and

$$RE_N = (UN_{+N} - UN_{0N})/N \dots\dots\dots(27)$$

Where:

GY is the grain yield (kg ha^{-1}),

UN is the plant N accumulation in aboveground biomass (kg ha^{-1})

N is the amount of fertilizer, or manure/biosolids-N applied (kg ha^{-1})

$_{+N}$ and $_{0N}$ refer to treatments with and without N application, respectively.

When manure/biosolids treatments are used, both the organic-N and $\text{NH}_4\text{-N}$ contained in the materials must be determined.

The following formula may be used to estimate the proportion of yield increase by N-Fertilizer.

$$\text{PYIN}_x = (\text{GY}_{+N} - \text{GY}_{0N}) \dots\dots\dots (28)$$

PYIN_x is the proportion of the yield increase by N fertilizer at x rate

GY is the grain yield (kg ha^{-1}),

N is the amount of fertilizer or manure/biosolids-N applied (kg ha^{-1}).

$_{+N}$ and $_{0N}$ refer to treatments with and without N application, respectively.

In an experiment using N^{15} two equations were used to estimate the efficiency of fertilizer (Karim et al., 1972):

$$\text{N-F}_x = \text{FN}_{\text{upx}} / \text{TN}_{\text{upx}} \dots\dots\dots (29)$$

Where:

N-F_x = Percent N in plants derived from fertilized at x time (%)

FN_{upx} = Fertilizer N uptake at x time (mg/plot)

TN_{upx} = Total N uptake at x time (mg/plot)

and

$$N-F_x = FN_{upx} / (TN_{upx} - TN_{upx}C) \dots\dots\dots(30)$$

Where:

FNU = Fertilizer N utilization (%)

$N-F_x$ = Percent N in plants derived from fertilizer at x time (%)

FN_{upx} = Fertilizer N uptake at x time (mg/plot)

TN_{upx} = Total N uptake at x time (mg/plot)

$TN_{upx}C$ = Total N uptake at x time (mg/plot) by the N-control. The N control does not receive N fertilizer, but could be fertilized with P and K. Absolute control (AC) indicates no N, P and K fertilization.

All the above nitrogen efficiency terminology follows from Karim et al. (1972), Moll et al. (1982), Pierce and Rice (1988), Dev and Bhardwaj (1991), Huggins and Pan (1993), Sowers et al. (1994), Delogu et al. (1998), López-Bellido and López-Bellido (2001), and Binder et al. (2002).

The percentage of applied fertilizer N taken into plants is often estimated by measuring the difference in plant N uptake between N-treated and check plots. This method has often overestimated plant fertilizer N uptake; however, other studies have shown the opposite. An experiment carried out by Schindler and Knighton (1999) found that corn uptake of fertilizer N as estimated by the isotopic and difference methods was 45% and 39% in 1993 and 40% and 22% in 1994, respectively. Nearly 42% and 36% of the applied labeled N was estimated be in the soil at the end of 1993 and 1994, respectively. They mentioned that the difference method did not overestimate plant N uptake because of high soil N availability, and that climatic difference had less effect on the results generated by the isotopic compared with the difference method. In other experiments with corn, N uptake was 40% of manure-N and 15% of compost-N in the first year and

was 18% for manure and 8% for compost in the second year after application (Eghball and Power, 1999).

Two experiments were carried out to estimate the use efficiency of N from anaerobically digested sewage sludge rates and N fertilizer in irrigated corn and rainfed sorghum (*Sorghum bicolor* L.) during 4-year field experiments at two sites on a silty clay loam soil (Binder et al., 2002). The maximum yields were achieved during the first year following application. Maximum biomass yields were 62 Mg ha⁻¹ with application of 441 kg of organic N ha⁻¹ on irrigated maize and 36 Mg ha⁻¹ with 257 kg organic N ha⁻¹ on rainfed sorghum. At those rates, the increase in relative yield (RY) was 33% in the year of application, 21% in the second year, 14% in the third year, and 9% in the fourth year. Approximately 40, 20, 10, and 5% of the total biosolids-N was recovered by the crops in the first, second, third, and fourth year, respectively. For irrigated maize, agronomic efficiency of biosolids-N decreased with increasing biosolids rate, but was similar to that of fertilizer-N. In rainfed sorghum, use efficiency of biosolids-N was lower than that of fertilizer-N. The efficiency in corn was from 29 to 13% with a high coefficient of variation of from 68 to 41% using mineral fertilizer N. Little NO₃ accumulated in soil when biosolids were applied at the recommended rate, but application in excess of that required for maximum yield increased NO₃ accumulation in soil. Recommendations for biosolids use should be based on total N input, cumulative plant recovery, and leaching potential across the 4-year period. Nitrogen use efficiencies were estimated using differences between N-fertilized treatments and unfertilized controls (Binder et al., 2002).

A 3-year field study found that wheat monoculture had poorer utilization of N compared with wheat-sunflower, wheat-chickpea (*Cicer arietinum* L.), wheat-faba bean (*Vicia faba* L.), and wheat-fallow rotations. Conventional tillage had greater N use efficiency and N uptake efficiency compared with no-tillage (López-Bellido and López-Bellido, 2001).

The efficiency of N uptake and N recovery by wheat and corn crops was increased with the addition of sugar cane trash compared with mustard straw, both at the rate of 5 t ha⁻¹. In the corn crop, the maximum recovery of N was 74%, and the N use efficiency was 36 (kg grain kg⁻¹ N) with sugarcane trash plus 120 kg N ha⁻¹. The efficiency was lower when mustard straw plus 120 kg N ha⁻¹ was used. The efficiency of applied N was computed using the formula given by Novoa and Loomis (1981).

The fractional efficiency of N, or percent recovery of added N has been found to range between 0.30 and 0.70 (Stanford, 1966), and will probably be near 0.5 when N is applied as a sidedressing on soils that are aerobic and where leaching is not excessive.

Variations of the conceptual model of fertilization

Østergaard et al. (1985) used the Stanford (1966) approach to estimate the requirement of barley following cereals for fertilizer N in Denmark. Their equation was:

$$N_{f\text{opt}} = \frac{N_c - N_s}{N_{rf}} \dots\dots\dots(31)$$

Where:

$N_{f\text{opt}}$ = economically optimum quantity of fertilizer N

N_c = total amount of N absorbed by the crop (top + roots) when $N_{f\text{opt}}$ is applied

N_s = N absorbed from the soil supply (estimated by the N in the tops and roots of the crop without N fertilization)

N_{rf} = fractional recovery of fertilizer N

$N_{f\text{opt}}$, N_c , and N_s are expressed in units of kilograms per hectare.

The value of N_c was estimated by the equation

$$N_c = 19x + 16 \dots\dots\dots(32)$$

where x = grain yield at 16% water content in megagrams per hectare.

The value for N_s was found by the equation

$$N_s = 0.80N_m + 20 \dots\dots\dots(33)$$

where N_m = mineral N in the soil in March to the depth to which rooting is expected to occur.

N_{rf} was estimated by the equation

$$N_{rf} = (0.75) (1 - e^{-0.015(N_c - N_s)}) + 0.08 \dots\dots\dots(34)$$

In France, Meynard et al. (1982) used the following equation to estimate the N requirement of wheat:

$$N_f = by + N_{mh} - (N_m + N_{ms} + N_{mr}) \dots\dots\dots(35)$$

Where:

N_f = fertilizer nitrogen required

b = total nitrogen per unit mass of grain

y = expected yield of grain with applications of N_f

N_{mh} = mineral nitrogen in the soil at harvest, at the same depth used for N_m

N_m = mineral nitrogen in the soil at the end of the winter to the depth to which rooting is expected

N_{ms} = nitrogen mineralized from the residues of the previous crop

N_{mr} = nitrogen mineralized residual.

Using this formula for predicting N_f , N_m would be measured directly, and b, N_{mh} , N_{ms} , and N_{mr} would have to be obtained from other experiments.

Smyth et al. (2004) created the computer program NuMaSS that uses the following algorithm:

$$N_{fert} = (Y_r * N_{cr}) - [(N_{soil}) + (N_{residue} * C_r) + (N_{manure} * C_m)] / E_f \dots\dots\dots(36)$$

This algorithm is a modification to the balance sheet model of George Stanford (Smyth et al., 2004).

Where:

N_{fert} = N fertilizer needed

Y_r = Target dry matter yield

N_{cr} = N concentration (%N)

N_{soil} = Nitrogen absorbed by the crop that is derived from soil organic matter and previous crop residue mineralization, and from atmospheric deposition during the growing season.

$N_{residue}$ = Nitrogen mineralized from green manures or residues, such as stover or compost that are added to the field.

C_r = Proportion of N mineralized from green manures or residues that are absorbed by the plant.

N_{manure} = Nitrogen mineralized from manure

C_m = Proportion of N mineralized from manure that the crop absorbs

E_f = Fertilizer efficiency.

Determining Crop N demand using NuMaSS (Smyth et al., 2004). The first step is to determine the total crop N need. The equation for this determination is:

$$\text{Total Crop N Needs} = (Y_r * N_{cr}) = Y_g * \%N_g + Y_s * \%N_s \dots\dots\dots(37)$$

Where:

Y_r = Total dry matter

N_{cr} = Nitrogen concentration in the total plant

Y_g = Reproductive yield

$\%N_g$ = Nitrogen concentration in the reproductive portion of the crop

Y_s = Vegetative yield

$\%N_s$ = Nitrogen concentration in the vegetative portion of the plant.

Determining Crop Available N using NuMaSS (Smyth et al., 2004). Once the amount of N is calculated for the target yield, the Nitrogen module calculates the amount of N available to the crop from the soil (N_{Soil}), manure (N_{Manure}), organic amendments (N_{Residue}), and green manure crops (N_{Residue}). The equation used to calculate crop available N is:

$$\text{Crop available N} = \text{NCrop(available_to)} = \text{N}_{\text{Soil}} + \text{N}_{\text{Manure}} + \text{N}_{\text{Residue}} \dots\dots\dots(38)$$

Determining Soil N accord with NuMaSS (Smyth et al., 2004). There are four different methods to determine the amount of N supplied by the soil (N_{Soil}).

Soil N is determinate in the following hierarchy:

1. The amount of N contained in an unfertilized crop gives an indication of the N supplying capacity of the soil. If the previous crop and the current crop are the same and the previous crop was not fertilized, then soil N supply can be calculated.
2. If soil N value is known, enter this value in the “Prediction/Fertilizer Application” of the model.
3. If the soil N value is unknown, use the default N value that is derived from the default table.
4. The least precise method for determining soil N supply is by calculating N mineralization either from soil organic matter, C or N content. The default rate of mineralization is 2% of the organic matter per year multiplied by the proportion of months the crop is grown.

This program has been divided into six parts: I. Program Integration, II. Data Base Development, III. Acidity Module, IV. Nitrogen Module, V. Phosphorus Module, and VI. Economics Section, unfortunately, NuMaSS doesn't mention how to estimate the efficiency of fertilizer uptake (Smyth et al., 2004).

Advantages and disadvantages of the conceptual model of fertilization

An advantage of a conceptual model is that it goes from the particular to the general, and can be analyzed both deterministically and stochastically. The data required to use it also goes from the particular to the general. Theoretically, the more data available the more accurate and precise will be the estimate of crop nutrient requirement. This model can be applied in both developing and developed countries, and under different

environment conditions. This model can also use the information actually available. It is theoretically based and tries to establish constant relationships.

A possible disadvantage of this model is that it doesn't consider interactions between nutrients. However, interactions are usually not present when optimum nutrients levels are applied or present in the soils (Colville, 1967; Koch and Mengel, 1974; Miller, 1974; Classen and Barber, 1977; Cralle, 1986; Faría et al., 1999, Khalifa and Zidan, 1999, Buah et al., 2000). The most general form of this model is apparently a linear relationship, but it actually is in an exploratory space. If all possible relationships are plotted, the graph shows a nomograph in a third dimension.

3. OBJECTIVES AND HYPOTHESES

Objectives

General objective

The overall objective of this research is to determine the validity, accuracy and precision of an algorithm which will calculate the N requirement for corn.

Specific objectives. Determine changes in the relationships of corn vegetative parameters over time. Estimate the N demand of corn, the supply of N by the soil, and the efficiency of N uptake under field and greenhouse conditions, and compare the vegetative parameters in both cases. Determine the accuracy and precision of a conceptual model to estimate the N requirement of corn under greenhouse and field conditions.

Hypotheses

General hypothesis

The conceptual model can estimate the nitrogen requirement with an accuracy and precision higher than 90%.

Specific hypotheses. Vegetative parameter relationships used in the model to calculate the N requirement of corn follow non-linear models. The existing theoretical base of knowledge is sufficient to establish a conceptual model to estimate the N requirement of corn under controlled and field conditions with an accuracy and precision higher than 90%.

4. MATERIALS AND METHODS

Estimate the nitrogen fertilizer requirement of corn

To estimate the amount of nitrogen fertilizer required by corn, it is necessary to determine the value of the parameters used in the following formula:

$$\text{Requirement of nitrogen} = \frac{\text{Nitrogen demand of the crop} - \text{Supply of nitrogen by soil}}{\text{Efficiency of nitrogen fertilizer}} \quad (39)$$

Three experiments were carried out; two in the field and one in the greenhouse. The first experiment in 2002 included three locations in the field. They were used to evaluate corn root index, plant moisture content, harvest index, and the relationships between dry and fresh weights of roots, aboveground biomass, and yield. In one location these vegetative parameters were measure through the whole life of the corn crop to determinate their behavior. The second experiment in 2003 in the greenhouse was carried out to estimate the root index, plant moisture content, and harvest index without and with 179 kg N ha⁻¹. This experiment was used to estimate the N demand of corn using the algorithm proposed, the N uptake efficiency (apparent recovery efficiency of applied N) using the difference method, and the soil N supply using a laboratory incubation to estimate soil N mineralization. A third experiment was carried out in 2003 in the field to confirm parameters estimated in the second experiment. The N concentrations and N demand of corn plants, the soil N supply, and the efficiency of N fertilizer uptake were measured at corn crop maturity in the three experiments. Pioneer hybrid 32R25 (P32R25) was used, except in one location of the 2002 experiment in which Dekalb 687 corn variety was used. Accuracy and precision were measured using the error propagation method which will be described in a later section.

2002 field experiment

Information was collected in the 2002 experiment from three different locations to compare the results of vegetative parameters (Fig. 2; sites A, B and C).

The first location was at the Texas A&M University Agricultural Experiment Station Farm near College Station (Fig. 2, site A), on a Ships clay soil (very fine, mixed, active, thermic Chromic Hapluderts; USDA-NRCS, 2002), using P32R25 corn. The density of population was 48,000 plants ha⁻¹ under dryland conditions. The row spacing was 1.04 m, and the spacing between plants was 0.20 m. The area planted with corn was approximately of 8 ha, but only the central part of this area was selected, avoiding the first 10 rows to reduce the border effect. Planting date for this experiment was 21 February 2002. The sampling area was approximately 4 ha and 179 kg N ha⁻¹ as 32-0-0 solution was sidedressed 30 days after planting. Corn plant samples were taken every seven days, from 46 days after planting (dap) to corn maturity (154 dap). The number of plant samples varied accord with the time required to take the root system, and ranged from 6 to 16 plants, but in general, the number of corn plant samples was 12. The harvest dates to evaluate fresh and dry weight of corn grains were July 13 and July 24, 2003, 143 and 154 days after planting, respectively. These two samples were used to evaluate the changes in root index, harvest index, moisture content, yield, N content and N demand in the last 11 days before harvest.

The selection of the corn plants sampled in all the three location for the 2002 field experiments followed a zig-zag pattern. The statistical analysis and elaboration of figures were similar in the three locations. Analysis of variance and Tukey test were used at $\alpha=0.05$ using the Statistical Analysis System (SAS) for Windows version 8.1. The graphics and fit of models used Excel from Microsoft Office XP, and they were validated with SAS using the command Proc REG. The analysis of variance was

calculated using Proc GLM of SAS. Figures 23 and 49 were prepared with SigmaPlot Version 9.0.



Fig. 2. Arrows point out the locations of the Texas A&M University Agricultural Experiment Station Farm (points A, C, and D correspond to Ships soil series), and the cooperating farmer's land (point B corresponds to a Weswood soil series). Points A, B and C were locations of the 2002 field experiment while point D was the location where the 2003 field experiment was established. The experiment at point C was established with Dekalb 687 corn variety.

The second location was with a cooperating farmer using this same corn hybrid grown in a Weswood silty clay loam soil (fine-silty, mixed, superactive, thermic, Aquic Haplustepts; USDA-NRCS, 2002) under dryland conditions (Fig. 2, site B). This location was divided into two sampling locations: East and West, given that the farmer was aware of soil variability. The area selected for sampling was approximately 2 ha for

each location. The density of population was 55,500 plants ha⁻¹, the row spacing was 0.90 m, and the spacing between plants was 0.20 m. The fertilization rate was 180 kg N ha⁻¹, and the planting date was February 19, 2002. The numbers of plant samples harvested were 12 for the east side and 12 for west; they were sampled on July 20 and July 21, respectively at maturity. These dates correspond to 152 and 153 days after planting.

The third location used Dekalb 687 variety grown in Ships clay soil under dryland conditions and no fertilization (Fig. 2 site C). This site has been a long term no-tillage experiment. This study was planted on February 21, 2002, and was harvested on August 3, 2002 (163 days to harvest). The population density was 44181 plants ha⁻¹. The row spacing was 1.06 m, and the spacing between plants was 0.21 m.

2003 greenhouse experiment

In the 2003 greenhouse experiment, P32R25 corn was grown in two groups of 20 pots, growing one corn plant in each pot. The pots were 20 liters in capacity and they were filled with soil. The spacing between pots was 60 cm. The soil water content was adjusted taking care of not to produce leaching. A completely randomized design (CRD) with a factorial arrangement was used, with 2 soils having 2 fertilizer levels and 10 repetitions per treatment. The factors were 2 kinds of soil, clay (Ships series from Texas A&M University Agricultural Experiment Station Farm, site A in Fig. 2) and silty loam soils (Weswood series from a cooperative Farmer's land located in site B in Fig. 2), and the 2 levels were fertilized and non-fertilized with N. The amount of N was 3.3788 g NH₄NO₃ per pot placed at 10-cm depth. This computes to 179 kg N ha⁻¹ or 2.53 g N per pot, calculated on an area basis. The formula used was 33-00-00. Only N was added as fertilizer to corn plants. The fertilizer was added sidedress at 10 cm depth at 40 days after planting. One group of the pots were of one kind of soil classified agronomically as "good" (Ships series) and another was classified as "poor" (Weswood series) according

to their potential to grow grain and seed crops (USDA-NRCS, 2002). Both soils are contrasting (USDA-NRCS, 2002). Soil Taxonomy Classification was used for a better description (Soil Survey Staff, 1999) using previous work in that area (USDA-NRCS, 2002). The plants were in the greenhouse until maturity. The planting date was December 20, 2002, and the harvest date was May 31, 2003 (162 days to maturity). The Statistical Analysis System (SAS) for Windows version 8.1 was used to calculate the analysis of variance, and Tukey's test and to validate the fit of models with Excel from Microsoft Office XP. The graphics and fit of models was using Excel. The models were validated with SAS using the command Proc REG. The analysis of variance was calculated using the Proc GLM of SAS.

2003 field experiment

A field experiment was established in 2003 at the Texas A&M University Experiment Station Farm near College Station with corn under dryland conditions on a Ships soil (Site D in Fig. 2). This experiment used a randomized complete block design (RCBD) having two treatments and four blocks (Fig. 3). The experimental units had an area 9 meters x 4.16 m (4 rows) excluding the border rows. The treatments were fertilized and non-fertilized with nitrogen 30 days after planting. The fertilizer was a liquid mixture of 35% urea, 45% NH_4NO_3 , 19.9% water, and 0.1% ammonium hydroxide. The formula was 33-0-0, with a rate of 179 kg N ha^{-1} . The fertilizer was placed sidedress at 10 cm of depth 30 days after planting. The equipment was calibrated for a plant population density of 59,000 plants per ha, however, with the time the plant population changed due to environmental factors. The planting date was April 22, 2002, and the harvest date was August 16, 2003 (116 days to maturity). The row spacing was 1.04 m, and the spacing between plants was variable according to the block. The number of plants with and without an ear measured by experimental unit, except in the first block where the number of corn plants without an ear was not measured due to technical difficulties. A total of 1214 corn ears were harvested by hand.

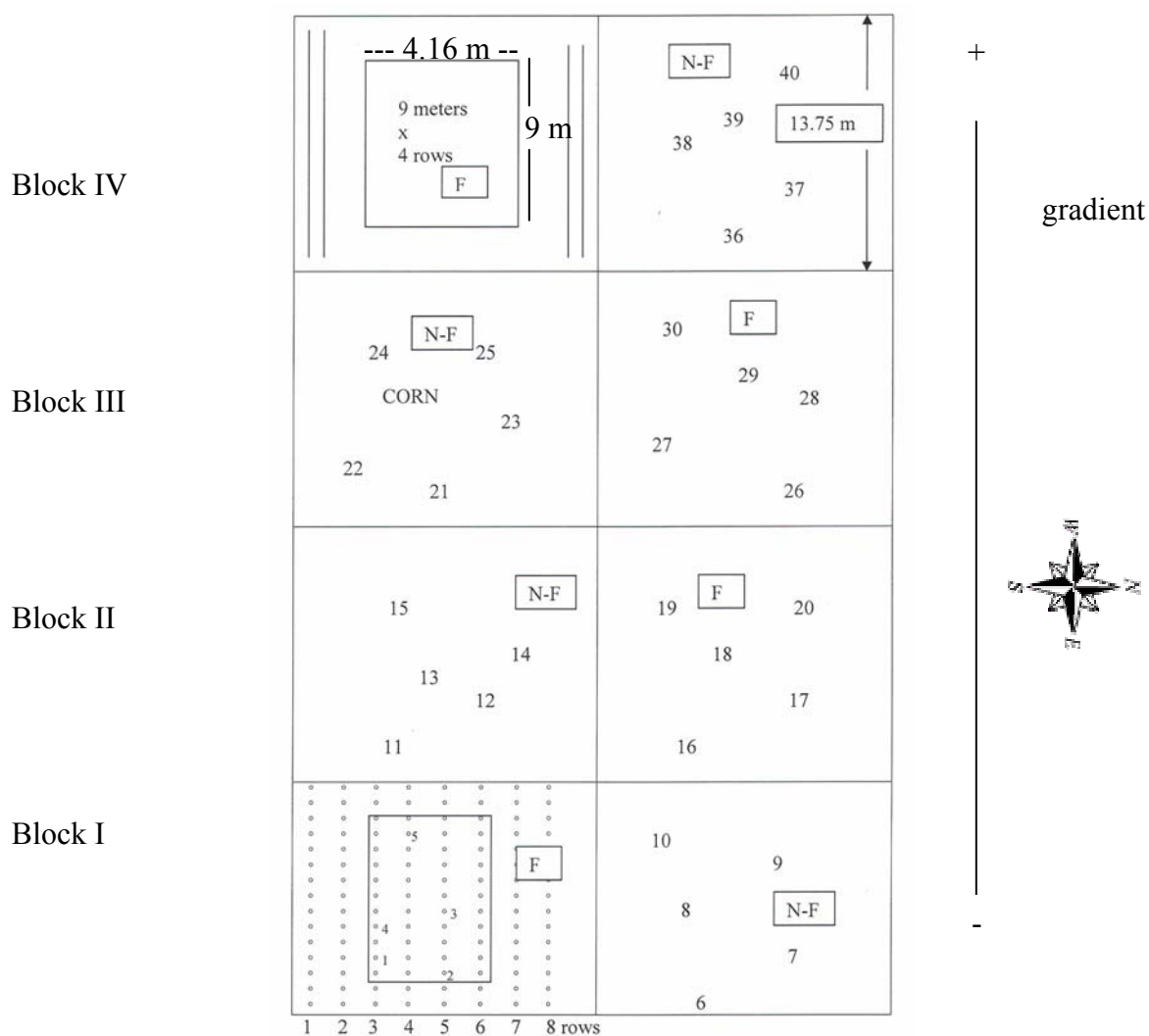


Fig. 3. Field experiment in 2003 showing treatments and plot measurements. F means fertilized, and N-F not fertilized. The figure is out of scale. The numbers inside of each experimental unit represent the plant number identification used at the sampling.

A gradient was observed in the number and size of corn plants along the rows (Fig. 3). From west to east there were more to fewer plants in the rows and the size of the plants was from bigger to smaller. To avoid this source of variation in the experiment a randomized complete block design was chosen. The source of variation came from differences in the soil properties given that the soil slope was less than 2% and the climate was the same for the entire plot. Differences are probably due to the relative

amount and type of clay and/or organic matter content. The average distance between rows was 103.47 cm (the number of data “n” were 15, and the std. dev. was 3.81), the number of plants in ten meters in the block I was 29 (std. dev. 0.577, 3 replications) and in the block IV was 59 (std. dev. 1.52, 3 replications). On average, the experiment had 43,533 plants ha⁻¹ in treatments with N fertilizer and 37,400 plants ha⁻¹ without N fertilizer.

Accuracy and precision of the formula to estimate the nitrogen requirement of corn

To determine the accuracy and precision of the conceptual model to calculate the N fertilizer requirement of corn, two experiments were carried out. One of them under greenhouse and another under field conditions, both during 2003. Each one used treatments without and with N fertilization. The experimental conditions were explained previously in the sections named “2003 greenhouse experiment” and “2003 field experiment”.

The precision of the formula used to calculate the rate of fertilizer needed was measured according to the error propagation method (Harris, 2002; Garland et al., 2003, Table 2). The error propagation in each parameter (corn plant N demand, soil N supply, and efficiency of N fertilizer) of the formula was measured using the equations for addition, subtraction, multiplication and division shown in Table 2. The formulas to calculate the error propagation in exponentiation, logarithmic and antilogarithmic calculations were not used, however, it is important to mention them.

Table 2. Error propagation in arithmetic calculations.

| Type of calculation | Example† | Standard deviation of y |
|----------------------------|--------------------------|---|
| Addition or subtraction | $Y=a+b-c$ | $S_y=(S_a^2+S_b^2+S_c^2)^{1/2}$ |
| Multiplication or division | $Y=a*b/c$ | $S_y/y=\{(S_a/a)^2+(S_b/b)^2+(S_c/c)^2\}^{1/2}$ |
| Exponentiation | $Y=a^x$ | $S_y/y=x (S_a/a)$ |
| Logarithm | $Y=\log_{10}a$ | $S_y=0.434 (S_a/a)$ |
| Antilogarithm | $Y=\text{antilog}_{10}a$ | $S_y/y=2.303 S_a$ |

† a, b, and c are experimental variables whose standard deviations are S_a , S_b , and S_c , respectively.

Accuracy was measured using the difference between the actual N fertilizer application (2.53 g N pot⁻¹ in the greenhouse and 179 kg N ha⁻¹ for field experiment) and the estimated of N requirement using the algorithms and methodologies used in the conceptual model of fertilization.

$$\text{Accuracy in \%} = 100 - \left(\left| \frac{\text{Real value} - \text{Estimated value}}{\text{Real value}} \right| \times 100 \right) \dots\dots\dots(40)$$

Calculation of the nitrogen demand of corn

Two field experiments and one greenhouse experiment were carried out to estimate each one of the parameters in the nutrient demand formula. The general conditions of these experiments were previously explained under the sections called “2002 field experiment”, “2003 greenhouse experiment”, and “2003 field experiment”. In the 2002 field experiment, plant samples were randomly taken during various growth stages from three different locations. The root weight, aboveground biomass, moisture content, dry weight, and N concentration of corn plants were measured. At corn crop maturity of the

three experiments, 53 and 40 samples were taken from the field and greenhouse, respectively, to measure the grain yield for each plant, along with the same parameters mentioned previously.

Plant samples were dried in an oven at 65°C for 72 hours and ground in a Thomas Wiley mill to pass a 40 mesh screen. In the case of corn grain, they were ground in a Glen mill type C11-1. The corn plant samples were digested using H₂SO₄ in heated digestion tubes for 3 hours, following pre-digestion during the previous night (Bremmer, 1996), and analyzed colorimetrically with a Technicon autoanalyzer (Technicon Industrial Systems, 1977a). Some ground grain samples were infested with Indianmeal moth (*Plodia interpunctella*). These samples were manually cleaned before analysis.

It's important to note that the units of nutrient demand can be of different magnitude. The units could be for only one plant or for all plants in a given area. In the case of the field experiment, the units used to estimate the nitrogen demand of a corn crop were kilograms of nitrogen per hectare of surface. In the case of the greenhouse experiment, the units used were grams of nitrogen per plant in a pot. To calculate the nitrogen demand, the following formula was used:

$$N.D. = \frac{I.R.Nu. \times (R.I. + 1) \times (1 - H) \times Y}{H.I.} \dots\dots\dots(41)$$

Where:

N.D. =Nutrient demand (kg ha⁻¹)

I.R.Nu. =Internal requirement of nutrient (g N g⁻¹ dry matter)

R.I. =Root index (g roots g⁻¹ agb). This relationship can be written as follows:

$$R.I. = \frac{\text{Weight of roots}}{\text{Weight of aboveground biomass}} \dots\dots\dots(42)$$

- 1 =The number one located in the expression (R.I. + 1) comes from the formula derivation and expresses the total aboveground biomass
- 1 =The number one located in the expression (1 - H) is a factor of conversion. It is used to convert fresh-weight to dry-weight
- H =Moisture content of plants (g water g⁻¹ total biomass)
- Y =Yield in kg ha⁻¹ or ton ha⁻¹ on a physiological or commercial basis
- H.I. =Harvest index (g commercial product g⁻¹ total biomass)
- Agb =Aboveground biomass.

Soil nitrogen supply

The supply of N to corn plants was measured using the inorganic nitrogen (NO₃⁺-N and NH₄⁺-N) production during aerobic incubation (Anderson, 1982, Bundy and Meisinger, 1994, Franzluebbers et al., 2000). The method used the following relationship:

$$\text{Nitrogen available in the soil} = (\text{NO}_3^- + \text{NH}_4^+)_{\text{initial}} + (\text{NO}_3^- + \text{NH}_4^+)_{\text{mineralized}} \dots\dots\dots(43)$$

The supply of N from the soil was estimated by soil N mineralization in the laboratory following incubation. Soil samples came from field and greenhouse experiment. The samples were analyzed for nitrate (NO₃⁺-N) and ammonium (NH₄⁺-N). In the case of the field and greenhouse experiment, the samples came from the same place and pots, respectively, as was used to evaluate the demand of nutrients. Dried soil samples were brought to approximately 50% of field capacity with distilled water. After that, soil samples were incubated at 25°C in 1-L glass jars with an alkali trap containing 10 mL of 1 M KOH to absorb CO₂ and a container with 10 mL water to maintain humidity. Traps were changed at 1, 3, 11, 21, and 30 d after incubation begun and titrated with 1 M HCl

(Anderson, 1982). Nitrogen mineralization was determined by subtracting the initial inorganic N concentration (NO_3^+ -N and NH_4^+ -N) of nonincubated soil samples from soil N extracted after 30 d of incubation. Inorganic N was extracted from 7-g soil subsamples using 28 mL of 2 M KCl. Samples were shaken for 30 min on a reciprocal shaker, filtered, and the extracts analyzed for NH_4^+ -N and NO_2^- -N plus NO_3^+ -N concentrations by colorimetric analysis using an autoanalyzer (Technicon Industrial Systems, 1977a, 1977b). The sum of the above N forms was designated as inorganic N.

Efficiency of nitrogen fertilizer use

The efficiency of fertilizer use was measured using the difference method. This is a comparison of experiments in which N was added and non-fertilized controls were used. In this case, N absorption was the parameter used to estimate the N uptake efficiency. The efficiency was measured in the 2003 field experiment and in the 2003 greenhouse experiment using hybrid P32R25. The following formula was used:

$$\text{RE}_N = (\text{UN}_{+N} - \text{UN}_{0N})/N \dots\dots\dots(44)$$

Where:

RE_N =The apparent recovery efficiency of applied N (kg N taken up kg^{-1} N applied)

UN =The plant N accumulation in aboveground biomass (kg N ha^{-1})

N =The amount of fertilizer N applied (kg N ha^{-1})

$+N$ and $0N$ =Refer to treatments with and without N application, respectively.

5. RESULTS AND DISCUSSION

Field experiment 2002

Variation of vegetative parameters

Changes in the coefficient of variation (C.V.) of the moisture content in aboveground biomass (agb) and roots were minimal compared to the rest of the variables (Sadler et al, 2000; Licht and Al-Kaisi, 2005; Farnham, 2001). Variations in C.V. of root index were moderate compared to other variables. The variation of the difference between the fresh and dry weight of agb and roots was low. This difference is called the moisture content. This means that the moisture content (H) in the formula of the conceptual model shows a small variation (Fig. 4) along the entire life cycle of the corn plant.

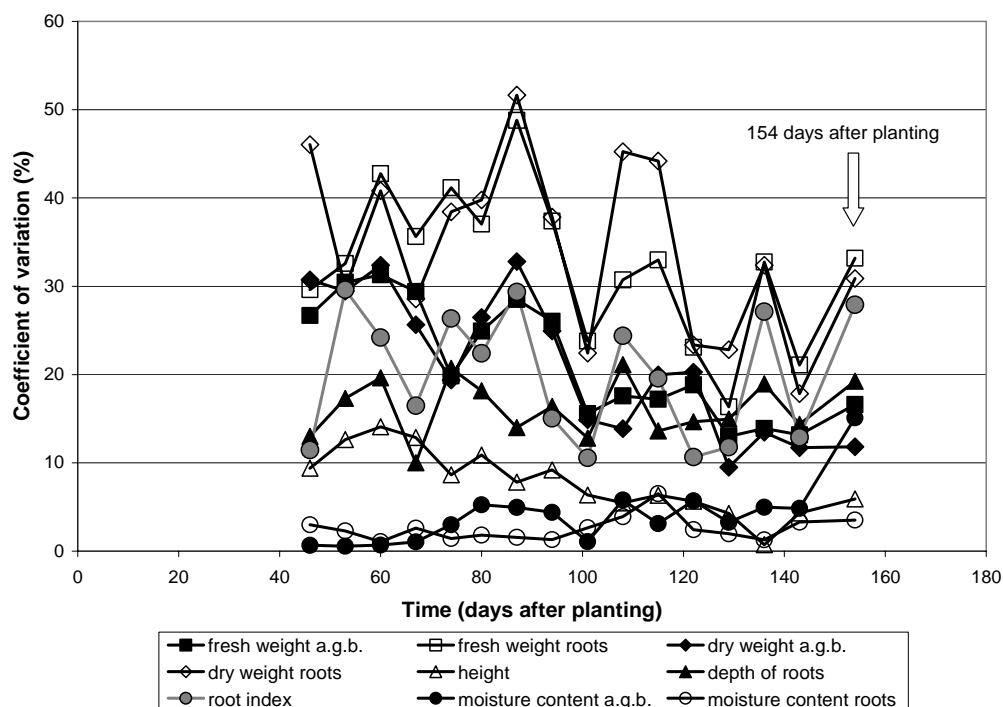


Fig. 4. Coefficients of variation for each variable, and their changes through time. Field experiment in 2002 on a Ships soil series (a.g.b.= aboveground biomass).

Changes in the C.V. of root index over time were higher than that of the moisture content of agb and roots but lower than that for plant height, depth of roots, and fresh and dry weight of agb and roots (Fig. 4).

The C.V. for plant height decreased with time. This means that the plant height became more stable as corn matured.

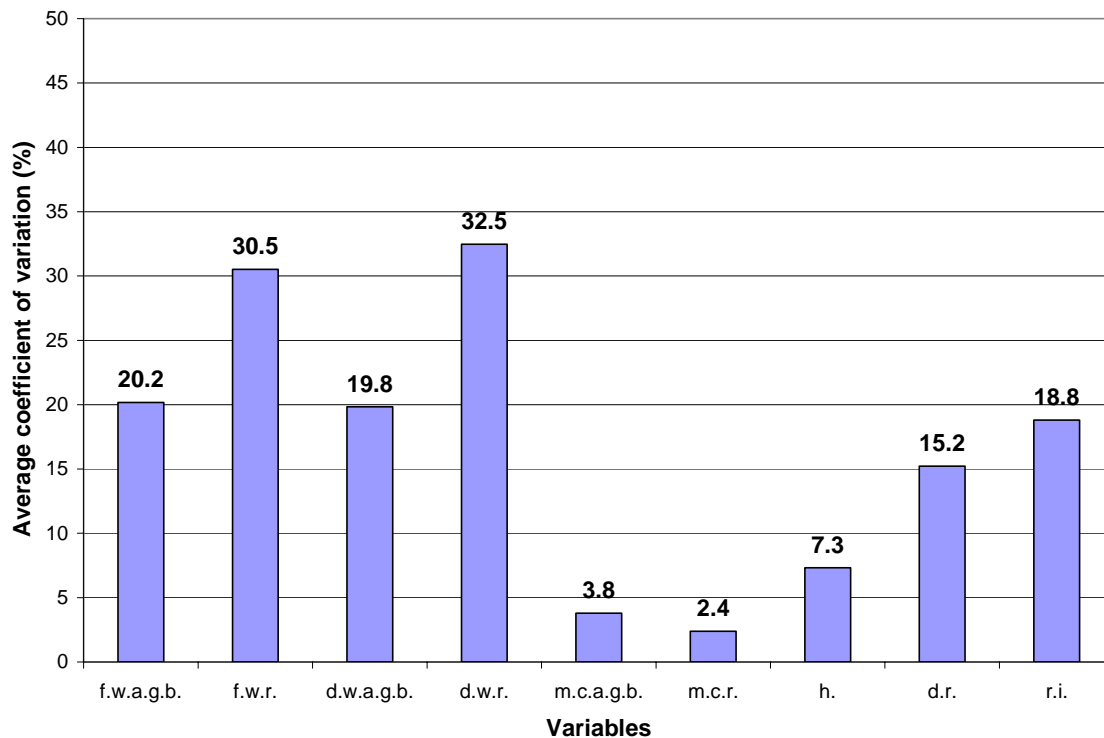


Fig. 5. Means of seasonal coefficients of variation (C.V.) for vegetative parameters of corn Pioneer hybrid 32R25. Field experiment in 2002 on a Ships soil series. f.w.a.g.b.: fresh weight aboveground biomass, f.w.r.: fresh weight of roots, d.w.a.g.b.: dry weight of aboveground biomass, d.w.r.: dry weight of roots, m.c.a.g.b.: moisture content of aboveground biomass, m.c.r.: moisture content in roots, h: plant height, r.d.: root depth, r.i.: root index.

Data in Fig. 5 show that C.V. depended on what variable was analyzed. The C.V. of the parameters used in the conceptual model should be small and changes over time should be stable and constant. That is, the C.V. of the moisture content of aboveground biomass

(m.c.a.g.b.), moisture content of roots (m.c.r.), and root index (r.i.) should preferably be small and their changes through time stable and constant. On average, the C.V. of m.c.a.g.b. and m.c.r. was small, while that for r.i. was higher. The C.V. of f.w.a.g.b., f.w.r., d.w.a.g.b., and d.w.r. were high; however, the differences of these parameters used to estimate m.c.a.g.b. and m.c.r. were low.

Root index

It was clear at the beginning of the growing season that there were significant changes in the relationship between the fresh weight of aboveground biomass and the fresh weight of roots, but 87 days after planting this relationship became more stable and constant (Fig. 6). This behavior was because plants preferentially develop root systems before the aerial portion, and then, during the reproductive phase, photosynthates went to the aerial part instead of roots, so the roots decreased their proportion of growth. In this case, the reproductive phase for P32R25 started around 67 days after planting.

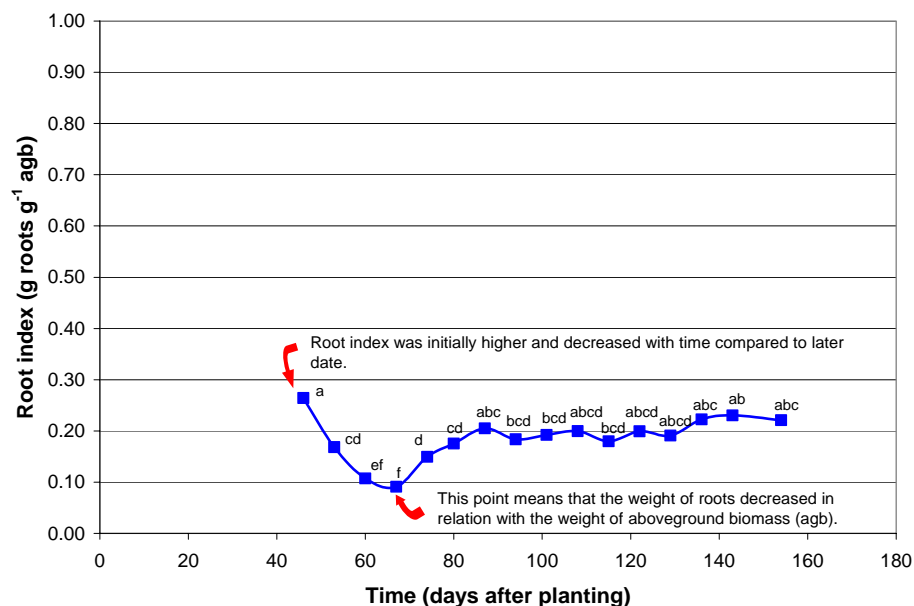


Fig. 6. Changes in root index after planting. Field experiment in 2002 on a Ships soil series. Means followed by the same letter are not different statistically at $\alpha = 0.05$ (a.g.b.= aboveground biomass).

The root index of corn hybrid P32R25 appeared to be good parameter for use in the conceptual model. The root index was essentially constant and stable from 80 to 154 days after planting (Fig. 6), although the average C.V. was 18% (Fig 5). The root:shoot ratio or root index in dry weight basis ranged from 0.09 to 0.17 using different N applications (Costa et al., 2002), and across genotypes the dry weight of roots maintained a logarithmic relationship with the dry weight of shoots (Hebert et al., 2001).

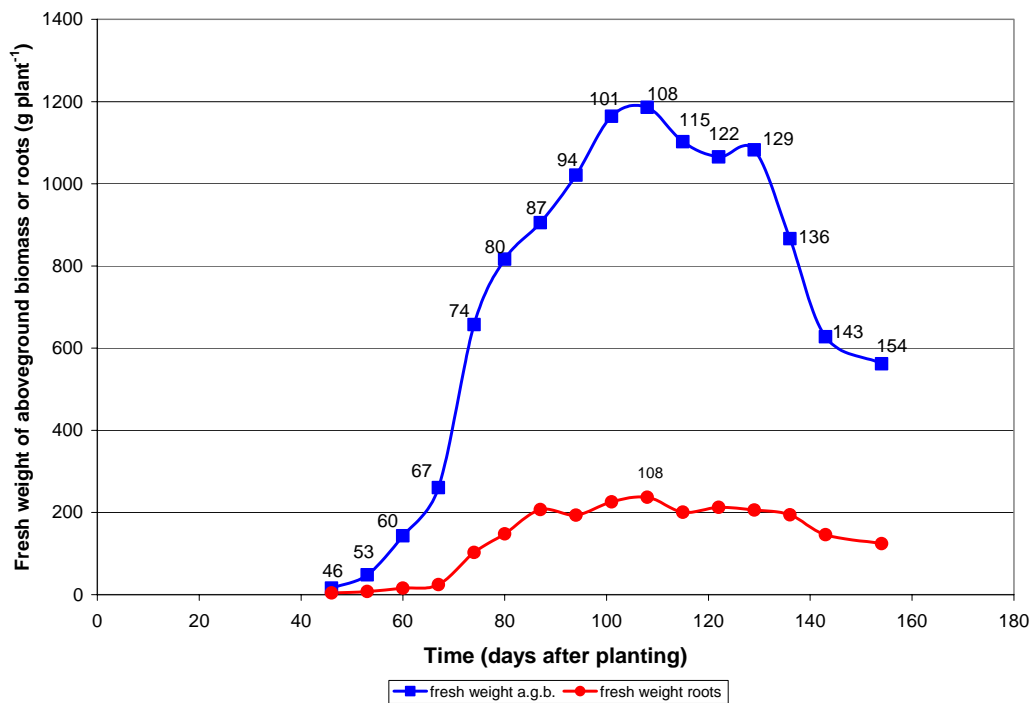


Fig. 7. Changes in fresh weight of aboveground biomass and roots after planting. Field experiment in 2002 on a Ships soil series.

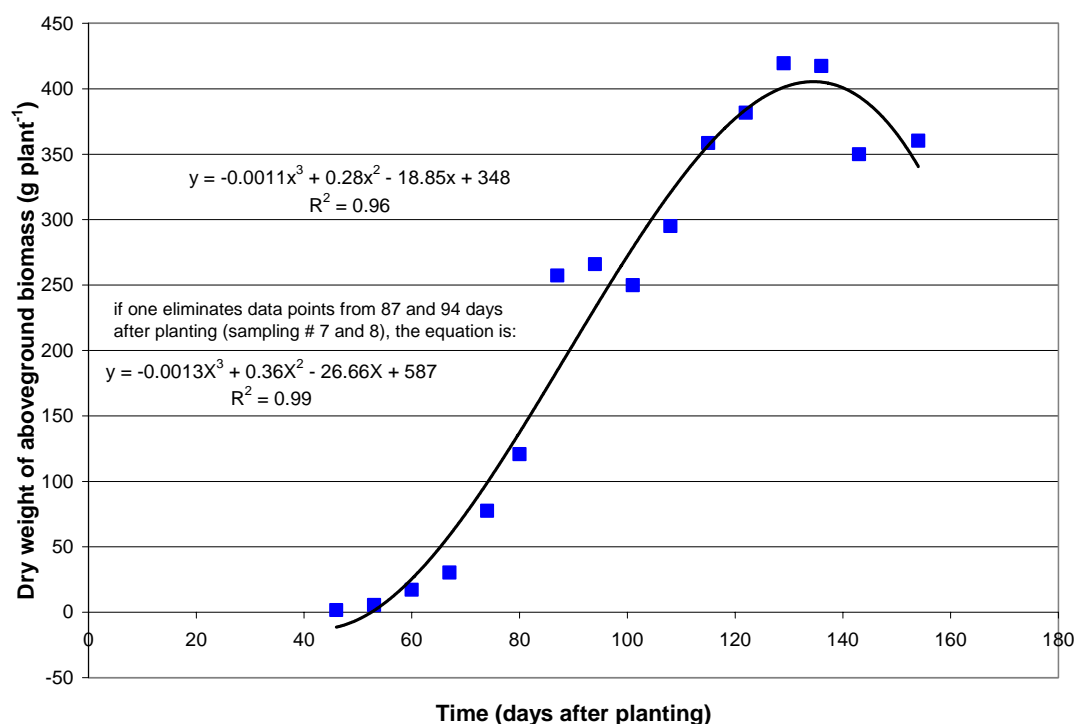


Fig. 8. Changes in the dry weight of aboveground biomass after planting. Field experiment in 2002 on a Ships soil series.

At approximately 108 days after planting, the fresh weight of aboveground biomass and roots began to decrease (Fig. 7). Plants on a relative basis were losing more water than dry organic matter of corn (Figs. 7, 8, 9 and 10). Changes in fresh weight were higher in the aboveground biomass than roots. The lack of a good set of dry samples for sampling numbers 7 (87 d.a.p.) and 8 (94 d.a.p.) produced a lower R^2 when these results were included in a polynomial model (Fig. 8). Eliminating these samplings, the R^2 increased from 0.96 to 0.99, the $P > F$ for both models were < 0.0001 . In Fig. 8, the last two data points showed a lower a.g.b. dry weight than the four previous points, probably because the corn plants were dried longer or material was lost in the transport from the field to the laboratory. Another possible reason is that these two sample sets were separated into all their components (leaves, stems, tassels, husks, grain, and cobs) and they may have lost more water than the others. This assumption would imply that the previous samples

were not completely dried. It could also be due to natural increase in maturity and drying in the field over time.

Data for sampling numbers 7 and 8 were fitted using interpolation. The result was the following polynomial:

$$y = -0.0013x^3 + 0.37x^2 - 27.87x + 625$$

$$R^2 = 0.98, n = 16, p = 0.0001.$$

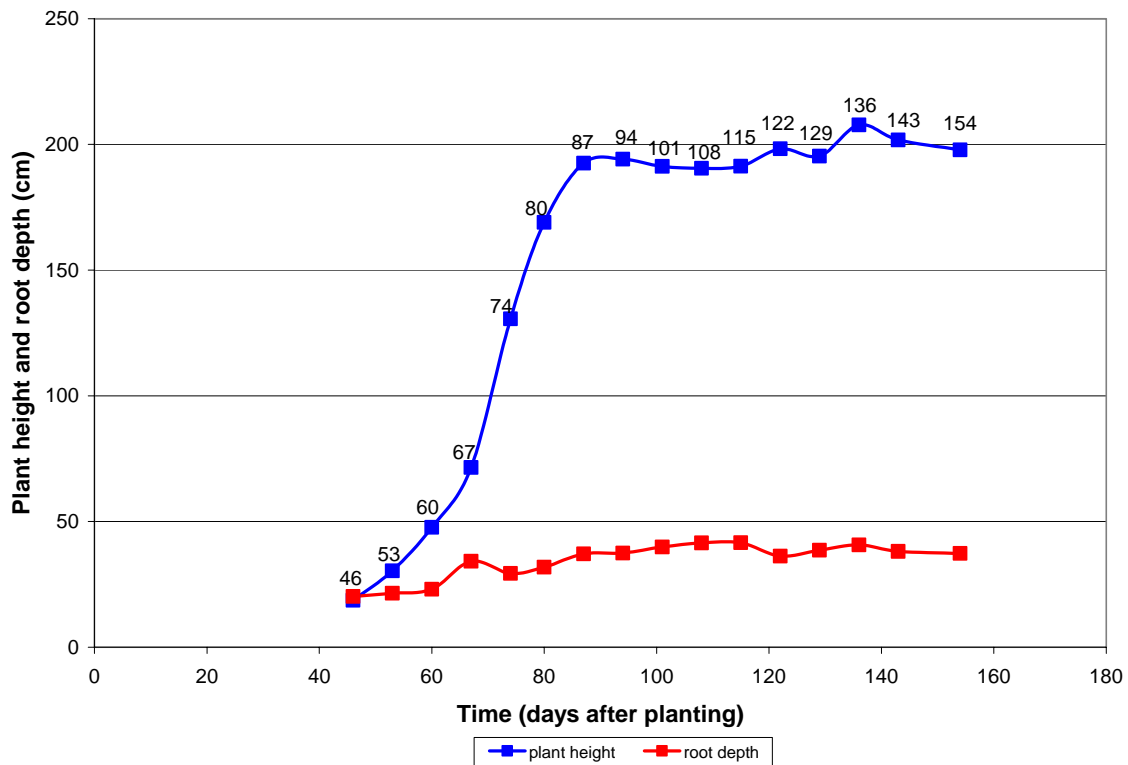


Fig. 9. Changes in plant height and rooting depth after planting. Field experiment in 2002 on a Ships soil series.

Although corn plants lost water and possibly organic material after 108 days after planting (Figs. 7 and 8), plant height was stable from 87 days after planting until harvest

(Fig. 9), and the depth of the root system was relatively stable, reaching its maximum at 115 days after planting and then decreasing slightly (Fig. 9). Plant height was measured from the base of aerial roots to the highest leaves where they began to bifurcate. Although the depth of roots was not the maximum depth of roots, this measurement comprised more than 95% percent of the root system on a fresh-weight basis.

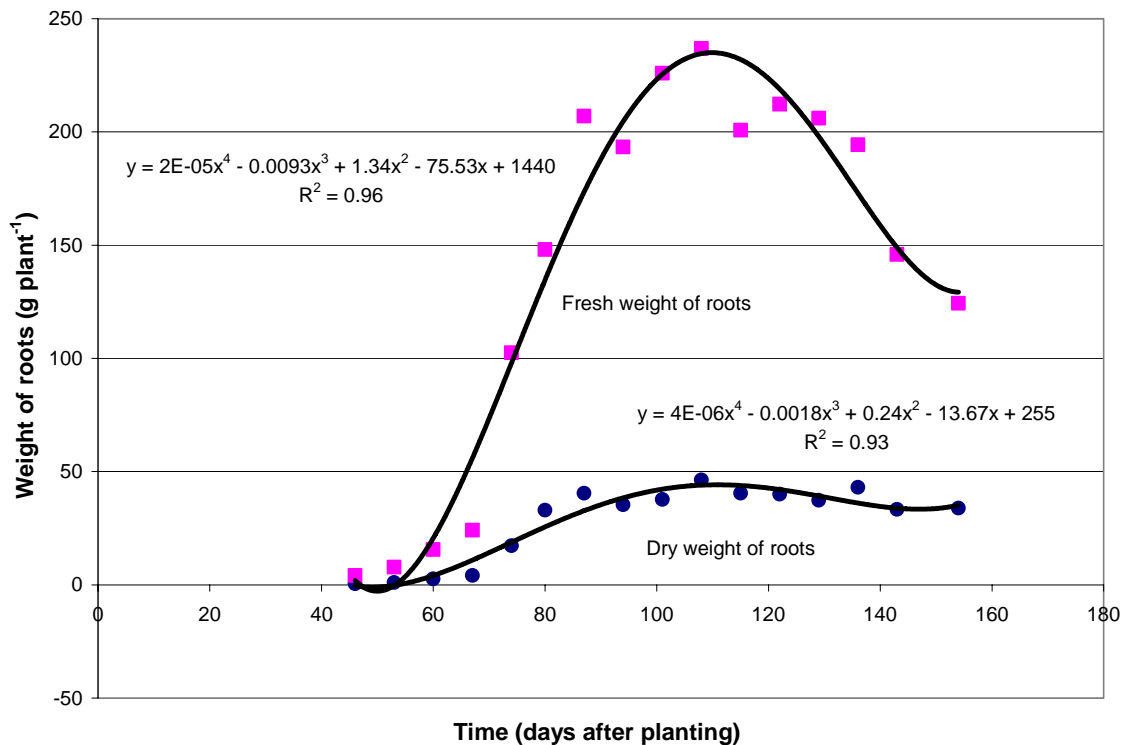


Fig. 10. Fresh and dry weight of roots over time. Field experiment in 2002 on a Ships soil series.

Root growth was fitted to a fourth degree polynomial ($P > F$ for both models was < 0.0001). This was accomplished for both fresh and dry weights of roots (Fig. 10). About 108 days after planting, the fresh and dry weight of roots decreased. This was because the roots started to get older, lose moisture, and decay. Fresh weight of roots changed more drastically with time than dry root weight. Using a polynomial third degree equation for fresh weight of roots, the strength of association between time and

fresh weight of roots was reduced from a R^2 of 0.91 ($P > F$ was < 0.0001) when using fresh weight to 0.88 ($P > F$ was < 0.0001) when using dry weight. The equations were: $y = -0.0004x^3 + 0.066x^2 + 1.36x - 190$, $R^2 = 0.91$ for fresh weight of roots, and $y = -4E-05x^3 + 0.0026x^2 + 1.07x - 57$, $R^2 = 0.88$, for dry weight of roots, where $n = 16$.

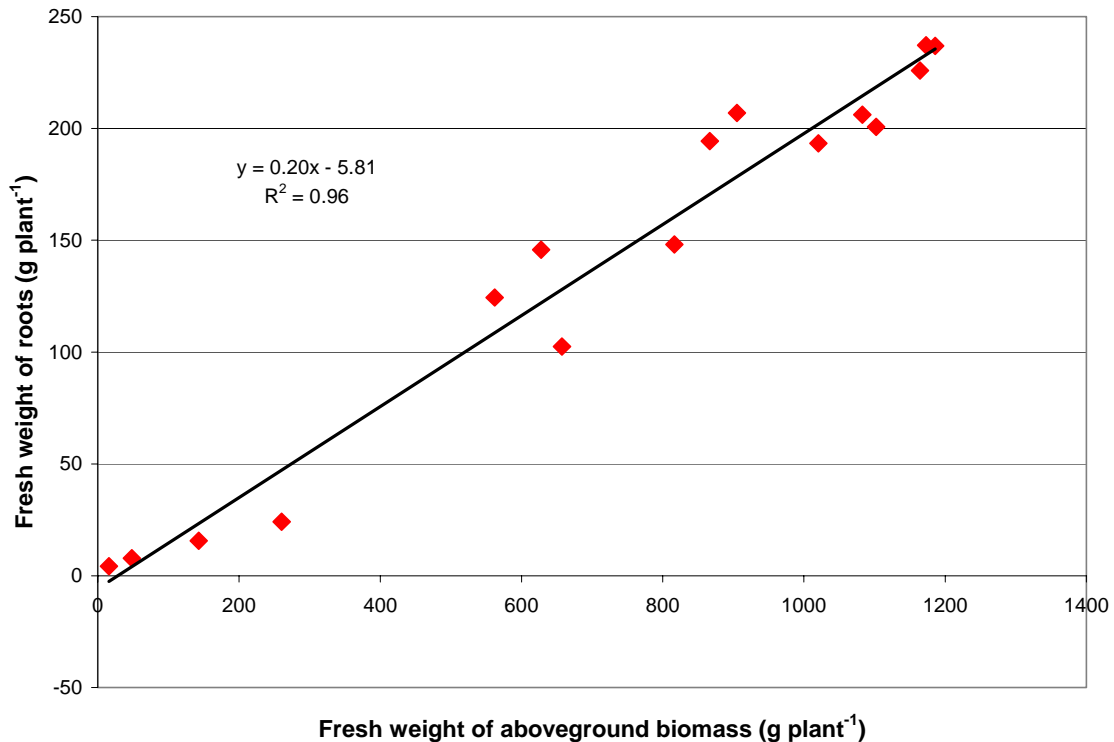


Fig. 11. Relationship between the fresh weight of aboveground biomass and fresh weight of roots. Field experiment in 2002 on a Ships soil series.

The overall data (Fig. 11) showed that the relationship between the mean fresh weight of aboveground biomass and mean fresh weight of roots was linear ($R^2 = 0.962$, $P > F$ was < 0.0001), although a second degree polynomial fit slightly better: $y = -2E-05x^2 + 0.22x - 9.67$, $R^2 = 0.963$, $P > F$ was < 0.0001 . This relationship was developed over time in the field, from 24 days after planting to harvest. The aboveground biomass and root biomass of the corn plants increased and decreased proportionally.

The relationship between root biomass and aboveground biomass is called root index, or root:shoot ratio. This relationship means that if the fresh weight of aboveground biomass increases so does the fresh weight of the root biomass. Sometimes this relationship is reversed and called shoot:root ratio.

Data in Fig. 12 shows that the individual aboveground biomass and root data fit a linear model ($R^2 = 0.871$, $p < 0.0001$), but a second grade polynomial fits slightly better ($R^2 = 0.873$, $p < 0.0001$). When 7 biased data points were eliminated, the data fit better (Fig. 13) to a second degree polynomial ($R^2 = 0.92$, $p < 0.0001$) than a linear model: $y = 0.20x - 13.39$, $R^2 = 0.91$, and $p < 0.0001$.

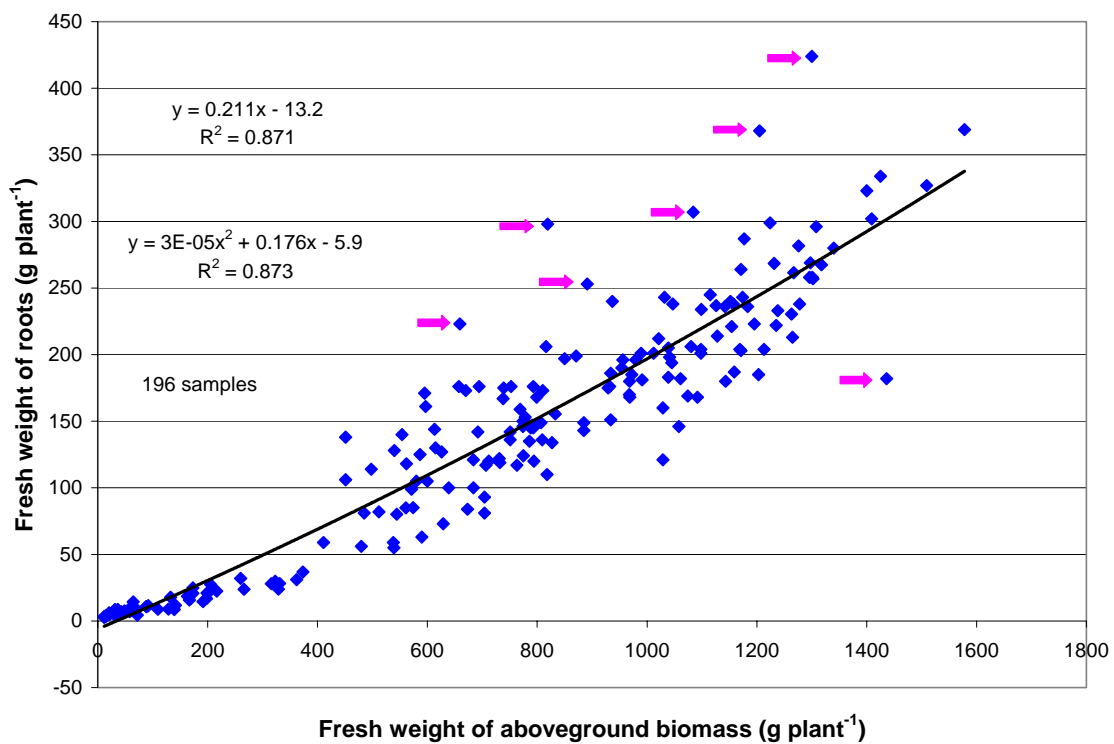


Fig. 12. Relationship between the fresh weight of aboveground biomass and fresh weight of roots, using all original data. Field experiment in 2002 on a Ships soil series.

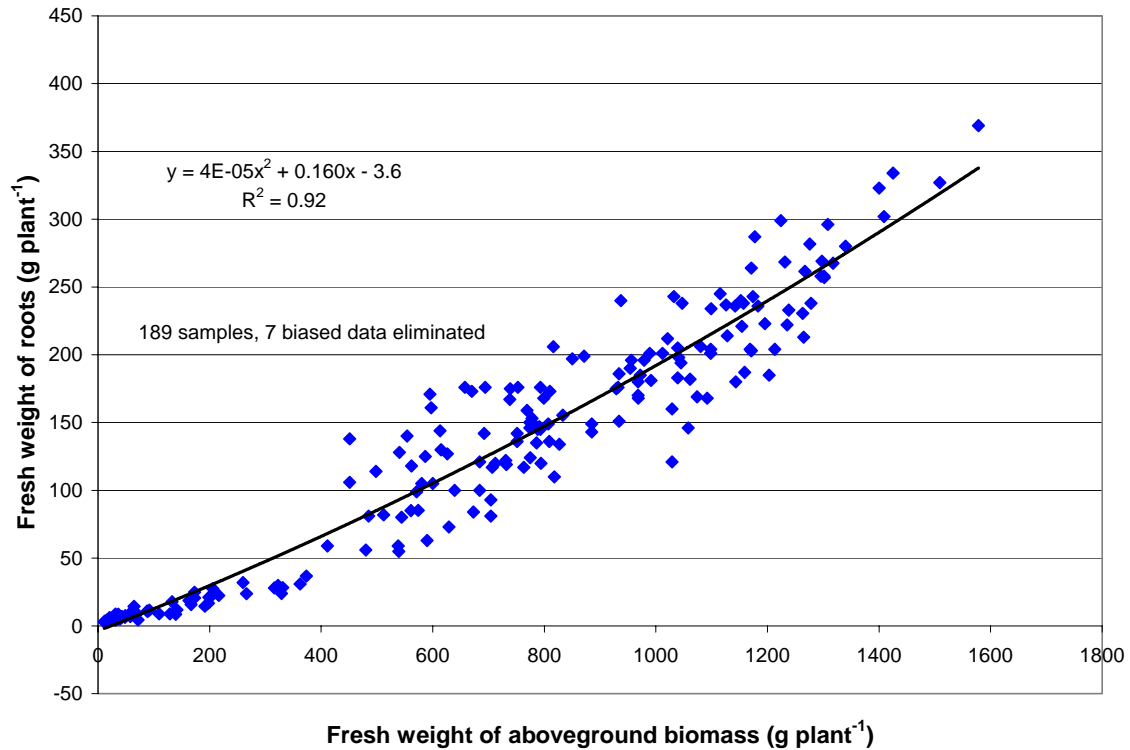


Fig. 13. Relationship between the fresh weight of aboveground biomass and fresh weight of roots, eliminating 7 biased data. Field experiment in 2002 on a Ships soil series.

Eliminating the 7 data points resulted in the elimination of 3.5% of the data. The reason for eliminating these data is based on a visual analysis. One plant grew over a rock, with a higher aboveground biomass (agb) compared to roots. Three corn plants showed a lower growth of aboveground biomass compared to the roots. This effect was more noticeable on roots growing in soil with a hard sublayer, in which loose soil was no deeper than 10 cm. Two plants showed serious insect damage on the foliage. One outlier resulted from one plant being drier than the rest of the population. Data presented in Fig. 11, 12, and 13 indicated that all relationships between the fresh weight of aboveground biomass and root biomass were very similar. These results indicated that larger aboveground biomass resulted in more root mass. In Fig. 13, the relationship fit better to a second degree polynomial model, but a linear model also worked well. The differences between R^2 values were small. When the data indicated with arrows in Fig. 12 were

eliminated in this analysis, the R^2 values increased to 0.92 and 0.91 for the polynomial and linear models, respectively; both models had a $p < 0.0001$. The linear model was: $y = 0.207x - 13.39$.

Relationships between the dry weight of aboveground biomass and dry weight of roots were also polynomial (Figs. 14, 15, 16 and 17). The original data in Fig. 14 had a lower R^2 ($R^2 = 0.69$ and $p < 0.0001$). The linear equation for Fig 14 is $y = 0.098x + 5.96$ with a $R^2 = 0.65$ ($p < 0.0001$). Figure 15 shows the adjusted data accord with estimated moisture content set for sampling number 7 and 8. The linear equation for Fig. 15 was $y = 0.093x + 8.10$, $R^2 = 0.57$ and $p < 0.0001$. Adjusting the data didn't increase the R^2 ($R^2 = 0.66$ and $p < 0.0001$). The data in Fig. 15 shows the original dry weight of aboveground biomass in axis "x" which were recalculate accord to the following procedure: the linear equation in Fig. 14 (page 43) was used to estimate the moisture content for sampling number 7 and 8. This average moisture content obtained by interpolation was used to estimate each one of the dry weight of aboveground biomass for the same samplings. This calculation was possible given that the fresh weight of aboveground biomass was recorded. Those corrected data were used in Figs. 17 and 19. This is the reason why in Fig. 19 the sampling numbers 7 and 8 didn't present a variation in the moisture content of aboveground biomass.

Regression using the means showed a clearer tendency (Figs. 16 and 17). Although a cubic polynomial fits better ($p < 0.0001$), so does a quadratic polynomial. The quadratic polynomial for Fig. 16 is $y = -0.0004x^2 + 0.25x - 0.16$, $R^2 = 0.95$ and $p < 0.0001$. The quadratic polynomial for Fig. 17 is $y = -0.0005x^2 + 0.28x - 0.52$, $R^2 = 0.92$ and $p < 0.0001$. Both Figs. 16 and 17 show a line which joins the points according with the sequence when they were sampled. This form to analyze the data showed the error in the moisture content of the dry weight of aboveground biomass. Data set samplings 7 (87 dap) and 8 (94 dap) show an error in calculation of dry weight.

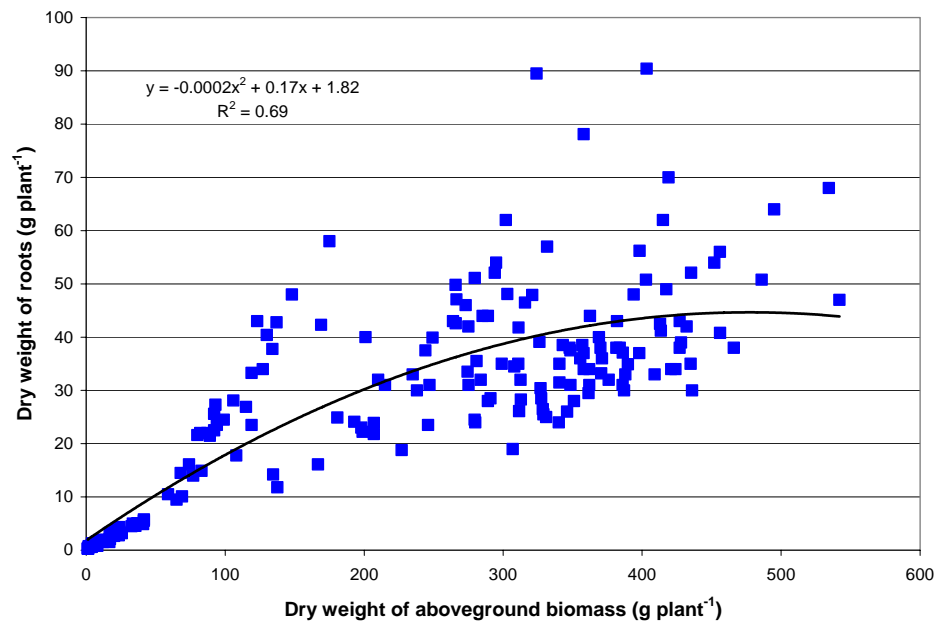


Fig. 14. Relationship between the dry weight of aboveground biomass and dry weight of roots. Original data. Field experiment in 2002 on a Ships soil series.

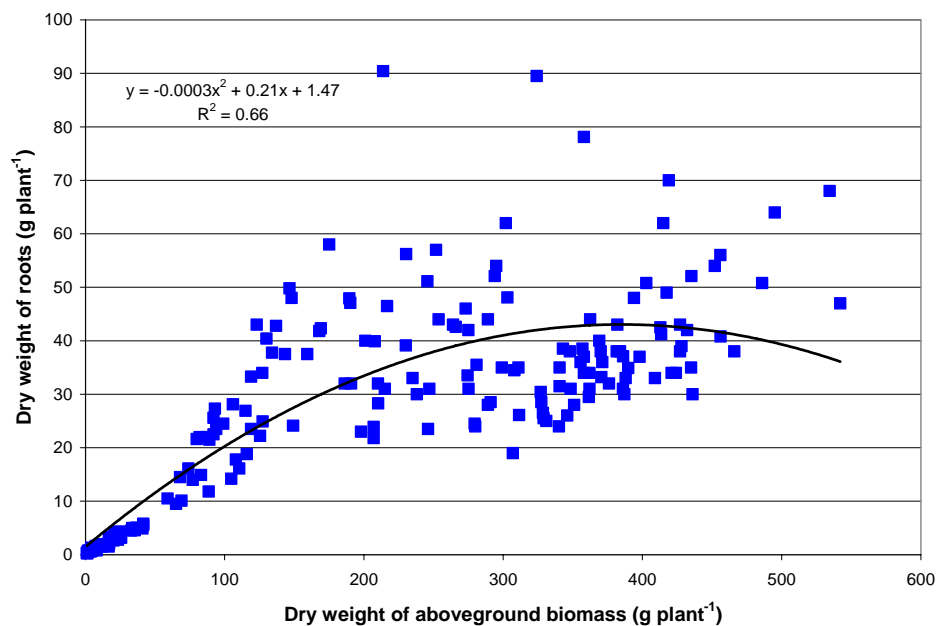


Fig. 15. Relationship between the dry weight of aboveground biomass and dry weight of roots. Data set from sampling number 7 and 8 were adjusted by interpolation. Field experiment in 2002 on a Ships soil series.

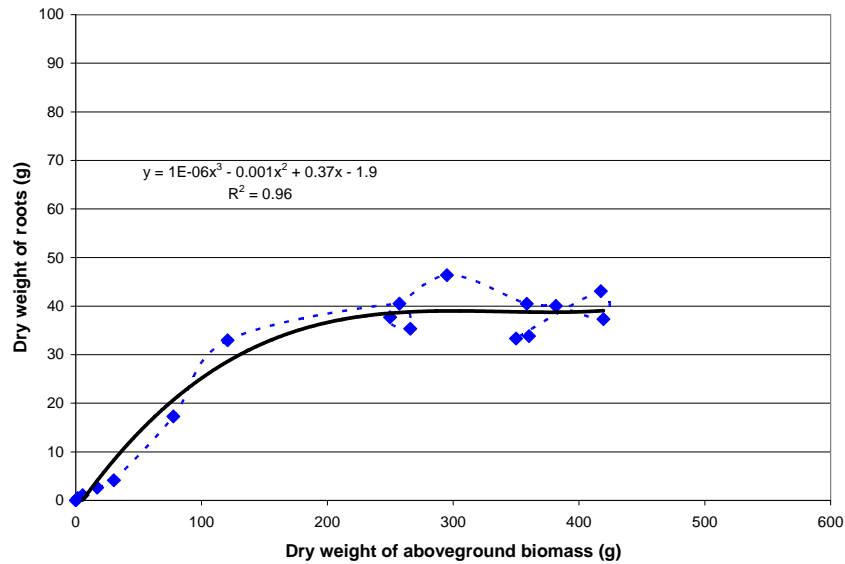


Fig. 16. Relationship between the means of dry weight of aboveground biomass and dry weight of roots at each sampling date. Original data are represented by individual points. Solid line represents the equation. Dashed line joins points in chronological sequence. Field experiment in 2002 on a Ships soil series.

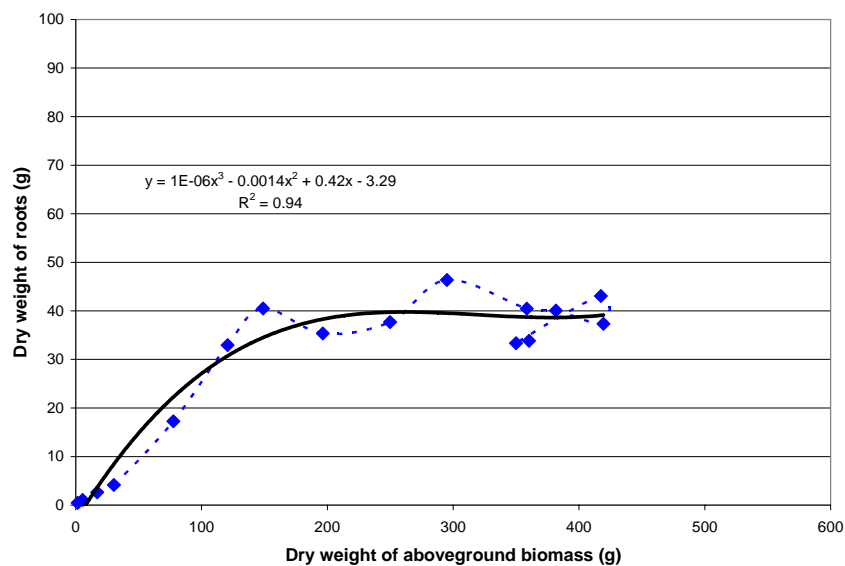


Fig. 17. Relationship between the means of dry weight of aboveground biomass and dry weight of roots. Data set from sampling number 7 and 8 were adjusted by interpolation. Original data are represented by individual points. Solid line represents the equation. Dashed line joins points in chronological sequence. Field experiment in 2002 on a Ships soil series.

Moisture content

The plant moisture content is needed for the conceptual model, but it must be stable and constant. The conceptual model could theoretically be used at any time, but given that the moisture content changed with time, it is necessary to consider these changes through time. The moisture content in roots was more stable than the moisture in the aboveground biomass, but was less predictable (Fig. 18). It was less predictable because there wasn't as much change over time so small variations in results had greater effects.

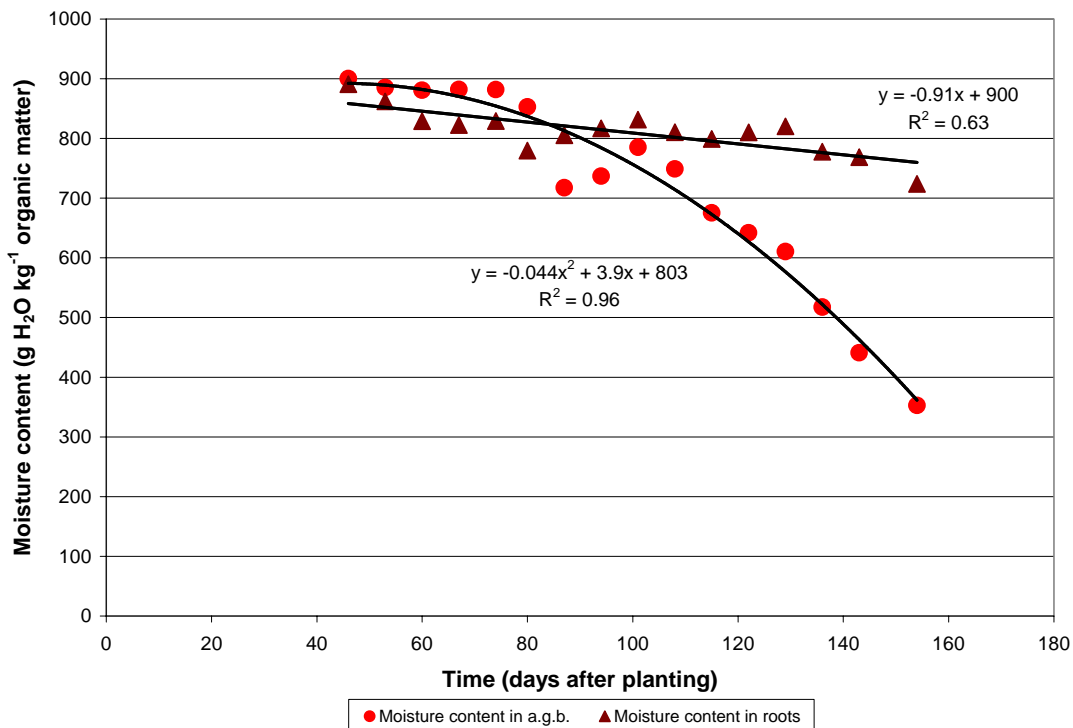


Fig. 18. Change in moisture content of corn aboveground biomass and roots over time in a field experiment in 2002 on a Ships soil series.

Although the moisture content of roots was more linear ($p < 0.0002$), the coefficient of determination (R^2) was low compared with the polynomial model of the moisture content of aboveground biomass (m.c.a.g.b.) in which the R^2 was high ($p < 0.0001$). The R^2 of the m.c.a.g.b. should be higher but there were some problems

with drying the samples from sampling numbers 7 and 8 at 87 and 94 days after planting, respectively. Eliminating these two sample sets and then adjusting to a polynomial model resulted in:

$$y = -0.057x^2 + 6.3x + 716 \dots\dots\dots (1)$$

$$R^2 = 0.99$$

$$n = 14, p < 0.0001$$

Adjusting (interpolating) these two samples sets resulted in:

$$y = -0.057x^2 + 6.27x + 718 \dots\dots\dots (2)$$

$$R^2 = 0.99$$

$$n = 16, p < 0.0001$$

The R^2 of m.c.a.g.b. increased after eliminating or interpolating these two data points. The problem with these two data sets was that there was not enough space in the ovens to dry the corn samples and not enough time was allowed to permit the samples to dry completely. In future analysis, data of dry weight of aboveground biomass will be presented as original and adjusted using the moisture content interpolated data from the equation (2).

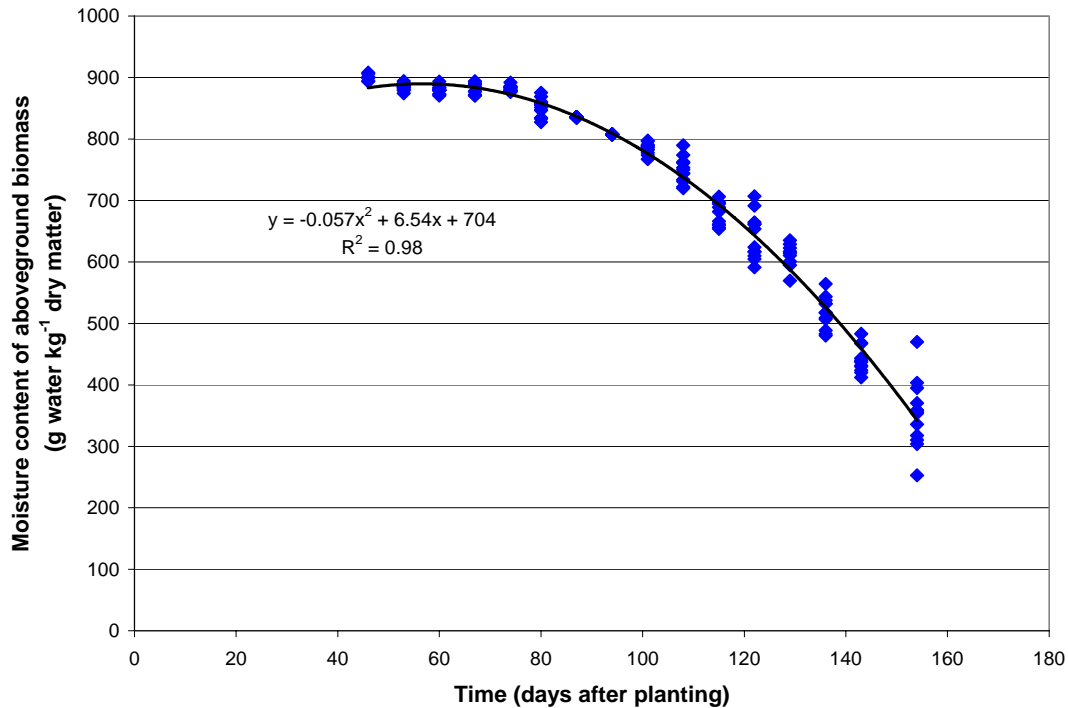


Fig. 19. The behavior of the moisture content of aboveground biomass after planting. All original data, except samplings 87 and 94 days after planting which were estimated using the following equation: $y = -0.057x^2 + 6.2x + 718$. $R^2 = 0.99$, $p < 0.0001$. Field experiment in 2002 on a Ships soil series.

Using all the data to establish the behavior of the moisture content of aboveground biomass gave a polynomial model with a high coefficient of determination ($R^2 = 0.98$, $p < 0.0001$) (Fig. 19). The data from 87 and 94 days after planting (dap) were interpolated. The variation in moisture content was higher at 154 dap compared with 40 dap (Fig. 19). The moisture content of the plant decreased throughout its growth cycle. This is a natural physiological mechanism, which is influenced by environmental conditions, principally precipitation, moisture content of the atmosphere, solar radiation, and wind.

Although the relationship between the fresh and dry weights of aboveground biomass was not close and apparently didn't follow a regular pattern (Fig. 20), the moisture content of aboveground biomass was predictable over time (Figs. 18 and 19).

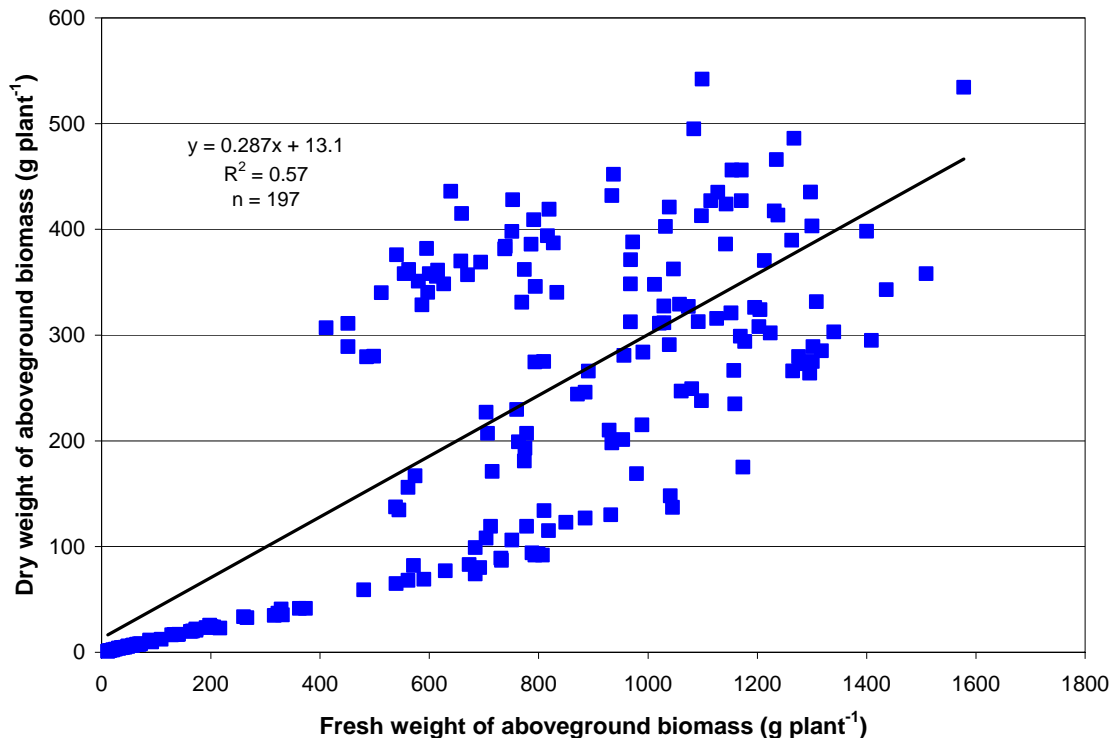


Fig. 20. Relationship between fresh and dry weights of aboveground biomass. Original data are represented by individual points. P value was <0.0001 . Field experiment in 2002 on a Ships soil series.

Data in Fig. 20, 21, 22 and 23 show the relationship between the fresh and the dry weights of aboveground biomass. Figure 20 shows the original data, Figure 21 shows the fitted data by interpolation of sampling numbers 7 and 8, and Fig. 22 shows mean data. Figure 23 includes a “z” axis: the time after planting. In this case, time is important because fresh and dry weights of a.g.b. were changing with time (Fig. 23). In Figs. 22 and 23, the dashed line represents an expected tendency. Corn plants were expected to lose moisture content, but not corn dry matter. In Figs. 22 and 23, the last two data

points showed a lower a.g.b. dry weight than the four previous points. It was probably because the corn plants were too dry or material was lost in transport from the field to the laboratory. Another possible reason is that these two samples sets were separated into all their components (leaves, stems, tassels, husks, grain, and cobs) and they may have lost more water than previous samples that were not separated into components. This assumption would imply that previous samples were not dried as much.

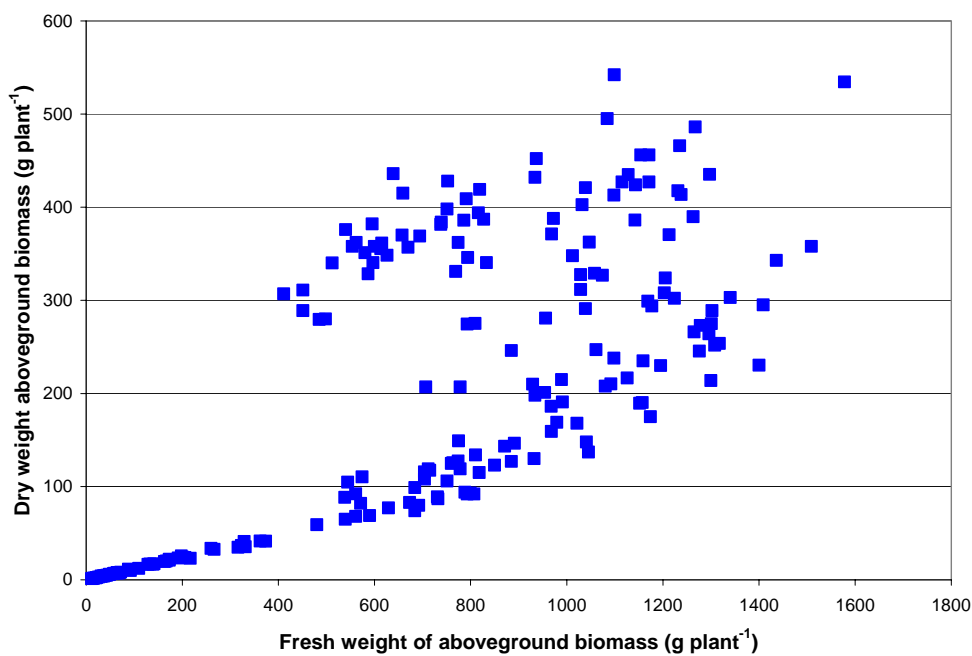


Fig. 21. Relationship between fresh and dry weight of aboveground biomass. The data from sampling numbers 7 and 8 were adjusted by interpolation. Field experiment in 2002 on a Ships soil series.

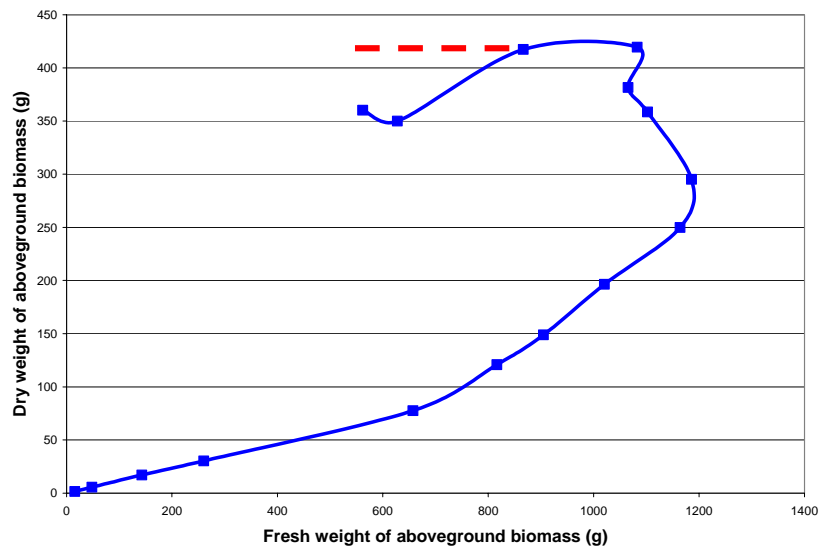


Fig. 22. Relationship between mean fresh and dry weights of aboveground biomass. Sampling numbers 7 and 8 were adjusted using interpolation. The dashed line represents the expected tendency. The solid line represents the time sequence in which the data were taken. Field experiment in 2002 on a Ships soil series.

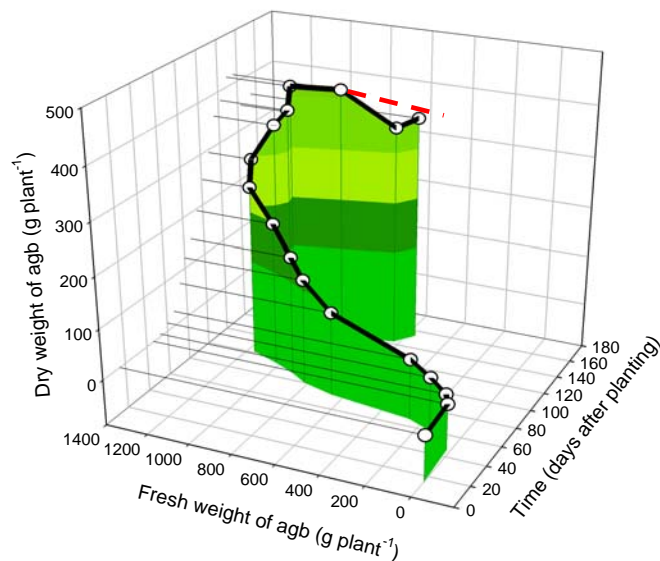


Fig. 23. Relationship between mean fresh and dry weights of aboveground biomass (agb) relative to time. Sampling numbers 7 and 8 were adjusted using interpolation. The dashed line represents the expected tendency. Field experiment in 2002 on a Ships soil series.

A close relationship between the fresh and dry weights of corn vegetative parts is important in order to use the weighted average of the moisture content in the model (the H factor). This relationship was closer for roots compared to above ground biomass which showed a higher variability in moisture content (Ritchie et al., 1997; Osborne et al., 2002). This was because roots were more protected in the soil than the aboveground biomass, so roots lost less water over time. Changes in root water content were lower than changes in moisture content of aboveground biomass.

Data in Fig. 24 show that the relationship between the fresh and dry weight of roots was adequately described by linear regression ($p < 0.0001$). This relationship included all data collected in the field for the entire life cycle of the corn crop. This relationship also indicates that the higher the fresh weight of roots, the higher the dry weight of roots. On the other hand, the slope is the average of the root dry matter content, and the inverse of the slope is the root moisture content. The average moisture content was around 80 %, which is accord with figure 18 (pag. 47), where the maximum moisture content was about 90 % and the minimum was 70 %.

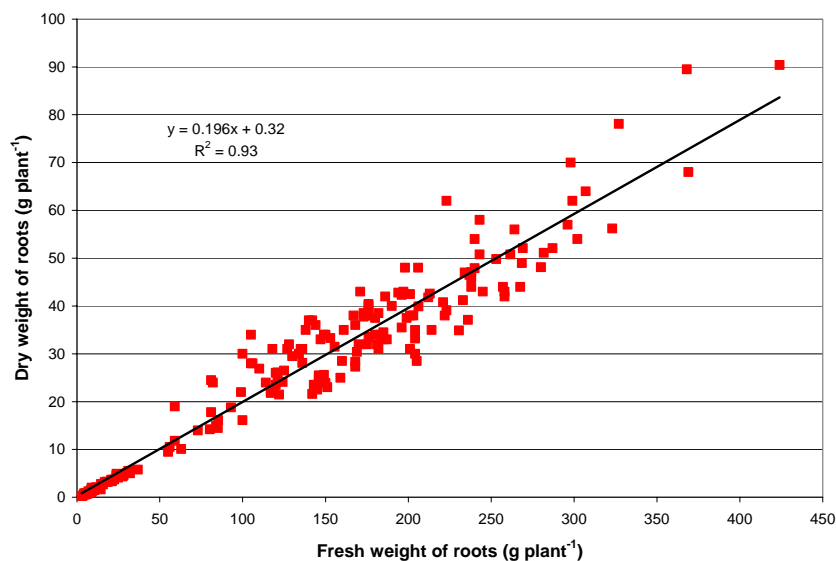


Fig. 24. Relationship between the fresh weight and dry weight of roots along the entire growth cycle of corn. Field experiment in 2002 on a Ships soil series.

Data in Fig. 25 show the linear relationship between the fresh and dry weight of corn grains for data from July 13, 2002 (Table 3). All the data showed linear relationships (Table 3). Fig. 25 shows an example of the association of the data of fresh and dry weight of corn grains. This distribution was similar for all samplings. In Table 3 and subsequent Tables the identification is as follow: the places Ships 143 dap and Ships 154 dap means the sampling taken in the Texas A&M University Experiment Station in a Ships soil series (clayed soil) at 143 and 154 days after planting (dap) the corn. All the samplings were taken in the field in 2002. Weswood East and West means that the samples came from a private field with a Weswood soil series (silt loam soil) divided in East and West because of soil variability. Ships Dekalb 687 identified the samples which came from a field at the Texas A&M University Experiment Station in a Ships soil series which had Dekalb 687 corn variety. All the rest experiments were established with Pioneer 32R25 corn variety.

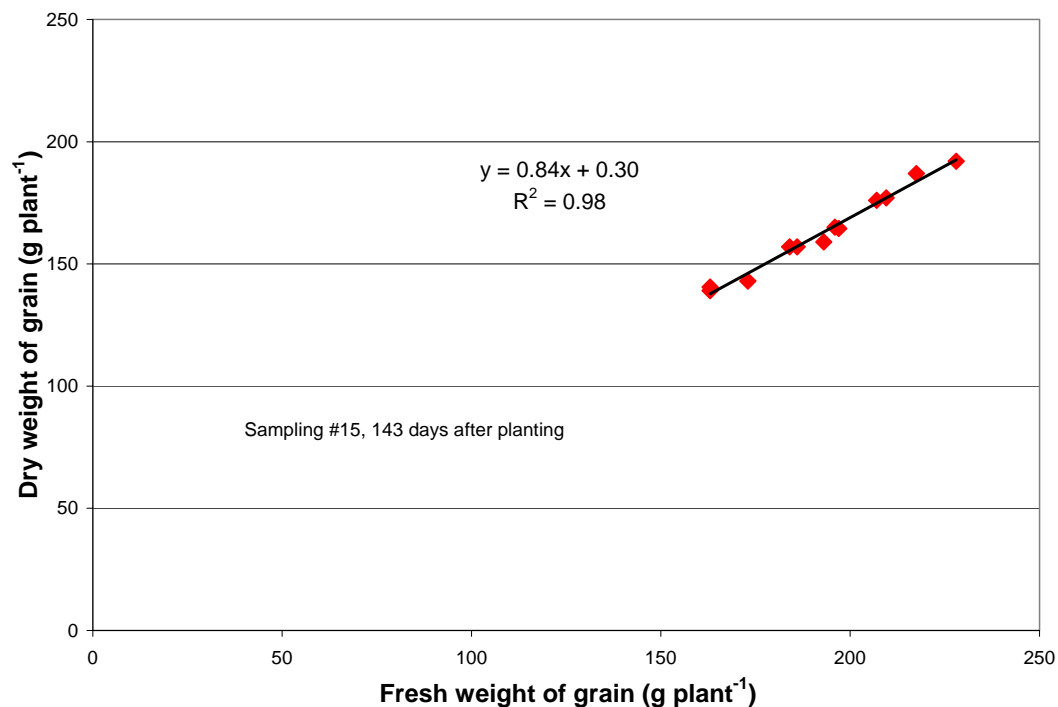


Fig. 25. Relationship between fresh weight and dry weight of grain. Field experiment in 2002 on a Ships soil series.

The data from the Table 3 suggest that the relationship between the fresh and dry weight of corn grain is high. This indicates that a weighted average is possible to estimate the dry weight using the moisture content in the expression $(1-H)$, where H is the weighted average of moisture content.

Table 3. Relationship between fresh and dry weights of corn grain in 2002 at different sampling times and locations.

| Soil | Cultivar | dap† | Date of sampling | Regression | P>F | R ² | n‡ |
|--------------|------------|------|------------------|---------------------|---------|----------------|----|
| Ships | P32R25 | 143 | July 13 | $y = 0.84x + 0.30$ | <0.0001 | 0.98 | 12 |
| Weswood East | P32R25 | 152 | July 20 | $y = 0.87x - 1.26$ | <0.0001 | 0.99 | 12 |
| Weswood West | P32R25 | 153 | July 21 | $y = 0.86x - 0.69$ | <0.0001 | 0.99 | 12 |
| Ships | P32R25 | 154 | July 24 | $y = 0.54x + 67.36$ | <0.0001 | 0.81 | 13 |
| Ships | Dekalb 687 | 163 | August 3 | $y = 0.90x + 0.22$ | <0.0001 | 0.99 | 14 |

† days after planting

‡ number of samples.

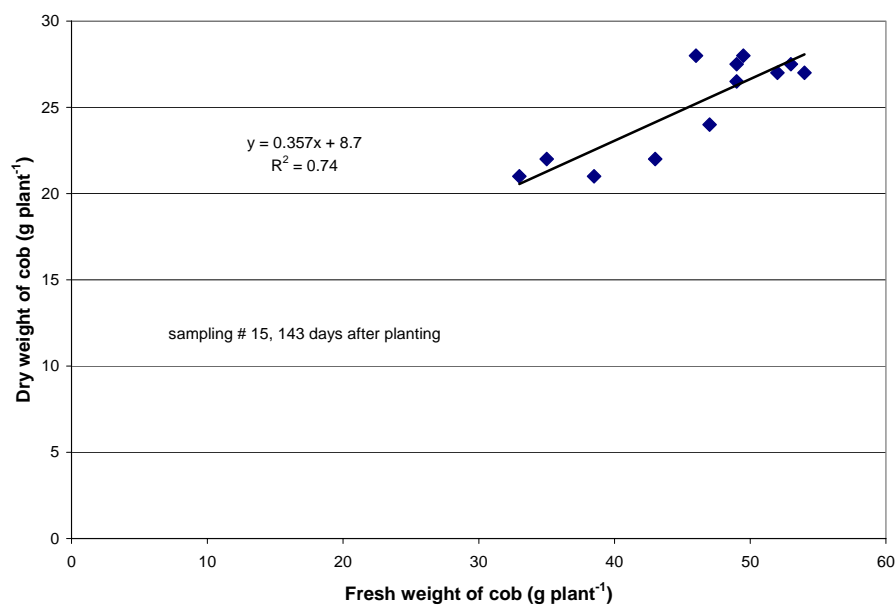


Fig. 26. Relationship between fresh weight and dry weight of cob taken July 13, 2002 at the Texas A&M University Agricultural Experiment Station Farm on a Ships soil series.

Table 4. Relationship between fresh and dry weights of corn cobs in 2002 at different sampling times and locations.

| Soil | Cultivar | dap† | Date of sampling | Regression | P>F | R ² | n‡ |
|---------|------------|------|------------------|---------------------|---------|----------------|----|
| Ships | P32R25 | 143 | July 13 | $y = 0.35x + 8.75$ | 0.0003 | 0.74 | 12 |
| Weswood | P32R25 | 152 | July 20 | $y = 0.49x + 3.36$ | <0.0001 | 0.96 | 12 |
| East | | | | | | | |
| Weswood | P32R25 | 153 | July 21 | $y = 0.53x + 2.33$ | <0.0001 | 0.92 | 12 |
| West | | | | | | | |
| Ships | P32R25 | 154 | July 24 | $y = 0.27x + 16.11$ | 0.0218 | 0.39 | 13 |
| Ships | Dekalb 687 | 163 | August 3 | $y = 0.84x + 1.39$ | <0.0001 | 0.97 | 14 |

† days after planting

‡ number of samples.

Linear relationships between the fresh and dry weights of corn cobs were also observed (Table 4). The lower R² from data for July 13 (Fig. 26) and July 24 probably resulted because some corn plants had two ears, however some of them didn't have grain. In these cases, only cobs were developed but they were drier than usual (the secondary ear). Linear relationships between the fresh and dry weights of husk were developed (Table 5 and Fig. 27). In general, the fresh and dry weights of roots, corn grains, cob, and husks maintained linear relationships. The relationship between the aboveground biomass and corn grain yield was higher on a dry-weight than on a fresh-weight basis. The fresh and dry weights of aboveground biomass did not result in a linear relationship (Fig. 23).

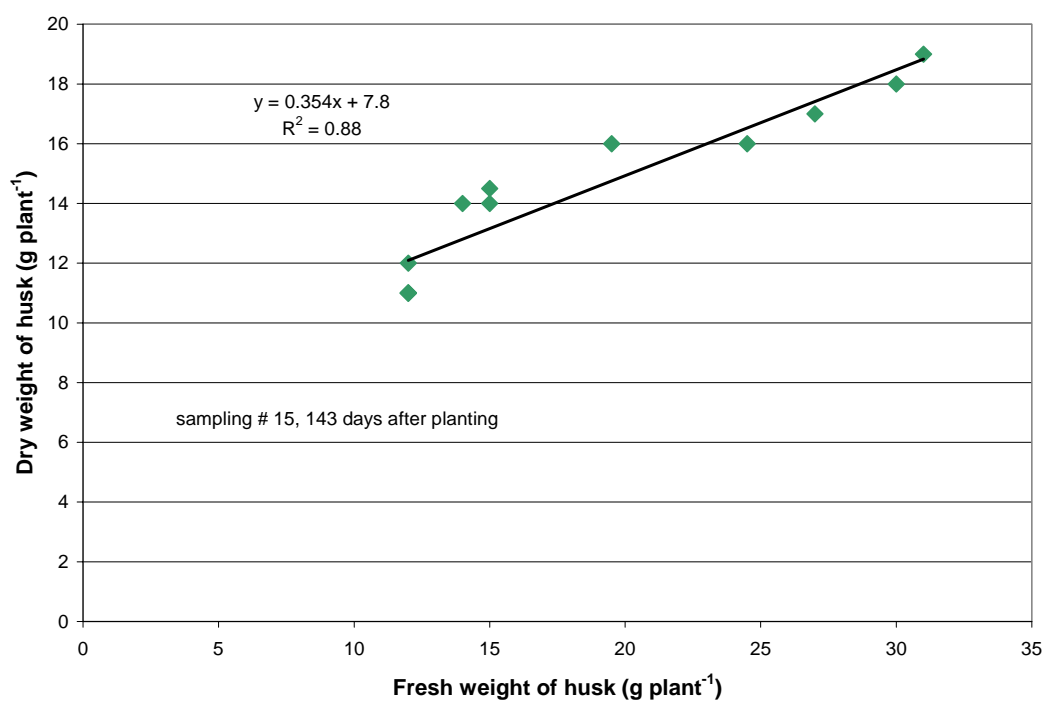


Fig. 27. Relationship between the fresh and dry weights of corn husks 143 days after planting at the Texas A&M University Agricultural Experiment Station Farm on a Ships soil series in 2002.

Table 5. Relationship between the fresh and dry weights of corn husks in 2002 at different sampling times and locations.

| Soil | Cultivar | dap† | Date of sampling | Regression | P>F | R ² | n‡ |
|--------------|------------|------|------------------|--------------------|---------|----------------|----|
| Ships | P32R25 | 143 | July 13 | $y = 0.35x + 7.83$ | <0.0001 | 0.88 | 12 |
| Weswood East | P32R25 | 152 | July 20 | $y = 0.77x + 1.00$ | 0.0002 | 0.76 | 12 |
| Weswood West | P32R25 | 153 | July 21 | $y = 0.66x + 2.30$ | <0.0001 | 0.86 | 12 |
| Ships | P32R25 | 154 | July 24 | $y = 0.61x + 4.64$ | 0.0002 | 0.73 | 13 |
| Ships | Dekalb 687 | 163 | August 3 | $y = 0.62x + 3.70$ | <0.0001 | 0.90 | 14 |

† days after planting

‡ number of samples.

Harvest index

The result of the relationship between the dry weight of total aboveground biomass and dry weight of corn grain is called the harvest index (H.I.). The H.I. reported for corn ranges from 0.30 to 0.50 on a dry-weight basis (Austin et al., 1980; Riggs et al., 1981).

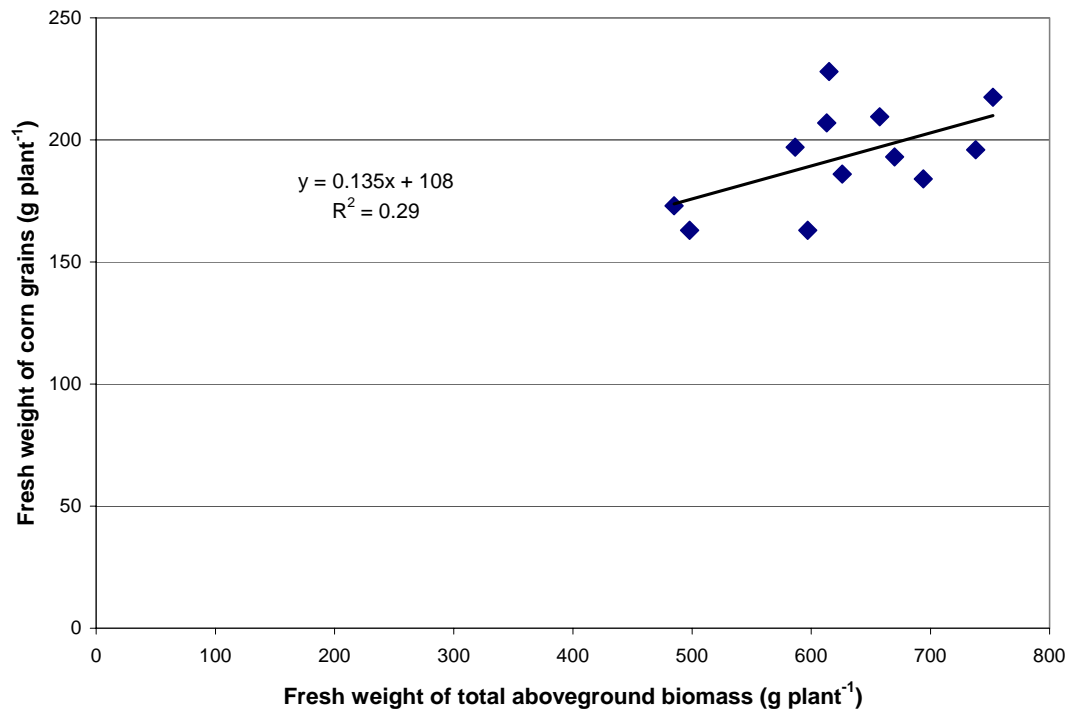


Fig. 28. Relationship between the fresh weight of total aboveground biomass and the fresh weight of corn grain. Samples were taken on 13 July 2002 at Texas A&M University Agricultural Experiment Station Farm on a Ships soil 143 days after planting.

Relationships between total aboveground biomass and corn yield were stronger on a dry compared with a fresh-weight basis (Table 6). For the samplings shown in Table 6, the relationships were linear (Fig. 28). The lower R^2 values for data taken on July 13, 2002 was probably because grain was not yet mature and was still gaining weight. Eleven days later (July 24, 2002) at the same experimental location the data showed an increase in the R^2 .

Table 6. Relationships between the fresh and dry weights in 2002 of total aboveground biomass (x) and fresh and dry weights of corn grain (y). Units are in g plant⁻¹.

| Soil | Cultivar | dap† | Date of sampling | Regression | P>F | R ² | n‡ |
|--------------------|------------|------|------------------|-------------------|---------|----------------|----|
| Fresh weight basis | | | | | | | |
| Ships | P32R25 | 143 | July 13 | $Y = 0.13x + 108$ | 0.0679 | 0.29 | 12 |
| Weswood East | P32R25 | 152 | July 20 | $Y = 0.38x - 16$ | <0.0001 | 0.92 | 12 |
| Weswood West | P32R25 | 153 | July 21 | $Y = 0.31x + 6$ | <0.0001 | 0.91 | 12 |
| Ships | P32R25 | 154 | July 24 | $Y = 0.34x + 18$ | 0.0024 | 0.58 | 13 |
| Ships | Dekalb 687 | 163 | August 3 | $Y = 0.21x + 62$ | <0.0001 | 0.74 | 14 |
| Dry weight basis | | | | | | | |
| Ships | P32R25 | 143 | July 13 | $Y = 0.31x + 53$ | 0.0069 | 0.53 | 12 |
| Weswood East | P32R25 | 152 | July 20 | $Y = 0.56x - 19$ | <0.0001 | 0.97 | 12 |
| Weswood West | P32R25 | 153 | July 21 | $Y = 0.48x - 3$ | <0.0001 | 0.95 | 12 |
| Ships | P32R25 | 154 | July 24 | $Y = 0.54x - 12$ | <0.0001 | 0.82 | 13 |
| Ships | Dekalb 687 | 163 | August 3 | $Y = 0.39x + 22$ | <0.0001 | 0.90 | 14 |

† days after planting

‡ number of samples.

Yield

The maximum yield for corn Pioneer 32R25TM during 2002 under field conditions was 311 grams of grain per plant in a fresh weight basis (Table 7). This yield was attained by a plant growing in Ships soil at the Texas A&M University Research Farm, and was harvested 154 days after planting. The largest difference in grain yield between plants occurred on the west side of the farmer cooperator's field on a Weswood soil. This range difference was 166 grams of grain on a fresh weight basis and represented 64% of the maximum yield for that sampling at that location. The corn yields in table 7 are in accord with data reported under different conditions under dryland (Mislevy et al., 2001; Wright et al., 2002)

Table 7. Means and ranges of corn grain yield using fresh and dry weights in 2002 at different sampling times and locations.

| Soil | Cultivar | dap† | Mean | S.D.‡ | C.V.§ | Minimum | Maximum | Difference |
|----------------------------|----------|------|---------------------------------|-------|-------|-----------------------------------|---------|------------|
| Fresh weight basis | | | | | | | | |
| sampling | variety | days | ----- g plant ⁻¹ --- | % | | ----- g plant ⁻¹ ----- | | |
| Ships | P32R25 | 143 | 193 | 20 | 10 | 173 | 228 | 55 |
| Ships | P32R25 | 152 | 213 | 42 | 19 | 168 | 311 | 143 |
| Weswood | P32R25 | 153 | 129 | 38 | 30 | 71 | 208 | 137 |
| East | | | | | | | | |
| Weswood | P32R25 | 154 | 180 | 43 | 24 | 93 | 259 | 166 |
| West | | | | | | | | |
| Ships | Dekalb | 163 | 141 | 19 | 14 | 112 | 184 | 72 |
| | 687 | | | | | | | |
| Dry weight basis | | | | | | | | |
| Ships | P32R25 | 143 | 163 | 17 | 10 | 139 | 192 | 53 |
| Ships | P32R25 | 152 | 183 | 25 | 13 | 151 | 248 | 97 |
| Weswood | P32R25 | 153 | 111 | 34 | 30 | 62 | 181 | 119 |
| East | | | | | | | | |
| Weswood | P32R25 | 154 | 154 | 37 | 24 | 78 | 221 | 143 |
| West | | | | | | | | |
| Ships | Dekalb | 163 | 127 | 17 | 14 | 101 | 168 | 67 |
| | 687 | | | | | | | |
| † days after planting | | | | | | | | |
| ‡ standard deviation | | | | | | | | |
| § coefficient of variation | | | | | | | | |

Greater variation in yield for corn growing on Weswood soil was probably due to higher variation in soil conditions. In fact, soil variation was the reason to divide the parcel into two parts, east and west. According to the farmer cooperator, the soil characteristics were different on both sides of the field, in spite of the surface soil color being similar.

Components of corn plants

Data in Table 8 show that grains represented the highest percentage of the corn plant on a dry weight basis. Corn grain represented about 42 % of the total dry weight of corn plants. This represents a H.I. of 42 on a dry-weight basis for this sampling date (136 dap). Each component of corn plants had a different variation. Tassel showed the greatest variation of all components. This is because the weights of tassels were low, and small changes in weight produced high variation. Tassels had the highest variation, cob had the lowest, and grain had the third lowest variation. All components were selected for comparison at 136 dap because after that date some vegetative parts like silks, tassels, and small parts of leaves began to fall from plants.

Table 8. Relative proportions of the different components of corn plants on a dry weight basis. Samples were taken from the field experiment on the Texas A&M University Agricultural Research Farm in 2002 on a Ships soil 136 days after planting.

| | tassel | husk | cob | roots | leaves | stems | grains |
|----------|--------|------|-----|-------|--------|-------|--------|
| | % | | | | | | |
| Mean (%) | 0.3 | 4.4 | 6.9 | 9.9 | 16.8 | 19.3 | 42.4 |
| S.D. | 0.1 | 0.9 | 0.6 | 2.5 | 1.8 | 2.9 | 5.2 |
| C.V. (%) | 32 | 19 | 9 | 25 | 10 | 15 | 12 |

Greenhouse experiment 2003

Root index

The relationship between the fresh weight of aboveground biomass and roots was low ($R^2 = 0.28$, $p = 0.0004$) compared with field experiment data, even when four data points that showed a deviation from the tendency were eliminated. The four plants representing these data points were re-planted at the beginning of the experiment due to a pest problem. Eliminating these four data points resulted in: $y = 0.30x - 0.57$, $R^2 = 0.54$, $p < 0.0001$ (Fig. 29). The four circled points in Fig. 29 showed atypical behavior compared to the rest of data. Three of the plants showed lower roots weight relative to

aboveground biomass, while one showed apparently higher root weight. Given that the root system was considered to include brace roots on the stem, roots of the plant with higher relative root dry weight (Figs. 29 and 30, circle A) included more brace roots. For data circled B and C, root fresh weight apparently was smaller compared with the corresponding aboveground biomass; however, when dry weights were considered (Fig. 30 circles B and C) they followed a normal tendency. Roots associated with point D showed relatively lower weight compared with the weight of aboveground biomass. This root system was possible smaller because of manual compaction of the soil just after replanting, however, the replanted corn plants produced higher aboveground biomass (Fig. 30). Eliminating points A and D in Fig. 30, the relationship became: $y = 0.06x + 2.6$, $R^2 = 0.53$, $p < 0.0001$.

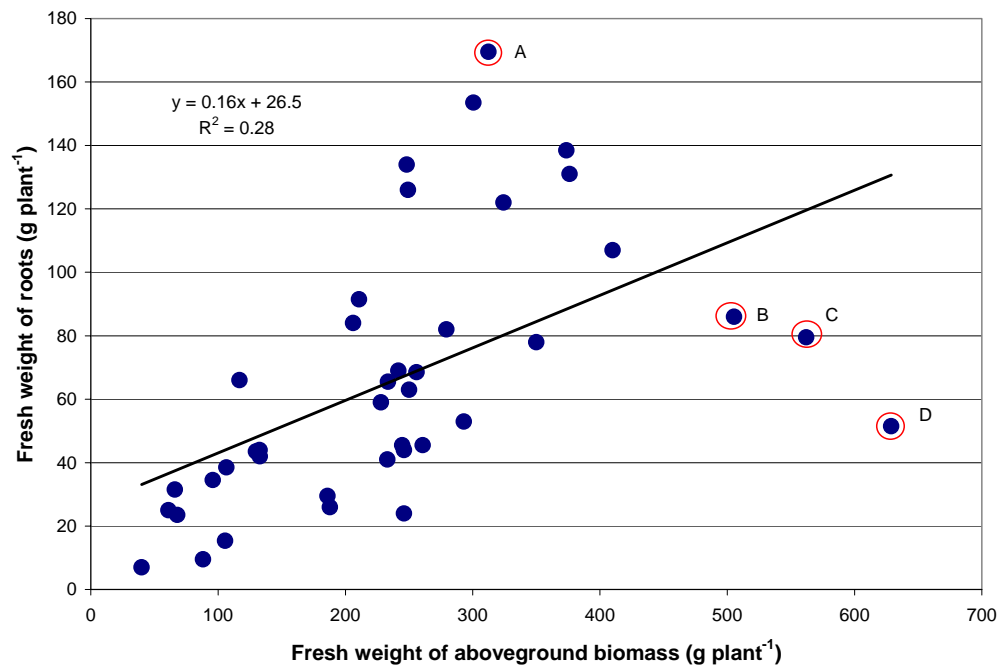


Fig. 29. Relationship between the fresh weight of corn aboveground biomass and fresh weight of roots in the greenhouse study. Both Ships and Weswood soil were included with and without N fertilizer.

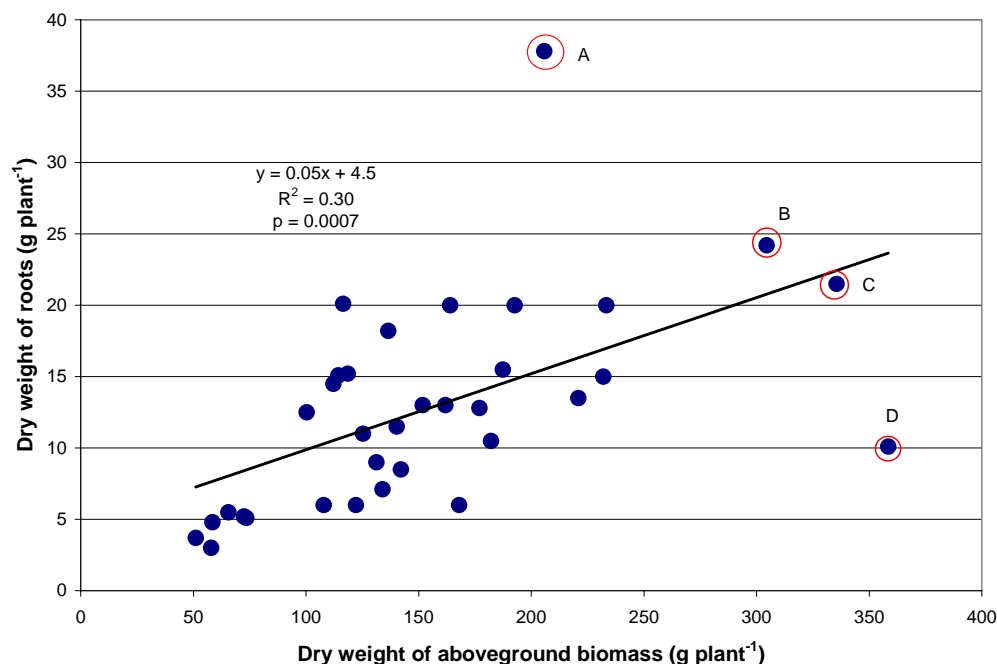


Fig. 30. Relationship between the dry weight of corn aboveground biomass and dry weight of roots in the greenhouse study. Both Ships and Weswood soils were included with and without N fertilizer.

This weak relationship between the fresh weight of aboveground biomass and roots may be due to changes in the root morphology observed in the greenhouse (Figs. 31, 32, 33, and 34). Roots growing in pots in the greenhouse were relatively heavier on a fresh-weight basis and the roots hairs were more numerous and longer than those growing in the field. The R.I. in the field was around 0.22 and 0.09 on fresh-weight and dry-weight bases, respectively, while in the greenhouse they were 0.30 and 0.06 on fresh-weight and dry-weight bases, respectively (Tables 11, 12, and 13). The R.I., expressed on a fresh-weight basis for plants growing in the greenhouse, was higher than in the field due to a greater relative growth of roots in relation with the aboveground biomass. This increased root growth may be due to a wall effect, by a hydraulic gradient which produced a down movement of nutrients and water into a deeper depth, or by a higher absorption or retention of water after washing roots. Retention of water by greenhouse roots was

observed after washing because of the fibrous morphology that acted like a sponge (Figs. 33 and 34).

One reason for high variation between the roots and aboveground biomass was because the roots started to deteriorate by harvest. It was observed that small fragments of roots were separated from the root system.



Fig. 31. Corn roots from a plant grown in Ships clay in a field experiment receiving 179 kg N ha⁻¹. The depth of the roots was approximately 25 cm, which contained more than 98% of the root biomass.



Fig. 32. Corn roots from a plant grown in Weswood silt loam soil in a field experiment receiving 179 kg N ha^{-1} . The depth of roots was around 35 cm which contained more than 98% of the root biomass.



Fig. 33. Corn roots from a plant grown in Ships clay soil in a greenhouse experiment receiving 179 kg N ha^{-1} .



Fig. 34. Corn roots from a plant grown in a Weswood silt loam soil in a greenhouse experiment receiving 179 kg N ha^{-1} .

Moisture content

Data in Figs. 35, 36, and 37 show that the relationships between the fresh and dry weights of roots, aboveground biomass, and grain were different, not only the equations, but also the R^2 's. It is possibly because the roots were washed (with water) before

drying, and they had to be removed from the soil, on the other hand, the moisture content of the aboveground biomass was attained to evapotranspirations process due to environment conditions, and the grains, which presented the higher relationship, was because the protection of the husk to avoid lost of water. A more constant relationship was observed for grain. According to these data, the mean moisture content at harvest for roots was 84%, aboveground biomass was 36%, and corn grain was 18%.

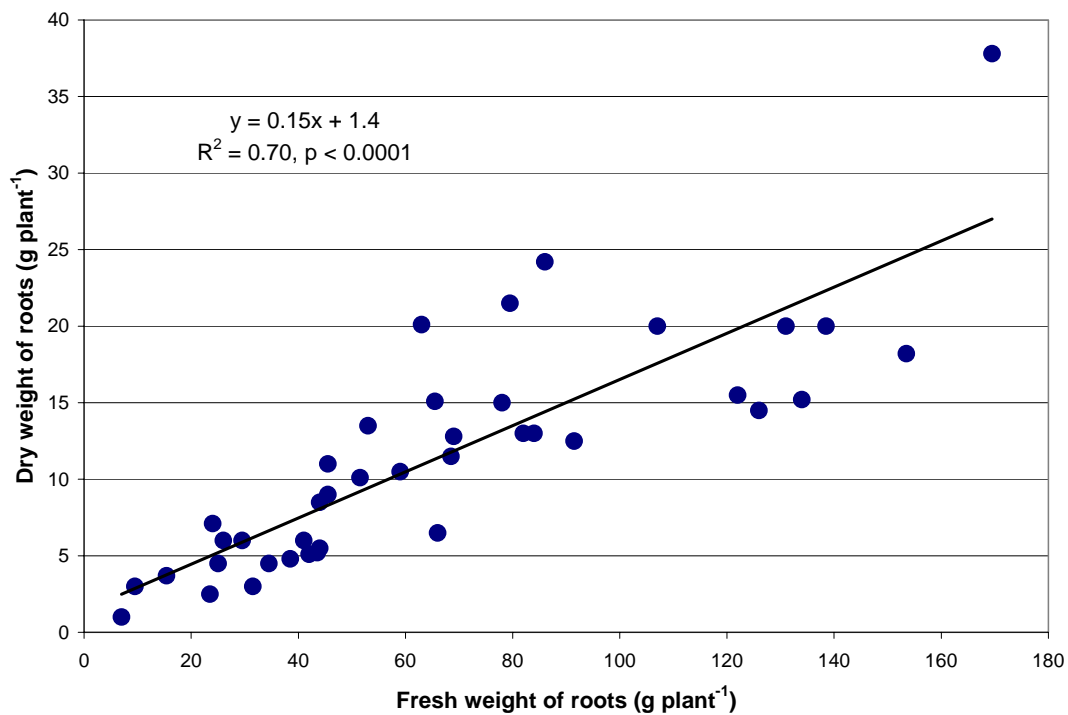


Fig. 35. Relationship between the fresh and dry weight of corn roots in the greenhouse study. Both Ships and Weswood soil were included, with and without N fertilizer.

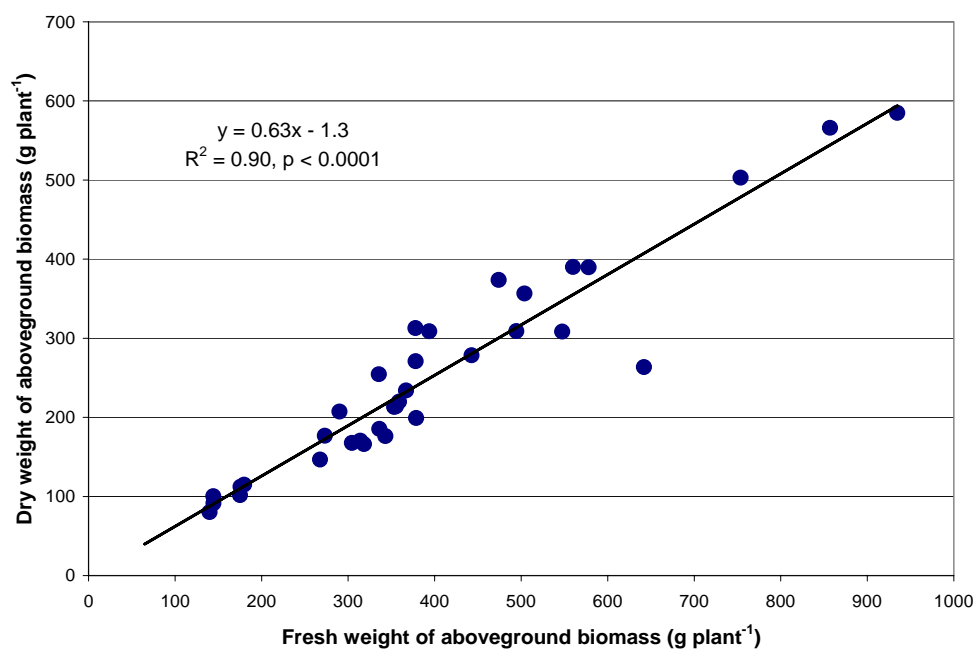


Fig. 36. Relationship between the fresh and dry weight of corn aboveground biomass in the greenhouse study. Both Ships and Weswood soils were included with and without N fertilizer.

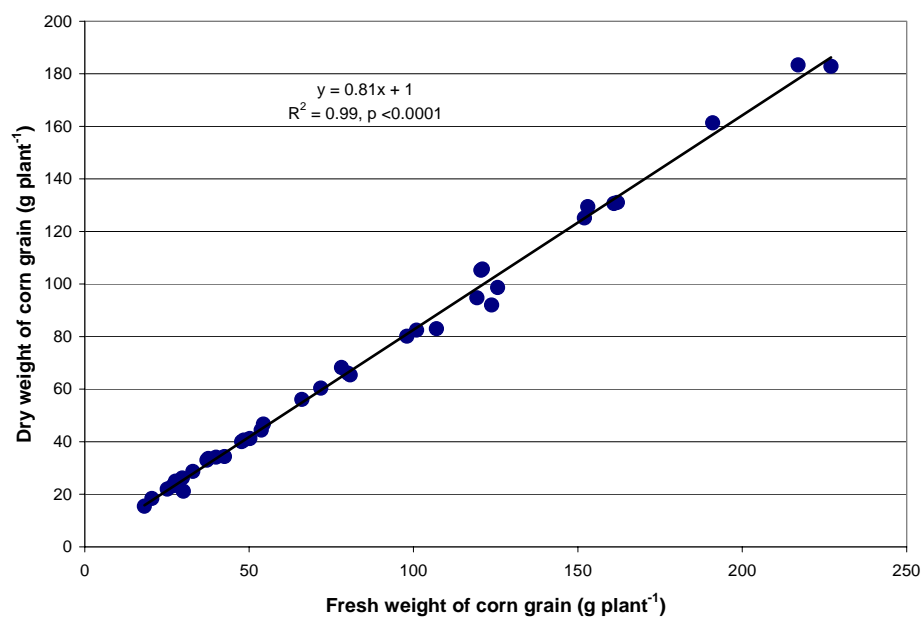


Fig. 37. Relationship between the fresh and dry weight of corn grain in the greenhouse study. Both Ships and Weswood soils were included with and without N fertilizer.

Harvest index

Data in Fig. 38 show the overall relationship between the fresh weight of aboveground biomass and fresh weight of corn grain yield in the greenhouse study. The R^2 of 0.80 indicated a close relationship between both parameters and that the higher the plant biomass, the higher the yield, regardless of soil and fertilization. The H.I. was around 30% or 0.30 grams of corn grain per gram of aboveground biomass ($0.30 \text{ g grain g}^{-1} \text{ agb}$). This H.I. was generally lower than that obtained from the field in 2002 and 2003. In the field, the H.I. on a fresh-weight basis ranged from 0.31 to 0.48 (Tables 11, 12 and 13, in pag. 76-77).

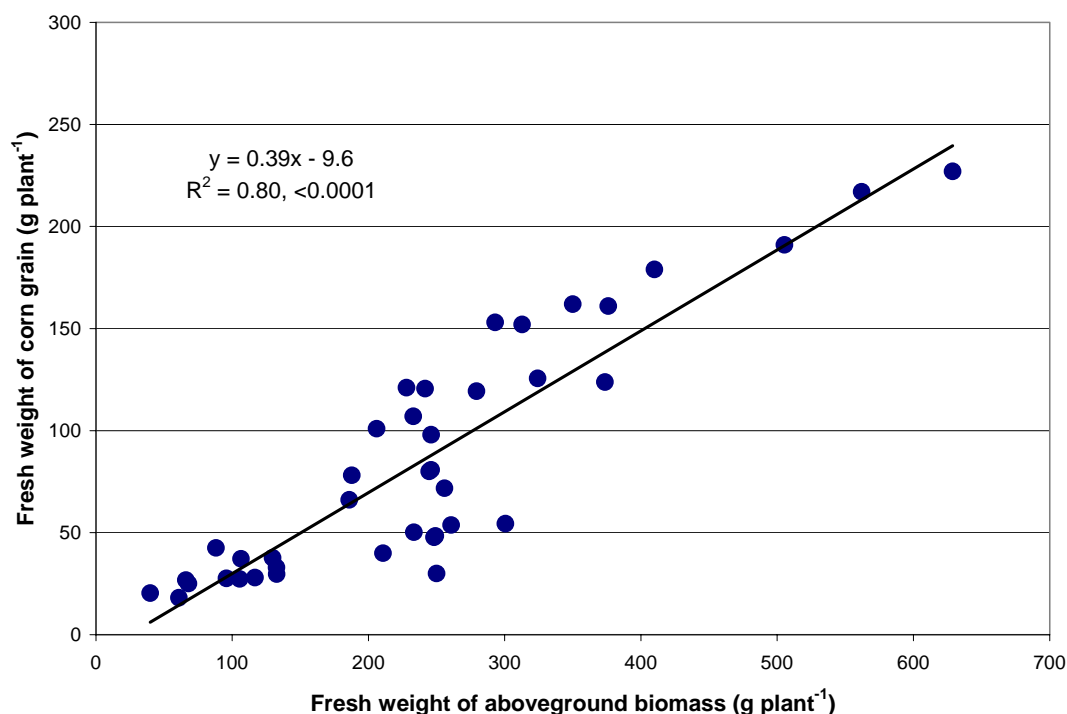


Fig. 38. Relationship between the fresh weights of aboveground biomass and corn grain in the greenhouse study. Both Ships and Weswood soil were included, with and without N fertilizer.

Yield

Data in Fig. 39 depicts the dispersion of corn yield from lowest to highest yield by plant and by treatment. The dispersion of grain yield with fertilizer added was greater than without fertilizer (Fig. 39, Table 9). This result might indicate that separate corn plants have different capacities to absorb N even though the soil, fertilization, and corn genetics were as homogeneous as possible in the greenhouse.

Plants grown in Ships soil had a higher grain yield than in Weswood soil. This difference could be due to a residual effect of fertilization, a higher nutrient content in Ships soil, or better soil physical, biological or chemical conditions which improved yield. This trend was similar for treatments without or with N fertilizer.

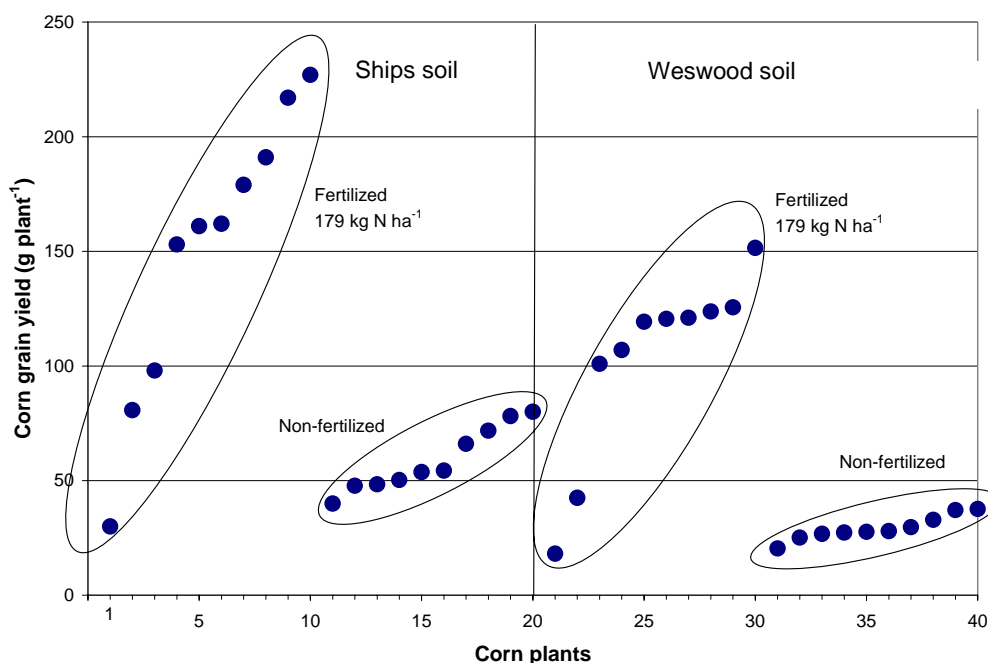


Fig. 39. Dispersion of corn yield data from lower to higher yield by plant and by treatment on a fresh-weight basis in the 2003 greenhouse study.

Table 9. Range of corn grain yield in the greenhouse on fresh-weight and dry-weight bases.

| Treatments | Mean | S.D.† | C.V.‡ | Minimum | Maximum | Difference |
|----------------------|---------------------------------|-------|-------|-----------------------------------|---------|------------|
| Soil Fertilizer | | | | | | |
| | kg N ha ⁻¹ | | | | | |
| Fresh-weight basis | | | | | | |
| | ----- g plant ⁻¹ --- | | % | ----- g plant ⁻¹ ----- | | |
| | -- | | | | | |
| Ships 179 | 149 | 62 | 41 | 30 | 227 | 197 |
| Ships 0 | 59 | 13 | 23 | 39 | 80 | 41 |
| Weswood 179 | 103 | 40 | 39 | 18 | 152 | 134 |
| Weswood 0 | 29 | 5 | 18 | 20 | 37 | 17 |
| Dry-weight basis | | | | | | |
| Ships 179 | 120 | 45 | 55 | 21 | 183 | 162 |
| Ships 0 | 49 | 12 | 24 | 34 | 68 | 34 |
| Weswood 179 | 83 | 33 | 40 | 15 | 125 | 110 |
| Weswood 0 | 25 | 4 | 18 | 18 | 33 | 15 |

† Standard deviation

‡ Coefficient of variation.

Field experiment 2003

Root index

The relationship between the fresh weight of aboveground biomass and the fresh weight of roots for the field experiment in 2003 was linear with a R^2 of 0.83 (Fig. 40). This ratio was calculated on a fresh-weight basis to be used in the conceptual model. The circled points in Fig. 40 were a normal-sized plant with small root systems, and probably was because the plants were growing in very dense soil. During the dry season, in some areas of the field experiment, the soils acquired a hard consistence. Some soil was so hard that it was necessary to use a pickax instead of the regular shovel.

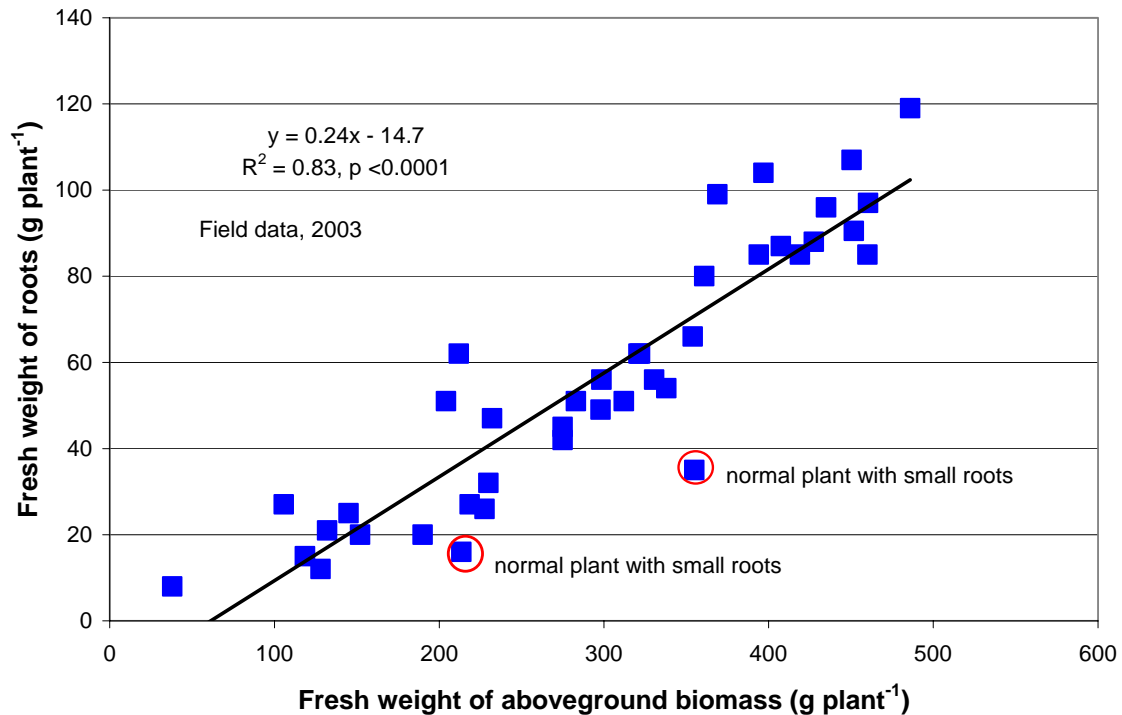


Fig. 40. Relationship between the fresh weight of above ground biomass and the fresh weight of roots for the field experiment located at the Texas A&M University Agricultural Experiment Station Farm on a Ships soil in 2003.

Moisture content

Data in Fig. 41 show the relationship between plant total fresh and dry weights in 2003 for individual replicates of two treatments (without N and 179 kg N ha⁻¹). At harvest, the overall corn plant moisture content was around 33%. The term “total fresh or dry weight of plants” means that the weight includes roots and aboveground biomass. The aboveground biomass includes all the sampled parts: leaves, stems, husks, grain, cobs, silks, and tassels. The close relationship between the total fresh and dry weights of plants (Fig. 41) indicated stable moisture content regardless of plant size. Plant moisture did not depend on the size of the plant nor N fertilization.

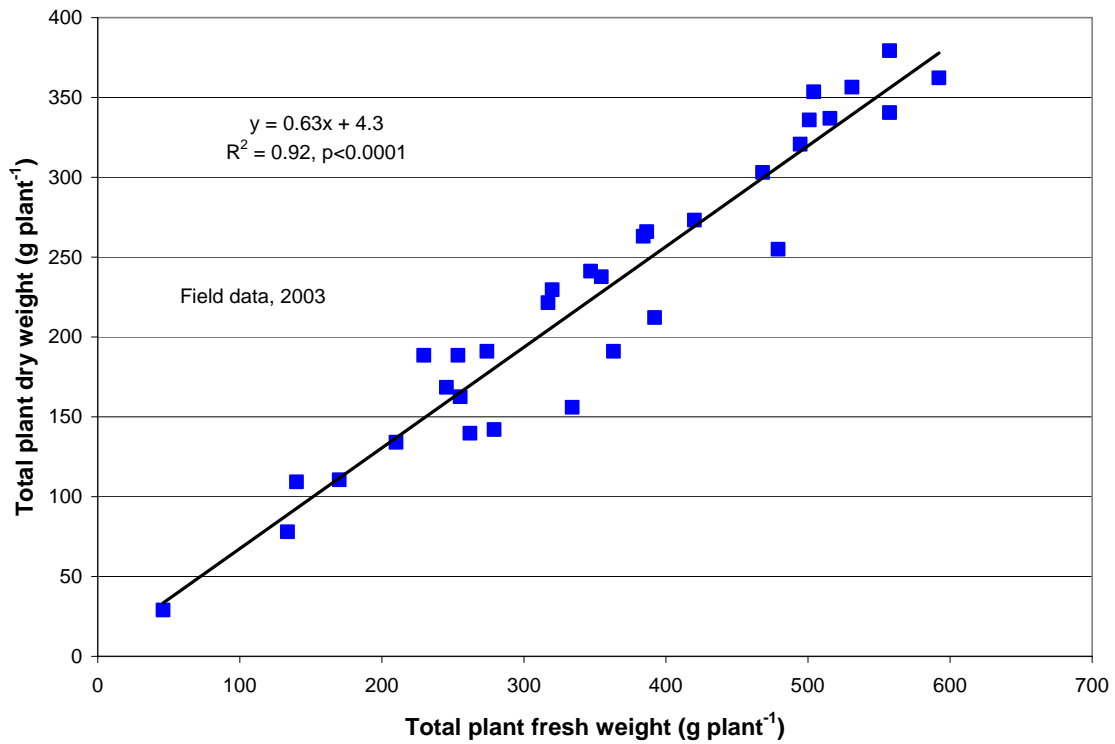


Fig. 41. Relationship between the total fresh and dry weights of corn plants for the field experiment on a Ships soil in 2003 located at the Texas A&M University Agricultural Experiment Station Farm.

Because of its consistency, plant moisture content may be a good vegetative parameter to be used in the conceptual model to estimate the N demand of corn.

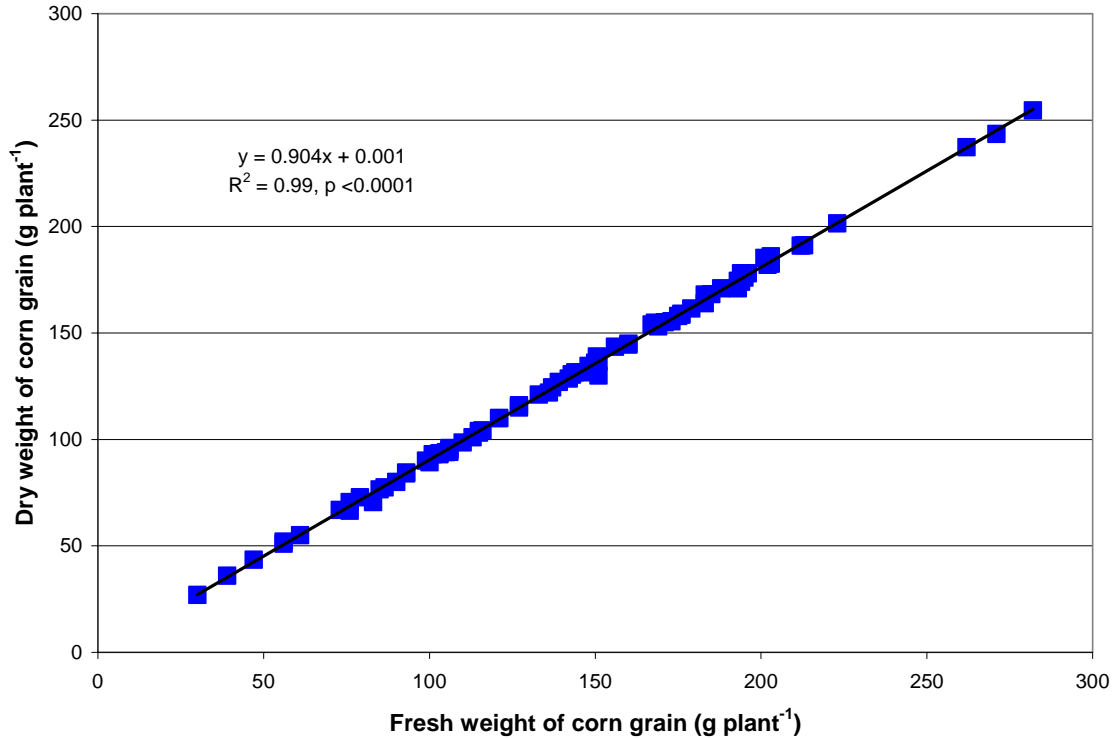


Fig. 42. Relationship between the fresh and dry weights of corn grain from the field study in 2003 located on a Ships soil at the Texas A&M University Agricultural Experiment Station Farm.

The relationship between fresh and dry weights of corn grains in 2003 for individual replicates of the two treatments (without N and with 179 kg N ha⁻¹) is shown in Fig. 43. Results were from plants growing in Ships soil. Based on the slope, the moisture content of corn grain at harvest was around 10 %. Grain yield ranged from 30 g to 282 g per plant (Fig. 42, Table 6). The moisture contents of each component (roots, stems, leaves, husks, grain, and cobs) were different. On average, the overall plant moisture content was 33% while that for grain was 10%.

Harvest index

The harvest index is the ratio between the dry weight of corn grain and the total dry weight of the aboveground biomass. This ratio on a fresh-weight basis is used in the formula of the conceptual model. The relationship in Fig. 43 between both parameters was linear for the individual replicates of the field experiment in 2003, for the two treatments (without N and with 179 kg N ha⁻¹). The R² is increased slightly when two plants that had obvious pollinization problems were eliminated from the analysis. The linear relationship without these two points was: $y = 0.464x + 5.4$, $R^2 = 0.93$ and $p < 0.0001$. The relationship was that heavier plants produced higher yield (Fig. 43).

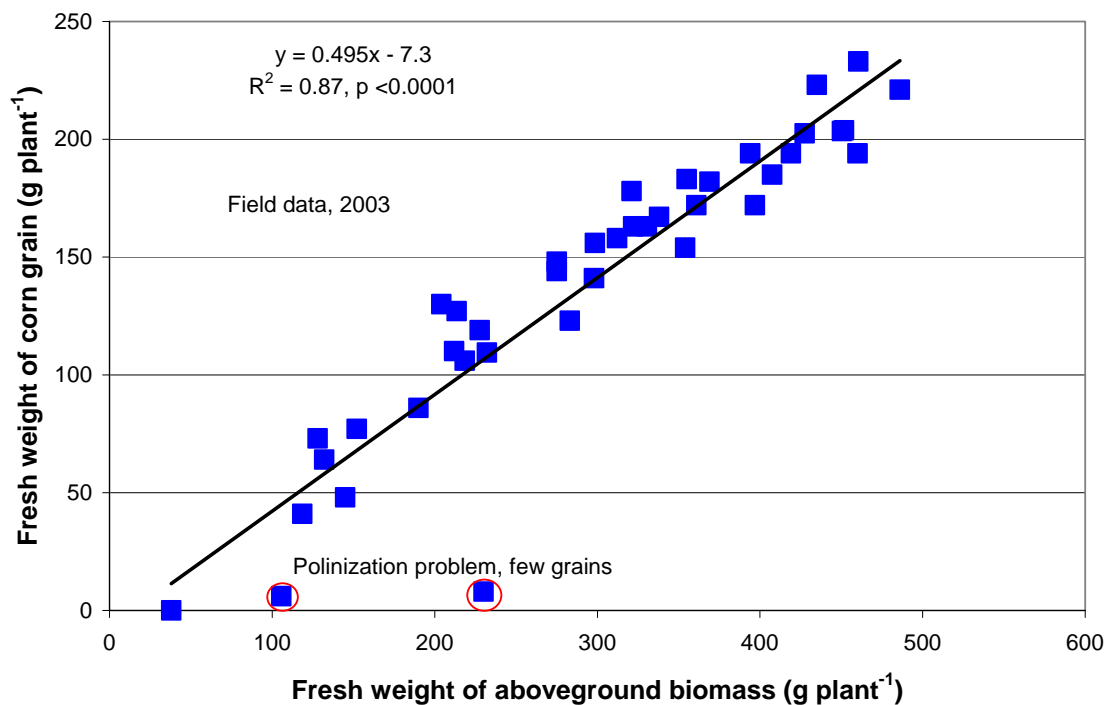


Fig. 43. Relationship between the fresh weights of aboveground biomass and corn grain for the field study in 2003 located on a Ships soil at the Texas A&M University Agricultural Experiment Station Farm. Plants from the circled data had pollinization problems.

Yield

Data on corn yield and plant population of the field experiment in 2003 are presented in Table 10. Although there were no statistically significant differences, the number of plants without ears increased in the blocks with lower yields, and with fertilizer addition in blocks number 2 and 3. Plants without ears were small plants with pollinization problems. The negative effect of N fertilization was probably due to the increased survival of corn plants with applied N and this difference of corn plant population (Table 20-24 Appendixes) produced increased competition for water and nutrients.

The relatively small number of plants without ears within an experimental unit resulted in a great difference in the population when it was extrapolated to a plants per hectare basis. In block 4 with N fertilizer added for example, a 6 plant difference in 37.5 m^2 resulted in 1600 plants per hectare without ears.

Table 10. Number of corn plants and grain yield for the 2003 field experiment. The sampled area was 37.5 m² (9 meter x 4.16 meter area) per replicate located on a Ships soil at the Texas A&M University Agricultural Experiment Station Farm.

| Parameter | Block 1 | | Block 2 | | Block 3 | | Block 4 | |
|--|--------------------|------------------------------|--------------------|------------------------------|--------------------|------------------------------|--------------------|------------------------------|
| | No N fertilizer | 179 kg N ha ⁻¹ | No N fertilizer | 179 kg N ha ⁻¹ | No N fertilizer | 179 kg N ha ⁻¹ | No N fertilizer | 179 kg N ha ⁻¹ |
| Total number of plants by plot | n.d.† | n.d. | 119 | 162 | 179 | 206 | 184 | 228 |
| Number of plants with ear | 111 | 100 | 107 | 140 | 166 | 191 | 177 | 222 |
| Number of plants without ear | n.d. | n.d. | 12 | 22 | 13 | 15 | 7 | 6 |
| Total corn plants per hectare | n.d. | n.d. | 31733 | 43200 | 47733 | 54933 | 49066 | 60800 |
| Corn plants per hectare with a ear | 29600 | 26666 | 28533 | 37333 | 44266 | 50933 | 47200 | 59200 |
| Total grain yield per plot (g) | 10939 | 12571 | 15820 | 19548 | 21636 | 24545 | 22834 | 29989 |
| Average corn grain yield (g plant ⁻¹) | 98 | 125 | 147 | 139 | 130 | 128 | 129 | 135 |
| Standard deviation | 51 | 59 | 63 | 63 | 56 | 51 | 59 | 39 |
| Corn grain yield (kg ha ⁻¹) | 2919 | 3352 | 4218 | 5212 | 5769 | 6545 | 6089 | 7997 |
| Maximum yield (g plant ⁻¹) | 231 | 322 | 314 | 337 | 298 | 262 | 369 | 212 |
| Minimum yield (g plant ⁻¹) | 4 | 12 | 5 | 2 | 3 | 0 | 3 | 4 |

† n.d. = not determined.

A block effect was observed for plant population. Block 1 contained the lowest plant population, while Block 4 had the highest plant population. Increasing plant population with increasing block number was likely due to better soil conditions for corn. Field observations indicated that in Block 1 flooded during rain, probably due to a higher clay content and lower elevation. The soil in Block 1 also appeared drier and harder during dry periods, which possibly reduced plant emergence and growth.

Data presented in Figs. 44 and 45 show the average grain corn yield per plant and per plot and the total yield by plot for the field study in 2003. The average grain corn yield per plant did not indicate a nitrogen application effect nor a block effect. This was because in some blocks there were plants with low yield in the non-nitrogen fertilizer treatments, in contrast with N-fertilizer treatments which produced a lower number of corn plants but higher yield (Appendix Tables 20-24). The changes in corn yield produced by N fertilization in each block are clearer when consider the total yield by plot area (37.5 m^2 in each experimental unit). The yield by plot and the number of plants with an ear were considered in the analysis of data. The plants without an ear were not considered in the calculation of N fertilizer requirement.

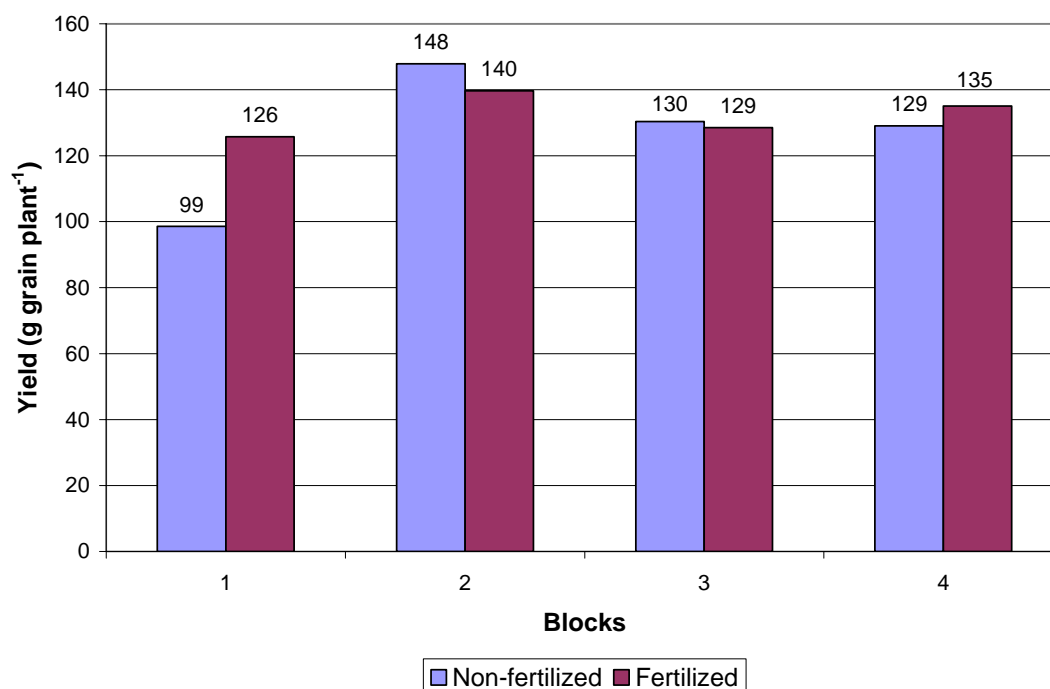


Fig. 44. Average corn grain yield for each block in the field experiment in 2003 located on a Ships soil at the Texas A&M University Agricultural Experiment Station Farm. Fertilized plots received 179 kg N ha^{-1} .

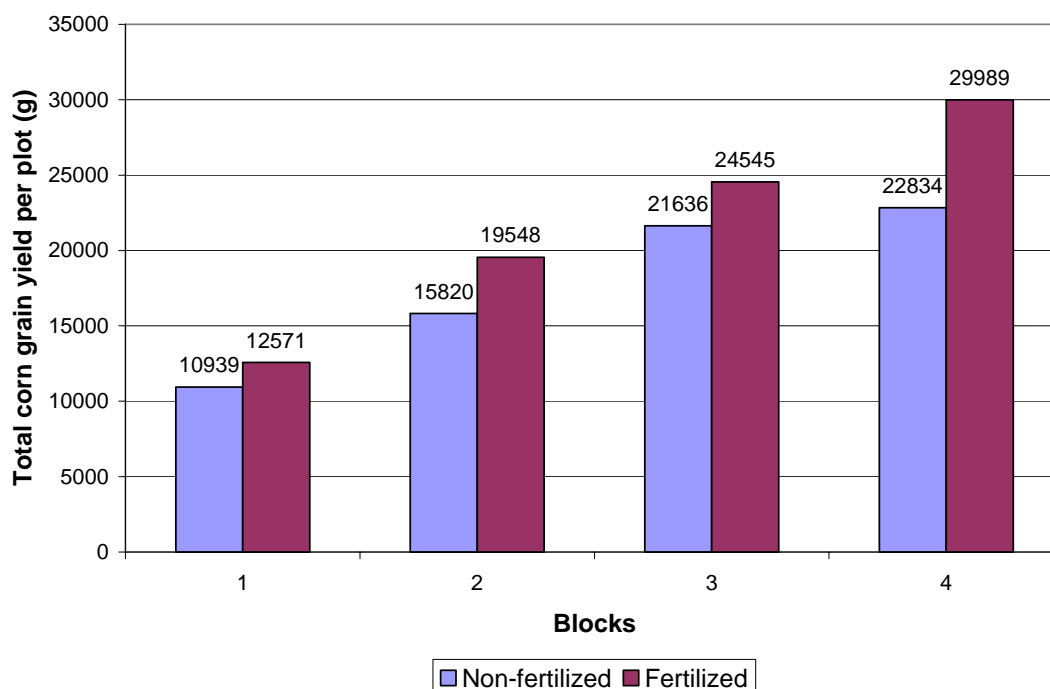


Fig. 45. Average total corn grain yield per plot in each block in the field experiment in 2003 located on a Ships soil at the Texas A&M University Agricultural Experiment Station Farm. Fertilized plots received 179 kg N ha^{-1} .

Summary of 2002 field and 2003 field and greenhouse experiments

Data in Tables 11, 12, and 13 provide summaries of the relationship obtained from the corn plant component parameters from the field and greenhouse experiments.

Considering the field and greenhouse experiments, the moisture content ranged from 37 to 57%. On average, the moisture content of plants growing in the greenhouse was higher than those growing in the field. Corn plants in the greenhouse were watered at least once a week whereas those in the field only received precipitation.

The number of days to harvest was also different. Plants growing in the field required fewer days to reach physiological and commercial maturity. Plants in the greenhouse

needed 162 days, while those in the field averaged 116 dap in 2003 and 154 days in 2002. Differences were likely related day length, solar irradiation, and growing degree units. In the greenhouse the number of days to harvest was higher because corn was planted in winter (December) when day length was shorter than in spring (Fig. 46, Appendix Tables 33-44; National Weather Service, 2005; The Weather Channel Interactive, 2005).

Statistically there was no difference in R.I. on a dry-weight basis in all experiments regardless of location (field or greenhouse), fertilizer, or soil (Weswood or Ships). The R.I. ranged from 0.05 to 0.10 in all cases on the same dry-weight basis. On the other hand, the R.I. on a fresh-weight basis was different only in the greenhouse experiment using Ships soil with 179 kg N ha⁻¹ (Table 12). Statistically, this R.I. (R.I.=0.19) is lower than the others. It could be due to replanting which reduced the corn root growth. The soil was compacted during replanting, and this compaction produced smaller roots (Figs. 29 and 30).

Data in Table 11 show two samplings collected at 143 and 154 days after planting. Comparing those two samplings, moisture content decreased from 50 to 42% in 11 days. The R.I. was statistically similar for those two samplings; however, H.I. was statistically different between dates on both a fresh and dry-weight basis. This likely indicated that grain was still in the filling process at the earlier sampling (Fig. 1).

The H.I. in the field ranged from 0.47 to 0.53 on a dry-weight basis (Tables 11 and 13), while in the greenhouse H.I. ranged from 0.26 to 0.32 (Table 12). Lower yield in the greenhouse was attributed to decreased pollinization due to lack of wind and high temperatures.

In the three experiments (field 2002, greenhouse, and field 2003), H.I. on a dry-weight basis was similar, even for the variety Dekalb 687 which was produced in a Ships soil

under a long-term management of no-tillage. Two exceptions were the samples collected from Ships soil at 143 dap in the field (Table 11), which were taken 11 days before commercial maturity, and samples from the Weswood soil in the greenhouse with no N applied, which had pollinization problems (Table 12).

Corn plant N concentration of the entire plant ranged from 6.4 to 10.9 g kg plant⁻¹ when compared across all data (Tables 11, 12, and 13). The N concentration was higher in corn with N fertilization than without in the greenhouse. This last classification includes the long-term experiment with no-tillage for Dekalb 687 corn variety (Table 11).

According to data in Fig. 47 in page 78, the physiologically optimum plant N concentration ranged from 7.0 to 12.0 g N kg plant⁻¹, although there was not a clearly defined limit. In Fig. 48 in page 78, the limit was somewhat clearer and the physiologically optimum concentration ranged from 10.0 to 12.5 g N kg plant⁻¹, at least where total plant N content was concerned. Total plant N content in plants was closely related to corn grain yield (Fig. 51).

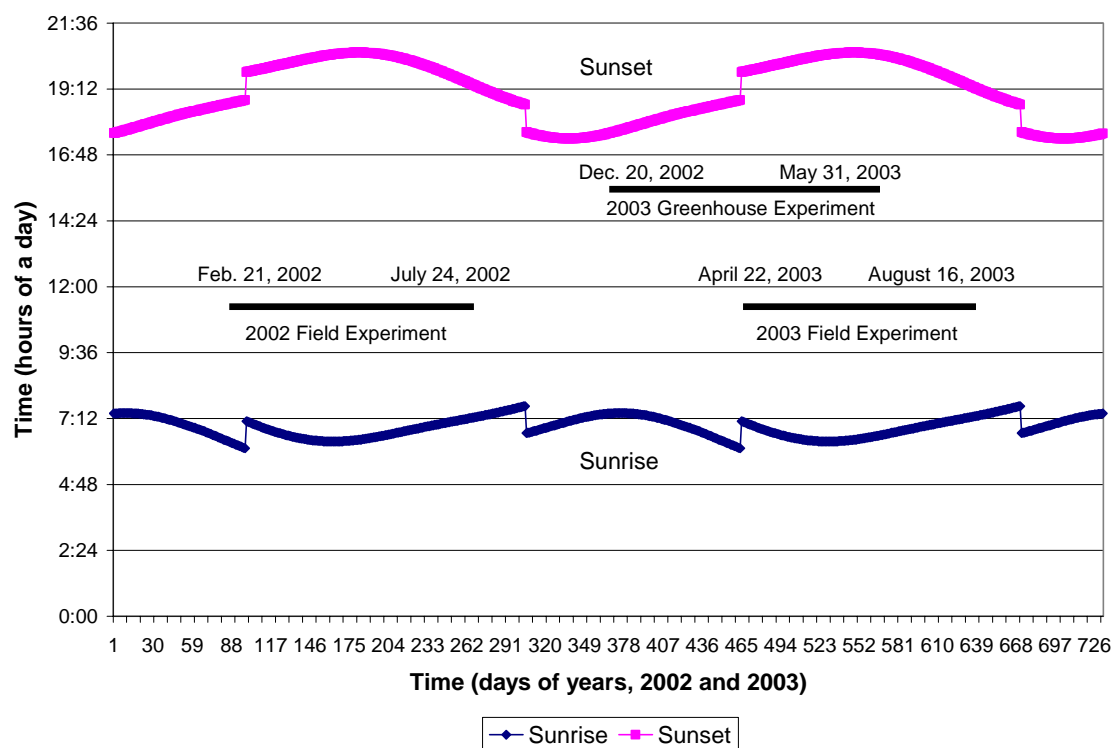


Fig. 46. Sunset and sunrise for College Station during the periods of field and greenhouse trials. The amount of daylight changed with season, but was practically constant every year (less than one minute per day corrected every four years).

Table 11. Moisture content, root index, harvest index, corn grain yield, and nitrogen concentration calculated on fresh-weight and dry-weight bases for the 2002 field study located on a Ship soil at the Texas A&M University Agricultural Experiment Station Farm.

| Treatments | Moisture Content | Root Index | | Harvest Index | | Grain yield | | N concentration [†] |
|----------------------------|---------------------|-------------------------|------------------|--------------------------|--------|-----------------------------------|--------|---------------------------------|
| | | Fresh | Dry | Fresh | Dry | Fresh | Dry | |
| | % | g roots g ⁻¹ | agb [‡] | g grains g ⁻¹ | agb | ----- g plant ⁻¹ ----- | | --- g kg ⁻¹ --- |
| Ships 143 dap [§] | 50 a [¶] | 0.23a | 0.095a | 0.31b | 0.46 b | 193 a | 163 a | 10.8 a |
| Ships 154 dap | 42 b | 0.22a | 0.087a | 0.38a | 0.50a | 213 a | 183 a | 10.8 a |
| Weswood east | 45 ab | 0.20a | 0.080a | 0.33b | 0.47ab | 129 c | 111 c | 10.3 ab |
| Weswood west | 46 ab | 0.21a | 0.092a | 0.32b | 0.47ab | 180 ab | 154 ab | 10.3 ab |
| Ships Dekalb 687 | 35 c | 0.25a | 0.099a | 0.38a | 0.47ab | 141 bc | 127 bc | 8.1 c |

[†] N concentration of whole the plant including the roots.

[‡] agb = aboveground biomass.

[§] dap = days after planting.

[¶] Means in each column with the same letter indicate no significant difference, Tukey HSD at 0.05 level.

Table 12. Moisture content, root index, harvest index, corn grain yield, and nitrogen concentration calculated on fresh-weight and dry-weight bases with and without nitrogen fertilizer at harvest time (162 days after planting) for the 2003 greenhouse study.

| Treatments | | Moisture Content | Root Index | | Harvest Index | | Grain yield | | N concentration [†] |
|------------|-----------------------|---------------------|-------------------------|------------------|--------------------------|---------|-----------------------------------|-------|---------------------------------|
| | | | Fresh | dry | Fresh | Dry | Fresh | Dry | |
| Soil | kg N ha ⁻¹ | % | g roots g ⁻¹ | agb [‡] | g grains g ⁻¹ | agb | ----- g plant ⁻¹ ----- | | --- g kg ⁻¹ --- |
| Ships | 179 | 48 ab [§] | 0.19b | 0.061a | 0.38ab | 0.32 a | 149 a | 115 a | 10.3 a |
| Ships | 0 | 57 a | 0.32ab | 0.083a | 0.26c | 0.28 ab | 59 b | 49 bc | 6.4 b |
| Weswood | 179 | 45 b | 0.32ab | 0.048a | 0.44a | 0.29 ab | 121 a | 83 ab | 10.2 a |
| Weswood | 0 | 56 ab | 0.36a | 0.065a | 0.32bc | 0.26 b | 29 b | 25 bc | 7.1 b |

[†] N concentration of whole the plant including the roots.

[‡] agb = aboveground biomass.

[§] Means in each column with the same letter indicate no significant difference, Tukey HSD at 0.05 level.

Table 13. Moisture content, root index, harvest index, corn grain yield, and nitrogen concentration calculated on fresh and dry-weight bases with and without nitrogen fertilizer at harvest time (116 days after planting) in the 2003 field study located on a Ship soil at the Texas A&M University Agricultural Experiment Station Farm.

| Treatments | | Moisture | Root Index | | Harvest Index | | Grain yield | | N | Grain yield |
|------------|-----------------------|-------------------|--|-------|------------------------------|-------|-----------------------------------|-------|----------------------------|---------------------|
| | | Content | Fresh | Dry | Fresh | Dry | Fresh | Dry | concentration [†] | fresh |
| Soil | kg N ha ⁻¹ | % | g roots g ⁻¹ agb [‡] | | g grains g ⁻¹ agb | | ----- g plant ⁻¹ ----- | | g kg ⁻¹ | kg ha ⁻¹ |
| Ships | 179 | 39 a [§] | 0.17 a | 0.09a | 0.48 a | 0.53a | 135 a | 122 a | 10.9 a | 5776 a |
| Ships | 0 | 37 a | 0.20 a | 0.10a | 0.47 a | 0.48a | 142 a | 135 a | 10.0 a | 4748 b |

[†] N concentration of whole the plant including the roots.

[‡] agb = aboveground biomass.

[§] Means in each column with the same letter indicate no significant difference, Tukey HSD at 0.05 level.

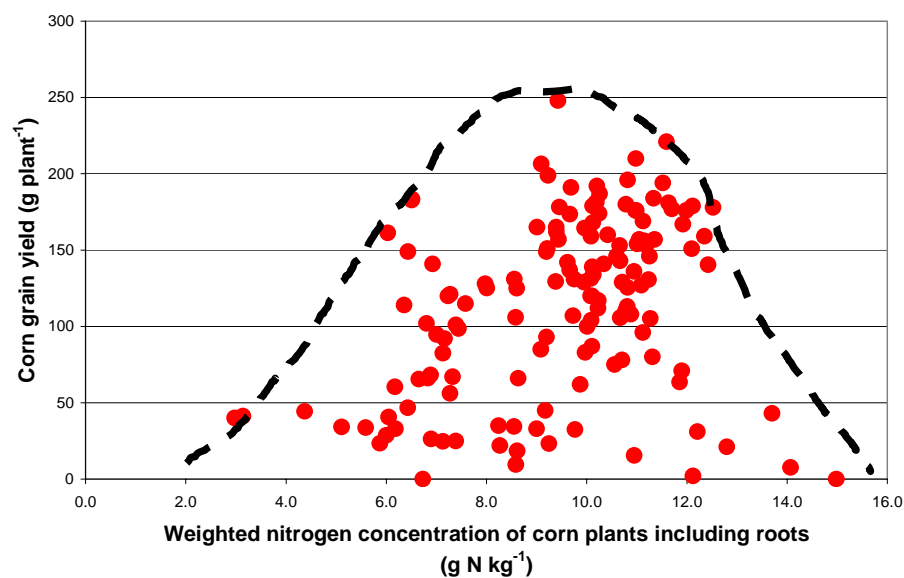


Fig. 47. Relationship between the weighted nitrogen concentration of corn plants, including roots and corn grain yield. Data are from the 2002 and 2003 field experiments and the 2003 greenhouse experiment. The dashed line approximates maximum limits.

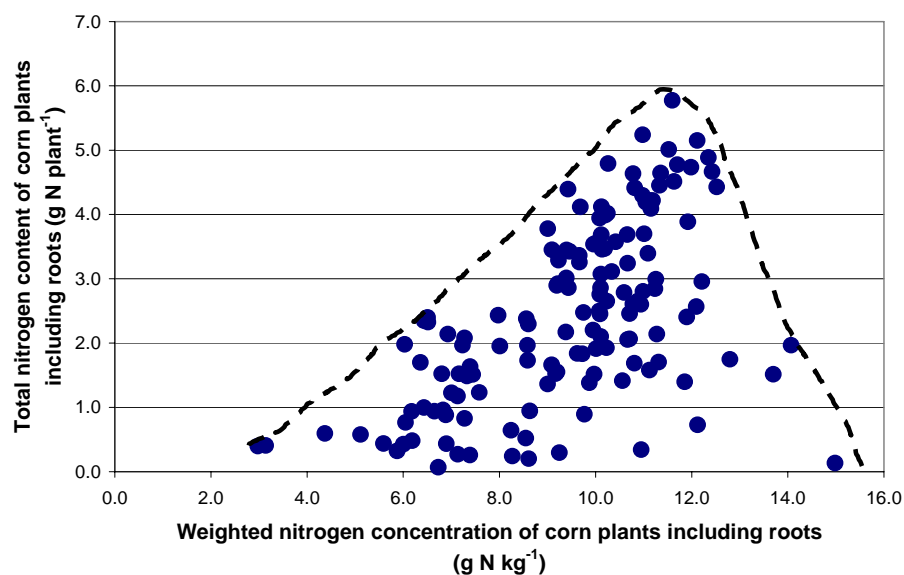


Fig. 48. Relationship between the weighted nitrogen concentration of corn plants and the total nitrogen content of plants including roots. Data are from the 2002 and 2003 field experiments and the 2003 greenhouse experiment. The dashed line approximates maximum limits.

Nitrogen demand by corn

Plant total dry weight in the 2002 field study on Ships soil increased 11 grams in eleven days (from 143 to 154 dap), and the N content increased by 0.13 grams N in the same period of time. The N concentration however didn't change over this time. Corn achieved commercial maturity for the Station environmental conditions in 2002 by 154 dap. The corn plants increased dry organic matter and N content in the last eleven days of maturity, while N concentration stayed similar.

Table 14. Total dry weights of corn plants (sum of roots, aboveground biomass, and corn grain), weighted nitrogen concentration, and total plant nitrogen contents for the 2002 field experiment.

| ID | Total plant dry weight | Weighted nitrogen concentration | Total plant nitrogen content | Nitrogen demand |
|----------------------------|------------------------|---------------------------------|------------------------------|-----------------------|
| | g plant ⁻¹ | g N kg ⁻¹ | g N plant ⁻¹ | kg N ha ⁻¹ |
| Ships 143 dap [†] | 383 a [*] | 10.8 a | 4.16 a | 198 a |
| Ships 154 dap | 394 a | 10.8 a | 4.29 a | 205 a |
| Weswood east | 249 b | 10.3 a | 2.59 b | 147 b |
| Weswood west | 356 ab | 10.3 a | 3.73 a | 210 a |
| Ships Dekalb 687 | 296 b | 8.1 b | 2.43 b | 107 b |

[†] dap = days after planting.

^{*} Means in each column with the same letter indicate no significant difference, Tukey HSD at 0.05 level.

Corn hybrid Pioneer 32R25™ had the higher total plant dry weight, N concentration and N content in Ships compared with the Weswood soil (Table 14). The variety Dekalb 687 without N application had lowest total dry weight, N concentration and N content. This reduction may have been due to lower soil N availability, the effect of no-tillage, or to characteristics of this variety. However, these conditions didn't reduce the average yield by plant (Table 7).

On average, the total dry weights corn plants were lower in the greenhouse in 2003 compared the field in 2002 (Tables 14 and 15), this occurred even though plants in greenhouse had the same fertilization as the Ships and Weswood soils used the same corn variety, and received water on a regular basis. Yield reduction occurred not only for total plant dry weight but also for total plant N content (Table 14 and 15).

Table 15. Total dry weight of corn (roots, aboveground biomass, and grain), weighted nitrogen concentration, and plant total nitrogen at harvest (162 days after planting for the greenhouse experiment in 2003).

| Treatments | | Total dry weight by plant | Weighted nitrogen concentration | Total plant nitrogen content | Nitrogen demand |
|------------|-----------------------|---------------------------|---------------------------------|-------------------------------------|-----------------|
| | kg N ha ⁻¹ | g plant ⁻¹ | g kg ⁻¹ | ----- g N plant ⁻¹ ----- | |
| Ships | 179 | 242 a [†] | 10.3 a | 2.49 a | 2.52 a |
| Ships | 0 | 132 b | 6.4 b | 0.84 bc | 0.85 b |
| Weswood | 179 | 162 b | 10.2 a | 1.65 ab | 2.42 a |
| Weswood | 0 | 50 c | 7.1 b | 0.35 c | 0.38 c |

[†] Means in each column with the same letter indicate no significant difference by Tukey's HSD at 0.05 level.

Table 15 shows that the N demand of Pioneer hybrid 32R25™ was higher with N fertilization than without. Given that the data came from a greenhouse experiment, they couldn't be extrapolated to field N demand. Plant N content was lower in the greenhouse than in the field (Tables 14, 15, and 16). In Table 15, the total plant N content was estimated by multiplying the original data of the total dry weight by the weighted N concentration. In this specific case, this procedure theoretically gives a more exact value than calculation of "N demand" using the proposed algorithm. The proposed algorithm requires optimal N concentration, R.I., moisture content, H.I., and yield.

Table 16. Total dry weight of corn (roots, aboveground biomass, and grain), weighted nitrogen concentration, and plant total nitrogen with and without nitrogen fertilizer at harvest (116 days after planting for the field experiment 2003).

| Treatments | | Total dry weight by plant | Weighted nitrogen concentration | Total plant nitrogen content | Nitrogen demand |
|------------|-----------------------|------------------------------|---------------------------------------|------------------------------------|---------------------|
| | kg N ha ⁻¹ | g plant ⁻¹ | g kg ⁻¹ | g plant ⁻¹ | kg ha ⁻¹ |
| Ships | 179 | 217 a [†] | 10.9 a | 2.36 a | 93 a |
| Ships | 0 | 247 a | 10.0 a | 2.47 a | 75 b |

[†] Means in each column with the same letter indicate no significant difference by Tukey's HSD at 0.05 level.

The N demand by Pioneer corn hybrid 32R25™ was 93 and 75 kg N ha⁻¹ for treatments with 179 kg N ha⁻¹ and without N fertilization.

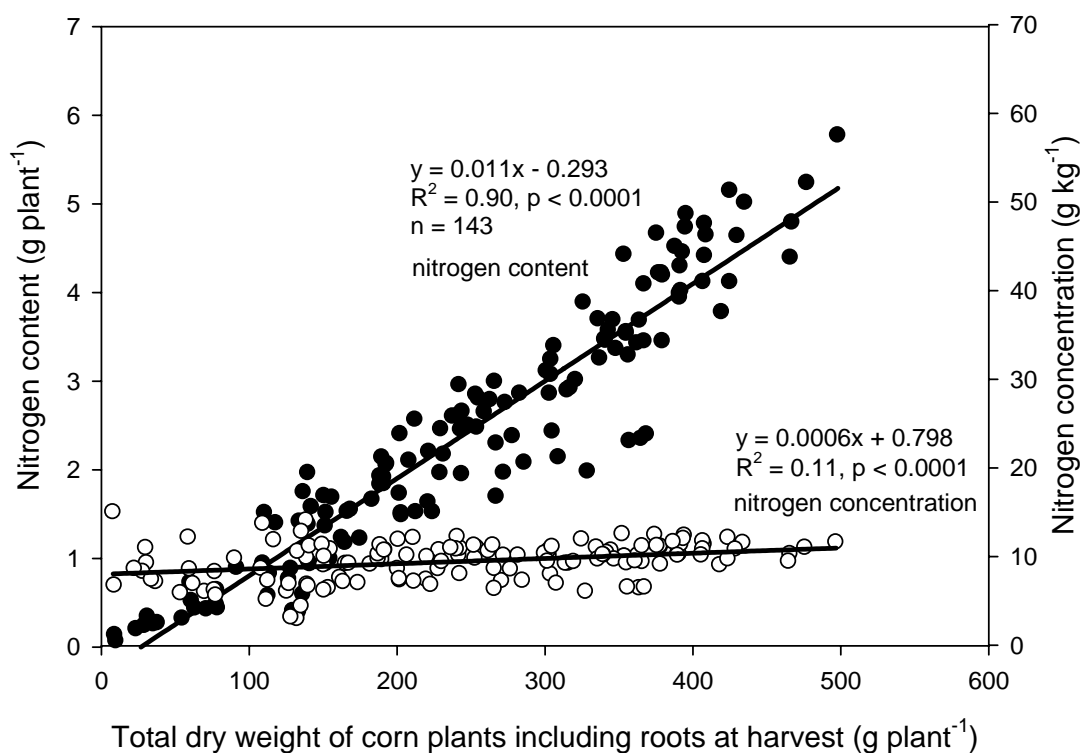


Fig. 49. Overall relationship between the total dry weight of corn plants including roots at harvest and the concentration and content of N. Data are from the 2002 and 2003 field experiments and the 2003 greenhouse experiment.

This hybrid exhibited an average N concentration of 1 % (Fig. 49). This value is lower than the 1.25% reported by Larson and Hanway (1977), Loué (1987), and Stanford (1966). The lower value of 1% is likely because this weighted nitrogen concentration included the N concentration of roots, which had lower N concentration than aboveground biomass. Corn plant N concentration wasn't related to plant size. However, plant N content (g N plant^{-1}) was highly related with plant size (Fig. 49). The greater the plant size, the greater the plant N content. In the same way, the N content of corn plants was closely related with the dry weight of corn grain (Fig. 51). This means that larger plants resulted in greater N content, and higher dry weight of grain. This relationship fitted slightly better to a second grade polynomial model ($y = -4.8x^2 + 61.4x + 2.1$, $R^2=0.80$) than a linear model ($y = 36.7x + 24.6$, $R^2 = 0.77$). The association was reduced because some plants had pollination problems.

The total biomass of corn plants was also linearly related with the nitrogen content (Fig. 49), and with the dry weight of corn grain (Fig. 50). The N content had a close and polynomial relationship with the dry weight of corn grain (Fig. 51). Reduced pollination was likely more related with reduced N supply than was the biomass of corn plants, according to the analyses shown in Figs. 49, 50 and 51.

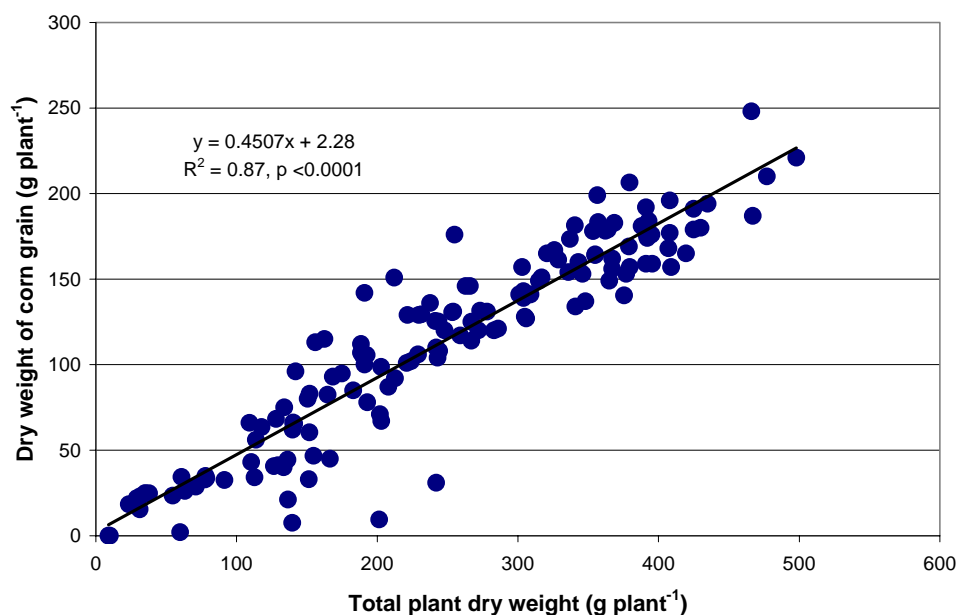


Fig. 50. Total dry weight of corn plants in relation to the dry weight of corn grain. Data are from the 2002 and 2003 field experiments and the 2003 greenhouse experiment.

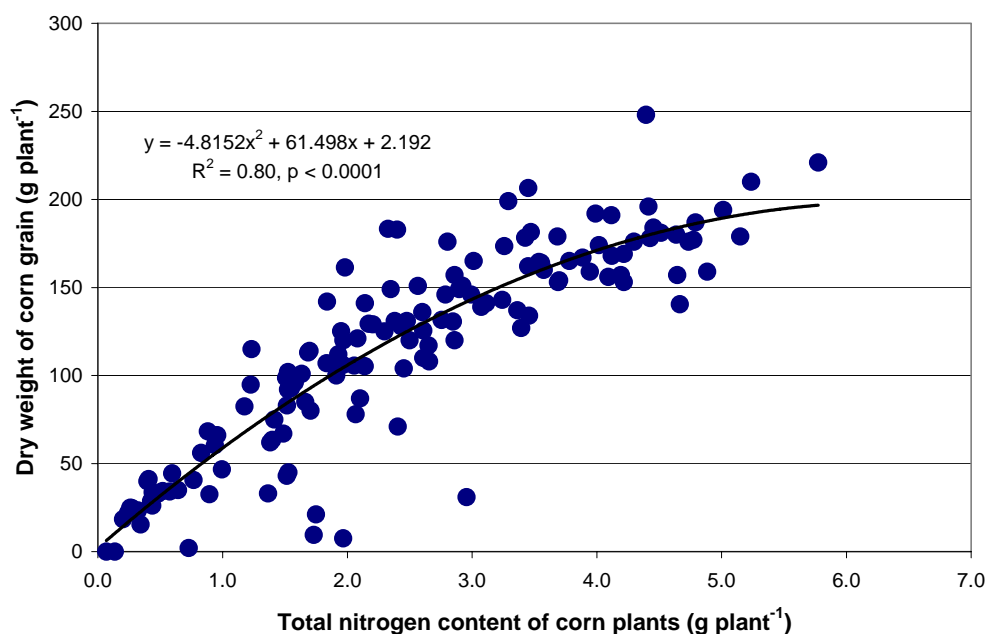


Fig. 51. Total nitrogen content of corn plants and its relationship with the dry weight of corn grain. Data are from the 2002 and 2003 field experiments and the 2003 greenhouse experiment.

Soil nitrogen supply

No differences in inorganic soil N concentrations or mineralized N by block were observed in the field study (Fig. 52). However, a tendency was seen for concentration of initial and mineralized N to increase with block number. This tendency was likely due to the presence of a small slope from the west to east in the experimental units (Fig. 3). This slope likely produced over time an accumulation of organic matter and clay in the lowest part of the field (Block I). Nitrogen fertilization tended to increase mineralized soil N probably due to increased microbial activity (Fig. 53).

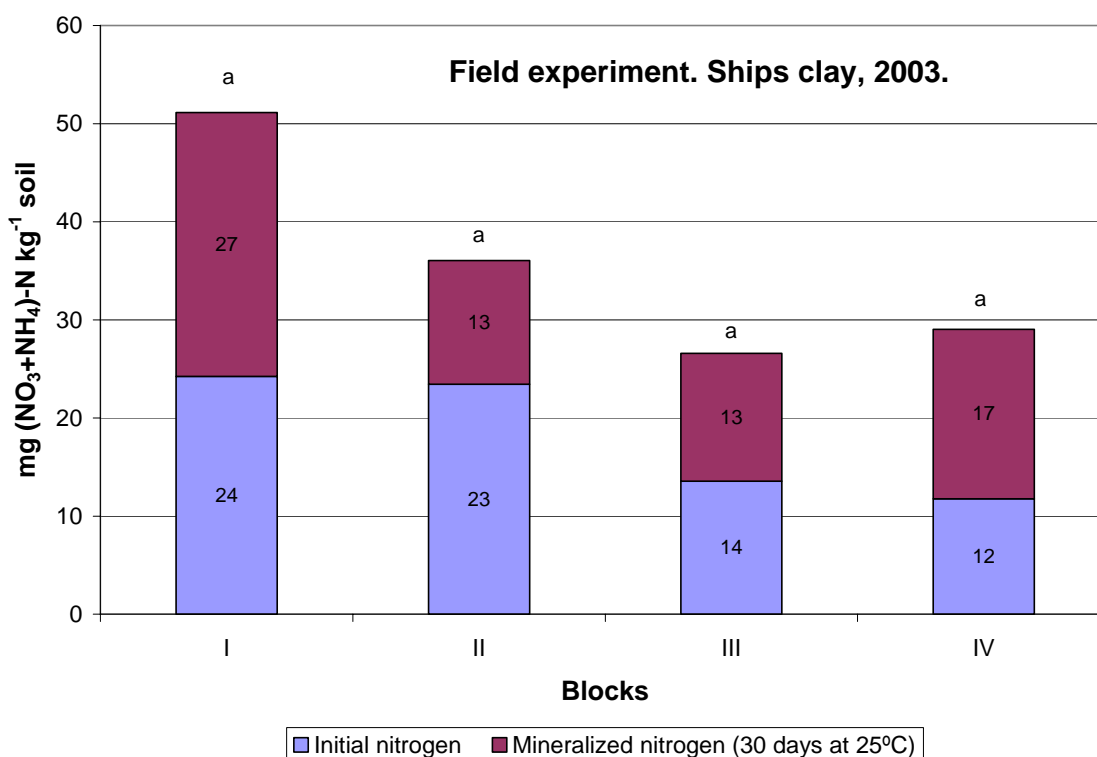


Fig. 52. Initial inorganic and mineralized nitrogen in soil of the 2003 field experiment. Replicates with the same letter are not statistically different (Tukey, $\alpha = 0.05$).

Data in Fig. 54 shows the initial inorganic and mineralized N concentrations of soils from the greenhouse study. The initial inorganic N concentration was similar for both

kinds of soils and N treatments (with 179 kg N ha⁻¹ and without N fertilization). The Ships clay soil had higher mineralized N than Weswood soil of no N controls, while the application of 179 kg N ha⁻¹ increased the soil N mineralization in both soils to similar levels.

There was no difference in soil N mineralization between the treatment with 179 kg N ha⁻¹ and without fertilizer in Ships soil (Figs. 52 and 53), while for the Weswood soil there was a significant difference between the treatment with and without fertilizer (Fig. 54). The 179 kg N ha⁻¹ added to Weswood soil increased mineralized N eight-fold (from 4 to 33 mg N kg soil⁻¹) likely due to a priming effect (Fountain et al., 2004).

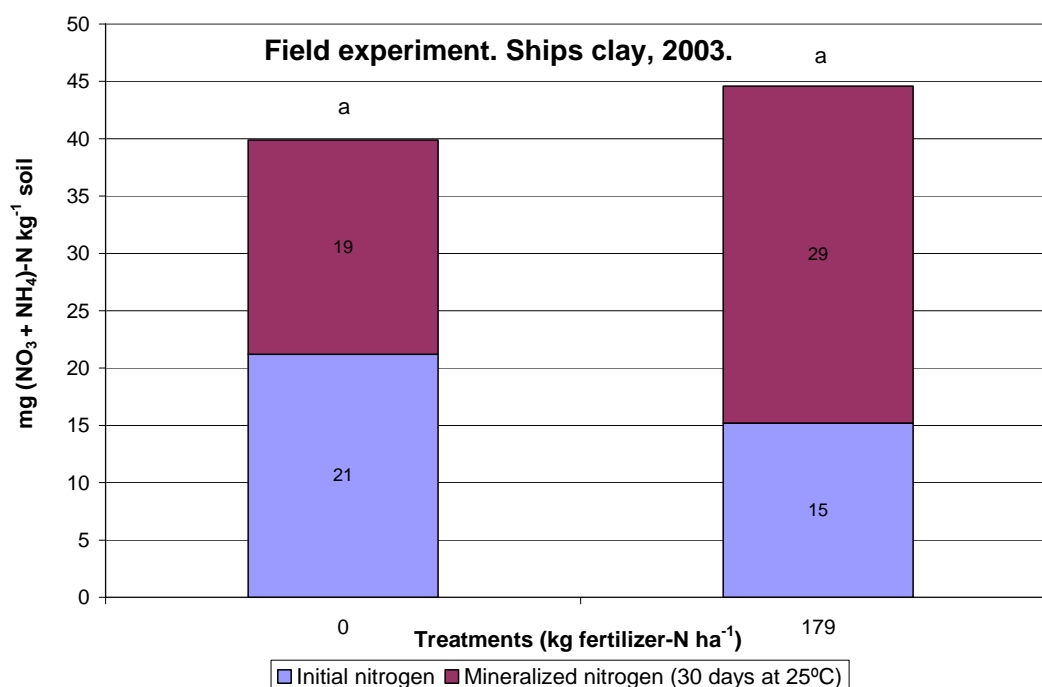


Fig. 53. Initial inorganic and mineralized nitrogen concentrations in soils of the 2003 field experiment. Treatments with same letter were not statistically different (Tukey, $\alpha = 0.05$).

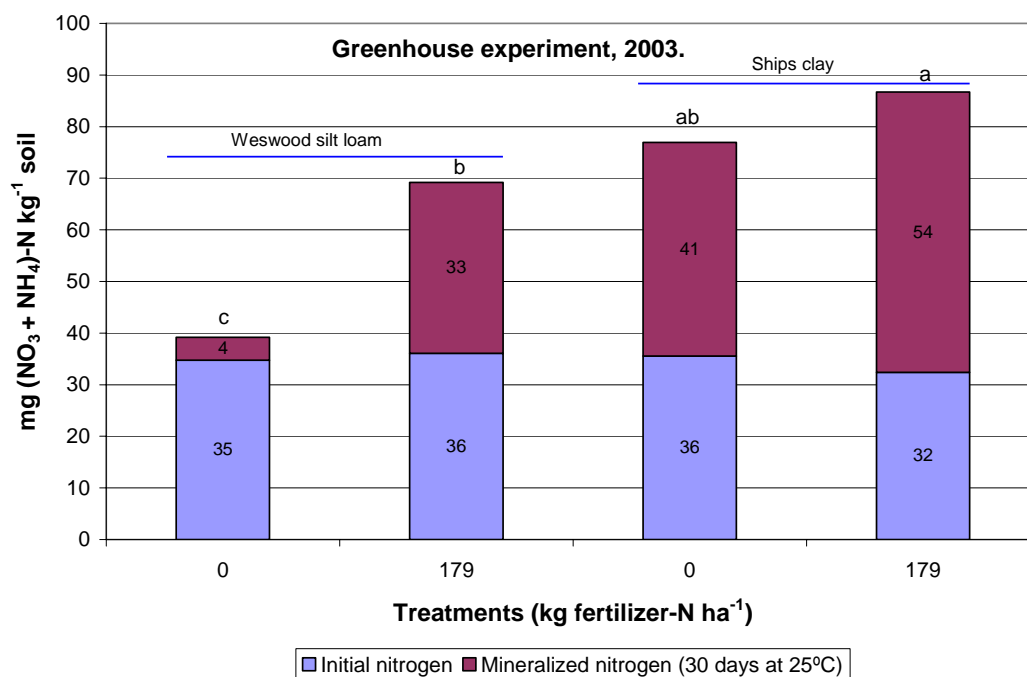


Fig. 54. Initial inorganic and mineralized nitrogen concentrations in soils of the 2003 greenhouse experiment. Treatments with same letter were not statistically different (Tukey, $\alpha = 0.05$).

Table 17. Soil nitrogen supply from the field and greenhouse experiments in 2003.

| Treatments | | N supply | S.D. | C.V. |
|------------|-----------------------|-----------------------------------|------|------|
| Soil | N Rate | | | |
| Greenhouse | | | | |
| | kg N ha ⁻¹ | ----- g N pot ⁻¹ ----- | | % |
| Ships | 179† | 1.04 | 1.02 | 98 |
| Ships | 0 | 0.79 | 0.99 | 126 |
| Weswood | 179 | 0.63 | 0.95 | 151 |
| Weswood | 0 | 0.08 | 0.63 | 756 |
| Field | | | | |
| | kg N ha ⁻¹ | ----- kg N ha ⁻¹ ----- | | % |
| Ships | 179 | 105 | 28 | 27 |
| Ships | 0 | 67 | 35 | 52 |

† 2.53 g N per pot were added in the N fertilizer treatments in the greenhouse experiment, this computes to 179 kg N ha⁻¹, calculated on an area basis.

Efficiency of added nitrogen fertilizer

The N fertilizer use efficiency (NUE) was calculated. The units are given as grams of N absorbed by corn plants divided by the grams of N fertilizer applied. Nitrogen use efficiency was estimated using in the numerator the differences between N-fertilized treatments and the unfertilized control (Binder et al., 2002). The error propagation method was used in the calculation of NUE to include the error produced. The formulas to estimate the error are given in Table 18 (Garland et al., 2003).

Table 18. Error propagation in arithmetic calculations.

| Type of calculation | Example† | Standard deviation of y |
|----------------------------|-----------|---|
| Addition or subtraction | $Y=a+b-c$ | $S_y=(S_a^2+S_b^2+S_c^2)^{1/2}$ |
| Multiplication or division | $Y=a*b/c$ | $S_y/y=\{(S_a/a)^2+(S_b/b)^2+(S_c/c)^2\}^{1/2}$ |

† a, b, and c are experimental variables whose standard deviations are S_a , S_b , and S_c , respectively.

Apparent recovery efficiency of applied N

The formula to estimate the RE_N , or apparent recovery efficiency of applied N (kg N taken up kg^{-1} N applied), is as follows. A modification to this formula was used. In the estimation of “UN or plant N accumulation”, not only the aboveground biomass but also the roots was also considered.

$$RE_N = (UN_{+N} - UN_{0N})/N$$

Where:

UN is the plant N accumulation in aboveground biomass and roots ($kg\ N\ ha^{-1}$)

N is the amount of fertilizer-N applied ($kg\ N\ ha^{-1}$)

$_{+N}$ and $_{0N}$ refer to treatments with and without N application, respectively

Error propagation calculation for the efficiency of fertilization using differential method

Field experiment with Ships soil, 2003. The formula to estimate the RE_N , or apparent recovery efficiency of applied N (kg N taken up kg^{-1} N applied), is as follows, with the addition of the standard deviation which follows the error propagation procedure to estimate the error of this formula. The standard deviation for the treatments with and without fertilizer came from the four blocks used in the experiment. This standard deviation is called random error. The standard deviation of the fertilizer added came from the specification provided by the manufacturer of the fertilizer machine; this parameter is named systematic error.

$$E.F. = \frac{N \text{ uptake in treatment with fertilizer (std. dev.)} - N \text{ uptake in treatment without fertilizer (std. dev.)}}{\text{kg N applied per hectare (std. dev.)}}$$

Where:

E.F. is efficiency of fertilizer uptake

$$\text{Efficiency of fertilizer} = \left(\frac{93(\pm 12.58) - 75(\pm 11.05)}{179(0.025)} \right) \times 100$$

In this example, the N uptake in treatments with and without fertilizer was the average of the four blocks used in the field experiment and its standard deviation, extrapolated to one hectare. The error propagation is calculated using the standard deviation (S) of the variables “N uptake in treatments with and without fertilizer” and formulas presented in Table 18. Efficiency of fertilizer uptake follows the procedures to estimate the error propagation using subtraction, addition, division and multiplication.

$$S_y = \sqrt{(12.58)^2 + (11.05)^2} = 16.10$$

$$\text{Efficiency of fertilizer} = \left(\frac{18(\pm 16.10)}{179(\pm 0.025)} \right) \times 100$$

$$S_y = \sqrt{\left(\frac{16.10}{18} \right)^2 + \left(\frac{0.025}{179} \right)^2} = 0.895$$

$$S_y = 0.1005 \times 0.895 = 0.09$$

$$S_y = 0.10 \pm 0.09$$

$$\text{Efficiency of fertilizer} = (0.10 \pm 0.09) \times 100$$

$$\text{Efficiency of fertilizer} = 10\% \pm 9\%$$

$$\text{C.V.} = 90\%$$

Greenhouse experiment with Ships soil, 2003. In this example, the N uptake in treatments with and without fertilizer is the average of ten plants which grew in the greenhouse.

$$\text{Efficiency of fertilizer} = \left(\frac{2.52(\pm 1.74) - 0.854(\pm 0.57)}{2.53(\pm 0.01)} \right) \times 100$$

$$S_y = \sqrt{(1.74)^2 + (0.57)^2} = 1.64$$

$$\text{Efficiency of fertilizer} = \left(\frac{1.66(\pm 1.64)}{2.53(\pm 0.01)} \right) \times 100$$

$$S_y = \sqrt{\left(\frac{1.64}{1.66} \right)^2 + \left(\frac{0.01}{2.53} \right)^2} = 0.98$$

$$S_y = 0.6561 \times 0.98 = 0.643$$

$$S_y = 0.6561 \pm 0.643$$

$$\text{Efficiency of fertilizer} = (0.65 \pm 0.64) \times 100$$

$$\text{Efficiency of fertilizer} = 65\% \pm 64$$

$$\text{C.V.} = 98 \%$$

Greenhouse experiment with Weswood soil, 2003. In this example, the N uptake in treatments with and without fertilizer is the average of ten plants which grew in the greenhouse.

$$\text{Efficiency of fertilizer} = \left(\frac{2.42(\pm 1.19) - 0.388(\pm 0.184)}{2.53(\pm 0.01)} \right) \times 100$$

$$S_y = \sqrt{(1.19)^2 + (0.184)^2} = 1.175$$

$$\text{Efficiency of fertilizer} = \left(\frac{2.032(\pm 1.175)}{2.53(\pm 0.01)} \right) \times 100$$

$$S_y = \sqrt{\left(\frac{1.175}{2.032} \right)^2 + \left(\frac{0.01}{2.53} \right)^2} = 0.5782$$

$$S_y = 0.803 \times 0.5782 = 0.464$$

$$S_y = 0.803 \pm 0.464$$

$$\text{Efficiency of fertilizer} = (0.80 \pm 0.46) \times 100$$

$$\text{Efficiency of fertilizer} = 80\% \pm 46\%$$

$$\text{C.V.} = 57\%$$

Accuracy and precision of the conceptual model

Requirement of fertilizer: an overall estimation in the 2003 greenhouse and field experiments

$$R.F. = \frac{\text{Nitrogen demand by crop} - \text{Supply of nitrogen by soil}}{\text{Efficiency of nitrogen fertilizer uptake}}$$

Where:

R.F. = Requirement of fertilizer.

$$R.F. = \frac{93 (\pm 28) - 67 (\pm 35)}{0.10 (\pm 0.09)}$$

Standard deviations of crop demand, nitrogen supply, and efficiency of uptake were ± 28 , ± 35 , and ± 0.09 , respectively, which is sometimes called the error. The standard deviation statistically is the deviation in relation to the mean (dispersion of data). In probability and statistics, the standard deviation is the most commonly used measure of statistical dispersion. Standard deviation is defined as the square root of the variance. It is defined this way in order to give a measure of dispersion that is (1) a non-negative number, and (2) has the same units as the data. There is a standard deviation σ (sigma) of a whole population or of a random variable, and the standard deviation s of a subset-population sample. The term standard deviation was introduced by Pearson in 1894 (Wales, 2005).

Simply put, the standard deviation tells us how far a typical member of the population (or sample) is from the mean value of that population (or sample). A large standard

deviation suggests that a typical member is far away from the mean. A small standard deviation suggests that members are clustered closely around the mean.

For example, the sets {0, 5, 9, 14} and {5, 6, 8, 9} each have a mean of 7, but the second set has a much smaller standard deviation. Standard deviation is often thought of as a measure of uncertainty. In physical science for example, when making repeated measurements, the standard deviation of the set of measurements is the precision or error of those measurements. When deciding whether measurements agree with a prediction, the standard deviation of those measurements is of crucial importance: if the mean of the measurements is too far away from the prediction (with the distance measured in standard deviations), then the measurement is considered as contradicting the prediction. This makes sense since the values fall outside the range of values that could reasonably be expected to occur if the prediction were correct.

$$S_y = \sqrt{(28)^2 + (35)^2} = 44.82$$

$$y = 93 - 67 = 26$$

$$\text{R.F.} = \frac{26 (\pm 44.82)}{0.10 (\pm 0.09)}$$

$$S_y / y = \sqrt{\left(\frac{44.82}{26}\right)^2 + \left(\frac{0.09}{0.10}\right)^2} = 1.94$$

$$y = \frac{26}{0.10} = 260, \text{ R.F.} = y = \text{variable.}$$

$$S_y = 260 \times 1.94 = 505.49$$

$$R.F. = 260 \pm 505$$

The actual nitrogen application per ha was 179 ± 5 kg N

Table 19. Requirement of nitrogen calculated with a conceptual model, using the nitrogen demand by crop, the nitrogen supply by soil, and the efficiency of fertilizer uptake, under field conditions in 2003 on a Ships soil series.

| | Nitrogen demand by corn | Nitrogen supply by soil | Efficiency of fertilizer uptake | Nitrogen requirement estimated with the model | Actual nitrogen application |
|----------|-----------------------------------|-------------------------------|---|---|-----------------------------------|
| | ----- kg N ha ⁻¹ ----- | | kg N uptake kg N applied ⁻¹ | ----- kg N ha ⁻¹ ----- | |
| Avg. | 93 | 67 | 0.10 | 260 a† | 179 a |
| S.D. | 28 | 35 | 0.09 | 505 | 5 |
| C.V. (%) | 30 | 52 | 90 | 194 | 3 |

† Same letter between nitrogen requirements estimated with the model and actual application indicate not statistically different, Tukey $\alpha = 0.05$.

$$\text{Nitrogen requirement} = \frac{93 (\pm 28) - 67 (\pm 35)}{0.10 (\pm 0.09)} = 260 (\pm 505)$$

Precision (± 505) was calculated using the error propagation method described previously.

Table 20. Requirement of nitrogen calculated with a conceptual model, using the nitrogen demand by crop, the nitrogen supply by soil, and the efficiency of fertilizer uptake, under greenhouse conditions, 2003.

| | Nitrogen demand by corn | Nitrogen supply by soil | Efficiency of fertilizer | Nitrogen requirement estimated with the model | Real application |
|----------|-------------------------------|----------------------------|---|--|---------------------|
| | g N plant ⁻¹ | g N pot ⁻¹ | g N uptake / g N applied ⁻¹ | ----- g N pot ⁻¹ ----- | |
| | Ships soil series | | | | |
| Avg. | 2.52 | 0.79 | 0.65 | 2.66 | 2.53 |
| S.D. | 1.7 | 0.9 | 0.6 | 3.9 | 0.01 |
| C.V. (%) | 67 | 126 | 98 | 150 | 0.4 |
| | Weswood soil series | | | | |
| Avg. | 2.42 | 0.08 | 0.80 | 2.92 | 2.53 |
| S.D. | 1.1 | 0.6 | 0.4 | 2.3 | 0.01 |
| C.V. (%) | 49 | 756 | 58 | 79 | 0.4 |

Tables 19 and 20 showed that the N requirement for Pioneer 32R25 was overestimated by 81 kg N ha⁻¹ in the field and 0.13 and 0.39 g N pot⁻¹ in the greenhouse, using the conceptual model of fertilization. The coefficient of variation (C.V.) in the field for the variables corn N demand, soil N supply, and efficiency of fertilizer uptake were 30, 52 and 90, respectively. The C.V. of these parameters was higher in the greenhouse than in the field. On the other hand, the corn N demand always had the lowest C.V. in both the field and greenhouse.

From the three parameters used in the conceptual model, corn N demand showed the lowest variation (Tables 19 and 20). This result was possibly due to the hybrid Pioneer 32R25™ having homogeneity in its genetic characteristics. Soil showed more variation in the supply of N compared with N uptake by plants. In the field (Table 19) there was not a clear response in the soil mineralization produced by the N application (Fig. 53).

To estimate accuracy, the following formula was used:

$$\text{Accuracy, \%} = 100 - \left(\left| \frac{\text{Actual value} - \text{Estimated value}}{\text{Actual value}} \right| \times 100 \right)$$

The accuracy of the model for the 2003 field experiment was:

$$\text{Accuracy, \%} = 100 - \left(\left| \frac{179 - 260}{179} \right| \times 100 \right) = 54.74 \%$$

The accuracy of the conceptual model to estimate the requirement of N in the field was around 55%. This accuracy was low primarily because of the low response of corn to N fertilization. The low N response by corn was probably due to excess residual and mineralizable N (Fig. 53).

Table 21. Accuracy and precision of the conceptual model under field and greenhouse conditions in 2003.

| Place | Soil | Accuracy | Precision |
|------------|---------|----------|-----------|
| | | % | |
| Field | Ships | 55 | 194 |
| Greenhouse | Ships | 95 | 150 |
| Greenhouse | Weswood | 85 | 80 |

The accuracy of the conceptual model was higher in the greenhouse than in the field (Table 21). Precision, measured as the dispersion of the data around the mean value, was better in the greenhouse than in the field, and, inside the greenhouse, was more precise in the Weswood soil than in Ships. Data presented in Fig. 39 showed that for treatments without N fertilizer the dispersion of the yield was lower than in fertilized treatments.

This could mean that the higher the availability of nitrogen, the higher the probability of finding a wider range of corn N uptake nitrogen as a consequence of a wider range of corn yield.

6. CONCLUSIONS

Nitrogen concentration, root index, moisture content, harvest index, and the yield of corn in the field and greenhouse varied, but followed predictable behavior.

The error propagation method estimated that the algorithm to calculate the errors for nitrogen demand in the field was 30%, to estimate the supply of nitrogen by the soil was 52%, and to estimate the precision of the efficiency of fertilizer uptake was 90%. In the greenhouse experiment, using Ships and Weswood soils, the precision of nitrogen demand was greater than the efficiency of fertilizer uptake, which was greater than nitrogen supply by soil.

The accuracy of the conceptual model was low under field conditions (55%) but high under greenhouse conditions (90%). The precision was low both in the field (194%) and the greenhouse (115%).

This research determined the range of variation of parameters used in the conceptual model, and measured the error of this model to estimate the corn plant requirement of N. The model overestimated the N requirement of corn not only in field, but also in greenhouse experiments. Overestimating the required N could produce groundwater contamination with NO_3 , atmospheric contamination with NO and N_2O , and lost profit from applying more N fertilizer than required by corn crop.

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APPENDIX

Table A1. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 46 days after planting (DAP).

| 1† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|----------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 46‡ | a.g.b.§ | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | Index |
| Plant number†† | | | g | | | % | | cm | % |
| 1 | 11.4 | 2.8 | 1.05 | 0.25 | 90.79 | 91.07 | 18 | 22.5 | 24.5 |
| 2 | 11.8 | 3.5 | 1.11 | 0.35 | 90.59 | 90.00 | 17 | 23.0 | 29.6 |
| 3 | 14.4 | 3.4 | 1.45 | 0.26 | 89.93 | 92.35 | 18 | 20.5 | 23.6 |
| 4 | 15.8 | 4.3 | 1.67 | 0.65 | 89.43 | 84.88 | 18 | 17.0 | 27.2 |
| 5 | 21.3 | 5.0 | 2.27 | 0.57 | 89.34 | 88.60 | 22 | 21.0 | 23.4 |
| 6 | 20.5 | 6.2 | 2.03 | 0.77 | 90.10 | 87.58 | 19 | 17.0 | 30.2 |
| Mean | 15.8 | 4.2 | 1.60 | 0.48 | 90.03 | 89.08 | 18 | 20.1 | 26.4 |
| SD | 4.23 | 1.24 | 0.49 | 0.22 | 0.59 | 2.67 | 1.75 | 2.62 | 3.03 |
| CV (%) | 26.7 | 29.6 | 30.73 | 46.04 | 0.66 | 3.00 | 9.38 | 12.99 | 11.45 |

† First sampling in 2002 field experiment.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root beginning to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The number of plants varies with the sampling date due to the time and effort used to collected, measure and prepare the samples in the same day.

Table A2. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 53 days after planting.

| 2† 53‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|---------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | | % | | cm | % |
| 1 | 25.60 | 6.00 | 2.80 | 0.72 | 89.06 | 88.00 | 24.0 | 18.5 | 23.44 |
| 2 | 42.80 | 6.90 | 4.83 | 0.82 | 88.71 | 88.12 | 28.0 | 26.0 | 16.12 |
| 3 | 48.30 | 6.40 | 5.59 | 0.83 | 88.43 | 87.03 | 30.0 | 18.0 | 13.25 |
| 4 | 68.90 | 8.70 | 7.30 | 1.23 | 89.40 | 85.86 | 34.0 | 22.0 | 12.63 |
| 5 | 31.60 | 4.30 | 3.63 | 0.60 | 88.51 | 86.05 | 27.0 | 32.0 | 13.61 |
| 6 | 56.70 | 8.99 | 6.38 | 1.21 | 88.75 | 86.54 | 34.0 | 23.0 | 15.86 |
| 7 | 36.40 | 8.60 | 4.22 | 1.30 | 88.41 | 84.88 | 27.5 | 19.0 | 23.63 |
| 8 | 69.20 | 9.25 | 7.80 | 1.33 | 88.73 | 85.62 | 37.0 | 20.0 | 13.37 |
| 9 | 36.60 | 4.95 | 4.15 | 0.64 | 88.66 | 87.07 | 28.0 | 22.0 | 13.52 |
| 10 | 64.45 | 10.50 | 7.11 | 1.46 | 88.97 | 86.10 | 33.0 | 22.0 | 16.29 |
| 11 | 48.65 | 7.60 | 5.88 | 1.20 | 87.91 | 84.21 | 30.0 | 19.0 | 15.62 |
| 12 | 39.80 | 5.10 | 4.54 | 0.85 | 88.59 | 83.33 | 30.5 | 20.0 | 12.81 |
| 13 | 58.10 | 7.00 | 6.84 | 1.25 | 88.23 | 82.14 | 33.0 | 19.0 | 12.05 |
| 14 | 31.25 | 8.70 | 3.93 | 0.93 | 87.42 | 89.31 | 25.0 | 18.0 | 27.84 |
| 15 | 64.40 | 14.40 | 7.73 | 1.65 | 88.00 | 88.54 | 35.0 | 23.0 | 22.36 |
| Mean | 48.18 | 7.83 | 5.52 | 1.07 | 88.52 | 86.19 | 30.4 | 21.4 | 16.83 |
| SD | 14.67 | 2.55 | 1.62 | 0.32 | 0.49 | 1.97 | 3.84 | 3.71 | 4.98 |
| CV (%) | 30.45 | 32.57 | 29.43 | 29.82 | 0.56 | 2.29 | 12.62 | 17.30 | 29.61 |

† Second sampling in 2002 field experiment.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A3. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 60 days after planting.

| 3† 60‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|---------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | | % | | cm | % |
| 1 | 88.71 | 10.72 | 10.36 | 1.89 | 88.32 | 82.37 | 40.5 | 20 | 12.08 |
| 2 | 205.61 | 27.45 | 23.94 | 4.34 | 88.36 | 84.19 | 52.0 | 30 | 13.35 |
| 3 | 172.99 | 20.70 | 20.80 | 3.65 | 87.98 | 82.37 | 58.0 | 25 | 11.97 |
| 4 | 172.92 | 24.89 | 21.96 | 4.11 | 87.30 | 83.49 | 54.0 | 20 | 14.39 |
| 5 | 109.31 | 8.83 | 12.21 | 1.52 | 88.83 | 82.79 | 44.0 | 17 | 8.08 |
| 6 | 162.98 | 18.69 | 19.61 | 3.19 | 87.97 | 82.93 | 49.0 | 21 | 11.47 |
| 7 | 166.66 | 15.77 | 20.10 | 2.65 | 87.94 | 83.20 | 48.0 | 23 | 9.46 |
| 8 | 91.99 | 11.51 | 9.80 | 1.77 | 89.35 | 84.62 | 37.0 | 22 | 12.51 |
| 9 | 200.80 | 21.13 | 24.35 | 3.33 | 87.87 | 84.24 | 54.0 | 28 | 10.52 |
| 10 | 141.23 | 11.83 | 17.09 | 2.09 | 87.90 | 82.33 | 48.0 | 17 | 8.38 |
| 11 | 132.60 | 17.85 | 16.90 | 3.27 | 87.25 | 81.68 | 48.0 | 29 | 13.46 |
| 12 | 198.69 | 21.10 | 23.67 | 3.68 | 88.09 | 82.56 | 56.0 | 27 | 10.62 |
| 13 | 88.11 | 10.98 | 11.41 | 1.95 | 87.05 | 82.24 | 40.0 | 26 | 12.46 |
| 14 | 71.83 | 4.34 | 8.11 | 0.79 | 88.71 | 81.80 | 37.0 | 16 | 6.04 |
| 15 | 139.07 | 8.65 | 16.66 | 1.51 | 88.02 | 82.54 | 49.0 | 25 | 6.22 |
| Mean | 142.90 | 15.63 | 17.13 | 2.65 | 88.06 | 82.89 | 47.6 | 23 | 10.73 |
| SD | 44.73 | 6.68 | 5.55 | 1.08 | 0.61 | 0.89 | 6.71 | 4.53 | 2.60 |
| CV (%) | 31.30 | 42.76 | 32.39 | 40.83 | 0.69 | 1.08 | 14.09 | 19.63 | 24.19 |

† Third sampling in 2002 field experiment.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A4. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 67 days after planting.

| 4† 67‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|---------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | % | | cm | | % |
| 1 | 260.00 | 32.0 | 33.55 | 5.00 | 87.10 | 84.38 | 68 | 32 | 12.31 |
| 2 | 373.40 | 36.8 | 41.45 | 5.79 | 88.90 | 84.27 | 77 | 33 | 9.86 |
| 3 | 316.05 | 28.0 | 34.88 | 4.80 | 88.96 | 82.86 | 80 | 28 | 8.86 |
| 4 | 216.48 | 22.5 | 23.00 | 3.69 | 89.38 | 83.60 | 74 | 35 | 10.39 |
| 5 | 331.02 | 28.2 | 35.40 | 4.55 | 89.31 | 83.87 | 87 | 40 | 8.52 |
| 6 | 191.50 | 14.6 | 23.40 | 2.80 | 87.78 | 80.82 | 60 | 39 | 7.62 |
| 7 | 322.83 | 29.9 | 36.80 | 5.07 | 88.60 | 83.04 | 75 | 35 | 9.26 |
| 8 | 128.55 | 8.9 | 16.45 | 2.00 | 87.20 | 77.53 | 58 | 33 | 6.92 |
| 9 | 266.22 | 23.8 | 32.70 | 4.50 | 87.72 | 81.09 | 73 | 33 | 8.94 |
| 10 | 198.00 | 16.8 | 25.60 | 3.17 | 87.07 | 81.13 | 63 | 34 | 8.48 |
| Mean | 260.41 | 24.1 | 30.32 | 4.14 | 88.20 | 82.26 | 71 | 34.2 | 9.12 |
| SD | 76.55 | 8.61 | 7.78 | 1.18 | 0.93 | 2.13 | 9.20 | 3.43 | 1.50 |
| CV (%) | 29.40 | 35.64 | 25.66 | 28.58 | 1.05 | 2.59 | 12.87 | 10.02 | 16.46 |

† Fourth sampling in 2002 field experiment.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A5. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 74 days after planting.

| 5† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 74‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 561 | 85 | 68.0 | 14.5 | 87.88 | 82.94 | 118.11 | 31.00 | 15.15 |
| 2 | 362 | 31 | 41.5 | 5.5 | 88.54 | 82.26 | 114.30 | 21.59 | 8.56 |
| 3 | 539 | 55 | 65.0 | 9.5 | 87.94 | 82.73 | 137.16 | 41.91 | 10.20 |
| 4 | 629 | 73 | 77.0 | 14.0 | 87.76 | 80.82 | 147.32 | 27.94 | 11.61 |
| 5 | 673 | 84 | 83.0 | 14.9 | 87.67 | 82.26 | 152.40 | 22.86 | 12.48 |
| 6 | 731 | 122 | 89.0 | 21.5 | 87.82 | 82.38 | 142.24 | 27.94 | 16.69 |
| 7 | 684 | 100 | 74.0 | 16.1 | 89.18 | 83.90 | 121.92 | 26.67 | 14.62 |
| 8 | 732 | 119 | 87.0 | 22.0 | 88.11 | 81.51 | 127.00 | 17.78 | 16.26 |
| 9 | 799 | 168 | 93.0 | 27.3 | 88.36 | 83.75 | 119.38 | 30.48 | 21.03 |
| 10 | 692 | 142 | 80.0 | 21.6 | 88.44 | 84.79 | 132.08 | 29.21 | 20.52 |
| 11 | 480 | 56 | 59.0 | 10.5 | 87.71 | 81.25 | 119.38 | 31.75 | 11.67 |
| 12 | 807 | 149 | 92.0 | 25.6 | 88.60 | 82.82 | 129.54 | 36.83 | 18.46 |
| 13 | 793 | 145 | 92.0 | 22.5 | 88.40 | 84.48 | 129.54 | 33.02 | 18.28 |
| 14 | 788 | 145 | 94.0 | 23.5 | 88.07 | 83.79 | 139.70 | 34.29 | 18.40 |
| 15 | 590 | 63 | 69.0 | 10.1 | 88.31 | 83.97 | 129.54 | 26.67 | 10.68 |
| Mean | 657.3 | 102.4 | 77.5 | 17.2 | 88.19 | 82.91 | 130.64 | 29.33 | 14.97 |
| SD | 130.49 | 42.17 | 15.03 | 6.64 | 0.42 | 1.19 | 11.29 | 6.07 | 3.94 |
| CV (%) | 19.85 | 41.15 | 19.37 | 38.42 | 0.47 | 1.44 | 8.64 | 20.70 | 26.34 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A6. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 80 days after planting.

| 6† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 80‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 1174 | 243 | 175 | 58.0 | 85.09 | 76.13 | 163.83 | 36.83 | 20.70 |
| 2 | 1045 | 194 | 137 | 42.8 | 86.89 | 77.94 | 193.04 | 36.83 | 18.56 |
| 3 | 932 | 176 | 130 | 40.4 | 86.05 | 77.05 | 168.91 | 35.56 | 18.88 |
| 4 | 571 | 99 | 82 | 22.0 | 85.64 | 77.78 | 154.94 | 30.48 | 17.34 |
| 5 | 329 | 24 | 41 | 4.9 | 87.54 | 79.58 | 140.97 | 27.31 | 7.29 |
| 6 | 818 | 110 | 115 | 26.9 | 85.94 | 75.55 | 119.38 | 33.02 | 13.45 |
| 7 | 1041 | 198 | 148 | 48.0 | 85.78 | 75.76 | 184.15 | 42.55 | 19.02 |
| 8 | 778 | 153 | 119 | 33.3 | 84.70 | 78.24 | 175.26 | 25.40 | 19.67 |
| 9 | 751 | 136 | 106 | 28.1 | 85.89 | 79.34 | 180.34 | 40.64 | 18.11 |
| 10 | 885 | 149 | 127 | 34.0 | 85.65 | 77.18 | 187.96 | 24.13 | 16.84 |
| 11 | 712 | 120 | 119 | 23.5 | 83.29 | 80.42 | 176.53 | 24.13 | 16.85 |
| 12 | 704 | 81 | 108 | 17.8 | 84.66 | 78.02 | 170.18 | 27.94 | 11.51 |
| 13 | 684 | 121 | 99 | 24.5 | 85.53 | 79.75 | 179.07 | 33.02 | 17.69 |
| 14 | 810 | 173 | 134 | 37.8 | 83.46 | 78.15 | 176.53 | 27.94 | 21.36 |
| 15 | 850 | 197 | 123 | 43.0 | 85.53 | 78.17 | 162.56 | 27.94 | 23.18 |
| 16 | 979 | 196 | 169 | 42.3 | 82.74 | 78.42 | 170.18 | 35.56 | 20.02 |
| Mean | 816.4 | 148.1 | 120.7 | 32.9 | 85.27 | 77.97 | 168.99 | 31.83 | 17.53 |
| SD | 203.45 | 54.86 | 31.98 | 13.11 | 1.27 | 1.41 | 18.38 | 5.78 | 3.93 |
| CV (%) | 24.92 | 37.04 | 26.48 | 39.77 | 1.49 | 1.80 | 10.87 | 18.15 | 22.41 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A7. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 87 days after planting.

| 7† 87‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|--------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | | % | | cm | % |
| 1 | 1152 | 240 | 321.0 | 47.9 | 72.14 | 80.04 | 205.0 | 29 | 20.83 |
| 2 | 1157 | 238 | 266.4 | 47.1 | 76.97 | 80.21 | 175.0 | 29 | 20.57 |
| 3 | 1300 | 424 | 403.2 | 90.4 | 68.98 | 78.68 | 184.0 | 43 | 32.62 |
| 4 | 1400 | 323 | 398.2 | 56.2 | 71.56 | 82.60 | 191.0 | 39 | 23.07 |
| 5 | 871 | 199 | 244.1 | 37.5 | 71.97 | 81.16 | 208.5 | 36 | 22.85 |
| 6 | 891 | 253 | 265.8 | 49.8 | 70.17 | 80.32 | 179.0 | 37 | 28.40 |
| 7 | 1021 | 212 | 311.1 | 41.8 | 69.53 | 80.28 | 195.0 | 38 | 20.76 |
| 8 | 763 | 117 | 199.0 | 22.2 | 73.92 | 81.03 | 207.5 | 44 | 15.33 |
| 9 | 704 | 93 | 227.0 | 18.8 | 67.76 | 79.78 | 203.0 | 44 | 13.21 |
| 10 | 538 | 59 | 137.5 | 11.8 | 74.44 | 80.00 | 199.5 | 36 | 10.97 |
| 11 | 774 | 146 | 180.8 | 24.9 | 76.64 | 82.95 | 206.0 | 39 | 18.86 |
| 12 | 968 | 180 | 348.4 | 37.5 | 64.01 | 79.17 | 162.0 | 32 | 18.60 |
| 13 | 715 | †† | 171.1 | | 76.07 | | 170.0 | | |
| 14 | 561 | | 156.0 | | 72.19 | | 197.0 | | |
| 15 | 760 | | 229.6 | | 69.79 | | 205.0 | | |
| Mean | 905 | 207 | 257.2 | 40.4 | 71.74 | 80.52 | 192.5 | 37.1 | 20.51 |
| SD | 258.04 | 101.02 | 84.39 | 20.92 | 3.56 | 1.25 | 15.03 | 5.20 | 6.02 |
| CV (%) | 28.51 | 48.80 | 32.80 | 51.66 | 4.96 | 1.56 | 7.81 | 14.00 | 29.35 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† Blank cells means there are no data, only aboveground biomass was taken. A threat of strong thunderstorm was coming.

Table A8. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 94 days after planting.

| 8† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 94‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 1080.0 | 206.1 | 249.2 | 39.9 | 76.93 | 80.64 | 204.0 | 36 | 19.08 |
| 2 | 1275.8 | 281.7 | 279.6 | 51.1 | 78.08 | 81.86 | 185.0 | 32 | 22.08 |
| 3 | 1195.2 | 223.0 | 326.1 | 39.1 | 72.72 | 82.47 | 204.0 | 38 | 18.66 |
| 4 | 1317.6 | 267.5 | 285.2 | 44.0 | 78.35 | 83.55 | 180.0 | 38 | 20.30 |
| 5 | 1308.2 | 296.1 | 331.6 | 57.0 | 74.65 | 80.75 | 195.0 | 51 | 22.63 |
| 6 | 544.2 | 80.2 | 134.5 | 14.2 | 75.28 | 82.29 | 200.0 | 38 | 14.74 |
| 7 | 967.9 | 170.0 | 312.6 | 32.0 | 67.70 | 81.18 | 207.0 | 35 | 17.56 |
| 8 | 991.0 | 181.1 | 283.9 | 32.0 | 71.35 | 82.33 | 225.0 | 38 | 18.27 |
| 9 | 1125.8 | 236.8 | 315.8 | 46.5 | 71.95 | 80.36 | 157.0 | 45 | 21.03 |
| 10 | 774.9 | 124.1 | 193.0 | 24.1 | 75.09 | 80.58 | 180.2 | 37 | 16.01 |
| 11 | 574.0 | 85.2 | 166.8 | 16.1 | 70.94 | 81.10 | 184.0 | 27 | 14.84 |
| 12 | 1091.9 | 168.0 | 312.8 | 28.3 | 71.35 | 83.15 | 208.1 | 34 | 15.39 |
| Mean | 1020.5 | 193.3 | 265.9 | 35.3 | 73.70 | 81.69 | 194.1 | 37.4 | 18.38 |
| SD | 265.71 | 72.25 | 66.32 | 13.37 | 3.24 | 1.07 | 17.84 | 6.14 | 2.77 |
| CV (%) | 26.04 | 37.37 | 24.94 | 37.82 | 4.39 | 1.31 | 9.19 | 16.39 | 15.04 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A9. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 101 days after planting.

| 9† 10‡1 | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|--------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | | % | | cm | % |
| 1 | 1159 | 187 | 235 | 33 | 79.72 | 82.35 | 168 | 36.0 | 16.13 |
| 2 | 954 | 190 | 201 | 40 | 78.93 | 78.95 | 203 | 34.5 | 19.92 |
| 3 | 1425 | 334 | 308 | 41 | 78.39 | 87.72 | 194 | 45.0 | 23.44 |
| 4 | 1061 | 182 | 247 | 31 | 76.72 | 82.97 | 172 | 43.5 | 17.15 |
| 5 | 929 | 175 | 210 | 32 | 77.40 | 81.71 | 200 | 36.5 | 18.84 |
| 6 | 934 | 151 | 198 | 23 | 78.80 | 84.77 | 201 | 52.0 | 16.17 |
| 7 | 1296 | 258 | 264 | 43 | 79.63 | 83.33 | 210 | 34.0 | 19.91 |
| 8 | 1278 | 238 | 273 | 46 | 78.64 | 80.67 | 200 | 42.0 | 18.62 |
| 9 | 1302 | 257 | 289 | 44 | 77.80 | 82.88 | 192 | 42.0 | 19.74 |
| 10 | 1409 | 302 | 295 | 54 | 79.06 | 82.12 | 187 | 40.0 | 21.43 |
| 11 | 1301 | 258 | 275 | 42 | 78.86 | 83.72 | 186 | 39.5 | 19.83 |
| 12 | 989 | 201 | 215 | 31 | 78.26 | 84.58 | 183 | 35.0 | 20.32 |
| 13 | 1098 | 204 | 238 | 30 | 78.32 | 85.29 | 190 | 38.0 | 18.58 |
| Mean | 1164.2 | 225.9 | 249.8 | 37.7 | 78.50 | 83.16 | 191.2 | 39.8 | 19.24 |
| SD | 181.25 | 53.76 | 37.16 | 8.45 | 0.84 | 2.20 | 12.15 | 5.10 | 2.03 |
| CV (%) | 15.57 | 23.80 | 14.87 | 22.42 | 1.07 | 2.65 | 6.36 | 12.81 | 10.56 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A10. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 108 days after planting.

| 10† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 108‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 1203 | 185 | 308 | 34.5 | 74.40 | 81.35 | 205 | 53 | 15.38 |
| 2 | 1265 | 213 | 266 | 42.6 | 78.97 | 80.00 | 177 | 47 | 16.84 |
| 3 | 1509 | 327 | 358 | 78.1 | 76.28 | 76.12 | 190 | 44 | 21.67 |
| 4 | 1224 | 299 | 302 | 62.0 | 75.33 | 79.26 | 182 | 53 | 24.43 |
| 5 | 1177 | 287 | 294 | 52.1 | 75.02 | 81.85 | 182 | 49 | 24.38 |
| 6 | 885 | 143 | 246 | 23.5 | 72.20 | 83.57 | 186 | 36 | 16.16 |
| 7 | 1039 | 205 | 291 | 28.5 | 71.99 | 86.10 | 179 | 30 | 19.73 |
| 8 | 1169 | 204 | 299 | 35.0 | 74.42 | 82.84 | 200 | 26 | 17.45 |
| 9 | 1205 | 368 | 324 | 89.5 | 73.11 | 75.68 | 183 | 33 | 30.54 |
| 10 | 1340 | 280 | 303 | 48.1 | 77.39 | 82.82 | 196 | 41 | 20.90 |
| 11 | 1436 | 182 | 343 | 38.5 | 76.11 | 78.85 | 205 | 41 | 12.67 |
| 12 | 778 | 150 | 207 | 23.9 | 73.39 | 84.07 | 201 | 45 | 19.28 |
| Mean | 1185.8 | 236.9 | 295.0 | 46.3 | 74.88 | 81.04 | 190.5 | 41.5 | 19.95 |
| SD | 208.44 | 72.79 | 40.92 | 20.98 | 2.09 | 3.17 | 10.39 | 8.76 | 4.86 |
| CV (%) | 17.58 | 30.72 | 13.87 | 45.25 | 2.79 | 3.91 | 5.45 | 21.12 | 24.38 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A11. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 115 days after planting.

| 11† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 115‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 1029 | 121 | 311.5 | 26.1 | 69.73 | 78.43 | 169 | 29 | 11.76 |
| 2 | 1012 | 201 | 347.8 | 38.0 | 65.63 | 81.09 | 199 | 39 | 19.86 |
| 3 | 809 | 136 | 275.1 | 31.0 | 66.00 | 77.21 | 201 | 39 | 16.81 |
| 4 | 1213 | 204 | 370.5 | 33.2 | 69.46 | 83.73 | 176 | 44 | 16.82 |
| 5 | 1074 | 169 | 327.0 | 30.4 | 69.55 | 82.01 | 194 | 47 | 15.74 |
| 6 | 1047 | 238 | 362.5 | 44.0 | 65.38 | 81.51 | 187 | 39 | 22.73 |
| 7 | 1238 | 233 | 413.5 | 41.2 | 66.60 | 82.32 | 198 | 38 | 18.82 |
| 8 | 1183 | 236 | 423.0 | 84.0 | 64.24 | 64.41 | 195 | 42 | 19.95 |
| 9 | 956 | 196 | 280.8 | 35.5 | 70.63 | 81.89 | 175 | 46 | 20.50 |
| 10 | 1578 | 369 | 534.5 | 68.0 | 66.13 | 81.57 | 192 | 39 | 23.38 |
| 11 | 1029 | 160 | 327.5 | 28.5 | 68.17 | 82.19 | 203 | 50 | 15.55 |
| 12 | 1058 | 146 | 329.1 | 25.5 | 68.89 | 82.53 | 207 | 47 | 13.80 |
| Mean | 1102.1 | 200.7 | 358.5 | 40.4 | 67.53 | 79.91 | 191.3 | 41.6 | 17.98 |
| SD | 189.65 | 66.22 | 71.64 | 17.87 | 2.10 | 5.20 | 12.13 | 5.66 | 3.52 |
| CV (%) | 17.21 | 32.98 | 19.98 | 44.19 | 3.12 | 6.51 | 6.34 | 13.62 | 19.57 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A12. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 122 days after planting.

| 12† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-------|
| 122‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index |
| Plant number | | | g | | | % | | cm | % |
| 1 | 706.5 | 117.0 | 207.0 | 21.8 | 70.70 | 81.37 | 185 | 34.0 | 16.56 |
| 2 | 793.0 | 176.0 | 274.5 | 33.5 | 65.38 | 80.97 | 192 | 36.5 | 22.19 |
| 3 | 1263.0 | 230.5 | 389.8 | 34.9 | 69.14 | 84.86 | 195 | 37.5 | 18.25 |
| 4 | 1297.5 | 269.0 | 435.2 | 52.1 | 66.46 | 80.63 | 187 | 30.0 | 20.73 |
| 5 | 1098.0 | 201.0 | 412.9 | 42.5 | 62.40 | 78.86 | 199 | 31.0 | 18.31 |
| 6 | 1231.2 | 268.5 | 417.4 | 49.0 | 66.10 | 81.75 | 200 | 42.0 | 21.81 |
| 7 | †† | | | | | | 200 | 39.0 | |
| 8 | 968.5 | 168.0 | 371.2 | 36.0 | 61.67 | 78.57 | 218 | 33.0 | 17.35 |
| 9 | 1142.0 | 236.0 | 386.2 | 37.1 | 66.18 | 84.28 | 178 | 31.0 | 20.67 |
| 10 | 833.0 | 155.5 | 340.5 | 31.5 | 59.12 | 79.74 | 212 | 49.0 | 18.67 |
| 11 | 1154.0 | 221.0 | 456.1 | 40.8 | 60.48 | 81.54 | 208 | 38.0 | 19.15 |
| 12 | 1032.0 | 243.0 | 402.8 | 50.8 | 60.97 | 79.09 | 197 | 32.0 | 23.55 |
| 13 | 1267.0 | 261.5 | 486.0 | 50.8 | 61.64 | 80.57 | 206 | 38.0 | 20.64 |
| Mean | 1065.5 | 212.2 | 381.6 | 40.1 | 64.19 | 81.02 | 198.2 | 36.2 | 19.82 |
| SD | 200.76 | 49.01 | 77.39 | 9.36 | 3.65 | 1.97 | 11.20 | 5.31 | 2.11 |
| CV (%) | 18.84 | 23.09 | 20.28 | 23.36 | 5.69 | 2.43 | 5.65 | 14.67 | 10.64 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† Blank cells means there are no data. Plant 6 shows the average between plant number 6 and 7. The roots of both plants were strongly interlaced.

Table A13. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 129 days after planting.

| 13† 129‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|---------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | % | | cm | | % |
| 1 | 1039 | 183 | 421 | 34 | 59.48 | 81.42 | 201 | 32 | 17.61 |
| 2 | 972 | 185 | 388 | 33 | 60.08 | 82.16 | 202 | 31 | 19.03 |
| 3 | 1171 | 203 | 427 | 38 | 63.54 | 81.28 | 188 | 34 | 17.34 |
| 4 | 1171 | 264 | 456 | 56 | 61.06 | 78.79 | 199 | 42 | 22.54 |
| 5 | 1143 | 180 | 424 | 34 | 62.90 | 81.11 | 204 | 37 | 15.75 |
| 6 | 769 | 159 | 331 | 25 | 56.96 | 84.28 | 180 | 40 | 20.68 |
| 7 | 1128 | 214 | 435 | 35 | 61.44 | 83.64 | 201 | 39 | 18.97 |
| 8 | 1115 | 245 | 427 | 43 | 61.70 | 82.45 | 196 | 49 | 21.97 |
| 9 | 1235 | 222 | 466 | 38 | 62.27 | 82.88 | 187 | 43 | 17.98 |
| Mean | 1082.5 | 206.1 | 419.4 | 37.3 | 61.05 | 82.00 | 195.3 | 38.5 | 19.10 |
| SD | 140.58 | 33.67 | 39.83 | 8.51 | 1.99 | 1.61 | 8.34 | 5.77 | 2.25 |
| CV (%) | 12.99 | 16.34 | 9.50 | 22.81 | 3.27 | 1.97 | 4.27 | 14.96 | 11.77 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A14. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 136 days after planting.

| 14† 136‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index |
|---------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|---------------|
| Plant number | | | g | | | % | | cm | % |
| 1 | 827 | 134 | 387 | 30 | 53.20 | 77.61 | 209 | 42 | 16.20 |
| 2 | 794 | 120 | 346 | 26 | 56.42 | 78.33 | 209 | 33 | 15.11 |
| 3 | 774 | 150 | 362 | 34 | 53.23 | 77.33 | 207 | 32 | 19.38 |
| 4 | 934 | 186 | 432 | 42 | 53.75 | 77.42 | 206 | 32 | 19.91 |
| 5 | 786 | 135 | 386 | 31 | 50.89 | 77.04 | 217 | 41 | 17.18 |
| 6 | 791 | 147 | 409 | 33 | 48.29 | 77.55 | 203 | 44 | 18.58 |
| 7 | 816 | 206 | 394 | 48 | 51.72 | 76.70 | 197 | 33 | 25.25 |
| 8 | 739 | 175 | 384 | 38 | 48.04 | 78.29 | 196 | 36 | 23.68 |
| 9 | 1099 | 234 | 542 | 47 | 50.68 | 79.91 | 180 | 53 | 21.29 |
| 10 | 937 | 240 | 452 | 54 | 51.76 | 77.50 | 179 | 52 | 25.61 |
| 11 | 1084 | 307 | 495 | 64 | 54.34 | 79.15 | 189 | 41 | 28.32 |
| 12 | 819 | 298 | 419 | 70 | 48.84 | 76.51 | 191 | 49 | 36.39 |
| Mean | 866.7 | 194.3 | 417.3 | 43.1 | 51.76 | 77.78 | 198.6 | 40.7 | 22.24 |
| SD | 120.42 | 63.65 | 56.22 | 13.95 | 2.57 | 0.99 | 12.02 | 7.70 | 6.03 |
| CV (%) | 13.89 | 32.76 | 13.47 | 32.38 | 4.97 | 1.28 | 6.05 | 18.94 | 27.12 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

Table A15. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 143 days after planting.

| 15† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root | Nitrogen |
|--------------|--------------|--------------|------------|------------|----------------|------------------|-----------|-----------|-----------------------------|-------------------------|
| 143‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index | content†† |
| Plant number | | | g | | | % | cm | | g roots g ⁻¹ agb | g N plant ⁻¹ |
| 1 | 498.0 | 114 | 280.0 | 24.0 | 43.78 | 78.95 | 192 | 35.0 | 0.23 | 3.07 |
| 2 | 626.0 | 127 | 348.5 | 31.0 | 44.33 | 75.59 | 220 | 37.5 | 0.20 | 4.19 |
| 3 | 586.5 | 125 | 328.5 | 26.5 | 43.99 | 78.80 | 203 | 33.4 | 0.21 | 3.53 |
| 4 | 738.0 | 167 | 381.5 | 38.0 | 48.31 | 77.25 | 206 | 39.0 | 0.23 | 3.77 |
| 5 | 615.0 | 130 | 361.5 | 29.5 | 41.22 | 77.31 | 185 | 41.5 | 0.21 | 3.99 |
| 6 | 613.0 | 144 | 355.5 | 36.0 | 42.01 | 75.00 | 200 | 36.4 | 0.23 | 4.29 |
| 7 | 670.0 | 173 | 357.0 | 38.5 | 46.72 | 77.75 | 204 | 34.0 | 0.26 | 4.88 |
| 8 | 485.0 | 81 | 279.5 | 24.5 | 42.37 | 69.75 | 203 | 42.0 | 0.17 | 3.24 |
| 9 | 597.0 | 161 | 340.5 | 35.0 | 42.96 | 78.26 | 200 | 41.6 | 0.27 | 4.66 |
| 10 | 694.0 | 176 | 369.0 | 40.0 | 46.83 | 77.27 | 201 | 31.0 | 0.25 | 4.64 |
| 11 | 657.5 | 17 | 370.0 | 38.0 | 43.73 | 78.41 | 197 | 34.5 | 0.27 | 4.77 |
| 12 | 752.5 | 176 | 428.0 | 39.0 | 43.12 | 77.84 | 210 | 51.3 | 0.23 | 4.79 |
| Mean | 627.7 | 145.8 | 349.9‡‡ | 33.3‡‡ | 44.11 | 76.85 | 201.7 | 38.1 | 0.23 | 4.15 |
| SD | 82.58 | 30.76 | 40.98 | 5.94 | 2.14 | 2.53 | 8.70 | 5.47 | 0.03 | 0.63 |
| CV (%) | 13.16 | 21.09 | 11.71 | 17.83 | 4.84 | 3.29 | 4.31 | 14.36 | 12.90 | 15.21 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The nitrogen content is the total nitrogen content in whole the corn plant.

‡‡ The dry weight of agb and roots at 143 dap is lower than at 136 dap probably due to the following reasons: lost of plant material due to management from the field to the laboratory, natural lost of dry matter including incorporation of roots organic matter to the soil and lost of tassel, corn hair, and small pieces of leaves. This last reason was evident at 143 dap given that the material was too dry and fragile.

Table A16. Plant characteristics from the 2002 field experiment with corn hybrid Pioneer 32R25, 154 days after planting.

| 16† 154‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant¶ | Depth of roots# | Root index | Nitrogen content†† |
|--------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|---------------------|--------------------|-----------------------------|-------------------------|
| Plant number | | g | | | % | | cm | | g roots g ⁻¹ agb | g N plant ⁻¹ |
| 1 | 600 | 105 | 358 | 34 | 40.33 | 67.62 | 206.0 | 32.0 | 0.18 | 4.01 |
| 2 | 639 | 100 | 436 | 30 | 31.77 | 70.00 | 214.0 | 39.5 | 0.16 | 4.39 |
| 3 | 580 | 105 | 351 | 28 | 39.48 | 73.33 | 200.0 | 46.5 | 0.18 | 4.21 |
| 4 | 659 | 223 | 415 | 31 | 37.03 | 72.20 | 180.0 | 38.0 | 0.34 | 5.23 |
| 5 | 451 | 138 | 311 | 35 | 31.04 | 74.64 | 202.0 | 28.0 | 0.31 | 3.68 |
| 6 | 451 | 106 | 289 | 28 | 35.92 | 73.58 | 195.0 | 30.0 | 0.24 | 2.92 |
| 7 | 512 | 82 | 340 | 24 | 33.59 | 70.73 | 189.0 | 31.0 | 0.16 | 3.68 |
| 8 | 562 | 118 | 362 | 31 | 35.59 | 73.73 | 181.0 | 37.0 | 0.21 | 4.45 |
| 9 | 595 | 171 | 382 | 43 | 35.80 | 74.85 | 202.5 | 39.0 | 0.29 | 5.15 |
| 10 | 554 | 140 | 358 | 37 | 35.38 | 73.57 | 191.0 | 37.0 | 0.25 | 4.73 |
| 11 | 751 | 142 | 398 | 37 | 47.00 | 73.94 | 218.0 | 35.1 | 0.19 | 5.01 |
| 12 | 411 | 59 | 307 | 19 | 25.30 | 67.80 | 204.5 | 37.0 | 0.14 | 3.88 |
| 13 | 540 | 128 | 376 | 32 | 30.37 | 75.00 | 189.0 | 55.0 | 0.24 | 4.41 |
| Mean | 561.9 | 124.4 | 360.2 | 31.5 | 35.28 | 72.38 | 197.8 | 37.3 | 0.22 | 4.29 |
| SD | 93.28 | 41.28 | 42.55 | 6.13 | 5.33 | 2.55 | 11.67 | 7.18 | 0.06 | 0.66 |
| CV (%) | 16.60 | 33.19 | 11.81 | 19.49 | 15.12 | 3.53 | 5.90 | 19.24 | 27.90 | 15.41 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The nitrogen content is the total nitrogen content in whole the corn plant.

Table A17. Plant characteristics from the 2002 field with corn hybrid Pioneer 32R25, at east part farmer field. Ships soil series.

| 1† | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root | nitrogen |
|--------------|--------------|--------------|------------|------------|----------------|------------------|----------|-----------|--------|-----------|
| 152‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant | of roots¶ | index# | content†† |
| Plant number | | | g | | | % | | cm | | |
| 1 | 206 | 26 | 135 | 5 | 34.47 | 80.77 | 225 | 30.0 | 0.13 | 1.38 |
| 2 | 454 | 98 | 290 | 25 | 36.12 | 74.49 | 226 | 43.7 | 0.22 | 2.89 |
| 3 | 360 | 70 | 224 | 18 | 37.78 | 74.29 | 222 | 37.1 | 0.19 | 2.60 |
| 4 | 327 | 78 | 190 | 18 | 41.90 | 76.92 | 206 | 34.5 | 0.24 | 2.10 |
| 5 | 307 | 102 | 179 | 23 | 41.69 | 77.45 | 199 | 36.0 | 0.33 | 2.40 |
| 6 | 568 | 156 | 349 | 39 | 38.56 | 75.00 | 197 | 40.5 | 0.27 | 4.51 |
| 7 | 371 | 68 | 232 | 16 | 37.47 | 76.47 | 215 | 34.6 | 0.18 | 2.50 |
| 8 | 439 | 109 | 258 | 25 | 41.23 | 77.06 | 209 | 45.0 | 0.25 | 2.85 |
| 9 | 277 | 39 | 172 | 11 | 37.91 | 71.79 | 219 | 40.3 | 0.14 | 1.66 |
| 10 | 393 | 84 | 226 | 17 | 42.49 | 79.76 | 211 | 31.5 | 0.21 | 2.45 |
| 11 | 405 | 67 | 230 | 14 | 43.21 | 79.10 | 226 | 32.0 | 0.17 | 2.65 |
| 12 | 483 | 83 | 284 | 17 | 41.20 | 79.52 | 206 | 47.4 | 0.17 | 3.11 |
| Mean | 382.5 | 81.7 | 230.7 | 19.0 | 39.50 | 76.89 | 213.4 | 37.7 | 0.21 | 2.59 |
| SD | 97.76 | 33.62 | 58.85 | 8.49 | 2.80 | 2.66 | 10.32 | 5.65 | 0.06 | 0.78 |
| CV (%) | 25.56 | 41.16 | 25.51 | 44.66 | 7.10 | 3.46 | 4.83 | 14.98 | 28.02 | 30.21 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Plant height measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The nitrogen content is the total nitrogen content in whole the corn plant.

Table A18. Plant characteristics from the 2002 field with corn hybrid Pioneer 32R25, at west part farmer field. Ships soil series.

| 1† 153‡ | Fresh weight a.g.b. § | Fresh weight of roots | Dry weight a.g.b. | Dry weight of roots | Moisture content a.g.b. | Moisture content of roots | Height of plant | Depth of roots¶ | Root index# | nitrogen content†† |
|--------------|--------------------------|--------------------------|----------------------|------------------------|----------------------------|------------------------------|--------------------|--------------------|-----------------------------|-------------------------|
| Plant number | | | g | | | % | cm | | g roots g ⁻¹ agb | g N plant ⁻¹ |
| 1 | 322 | 60 | 214 | 15 | 33.54 | 75.00 | 198 | 48.5 | 0.19 | 1.96 |
| 2 | 525 | 116 | 314 | 29 | 40.19 | 75.00 | 183 | 53.0 | 0.22 | 3.57 |
| 3 | 573 | 93 | 329 | 26 | 42.58 | 72.04 | 187 | 46.0 | 0.16 | 3.55 |
| 4 | 667 | 143 | 395 | 35 | 40.78 | 75.52 | 189 | 44.0 | 0.21 | 4.63 |
| 5 | 586 | 149 | 342 | 35 | 41.64 | 76.51 | 184 | 43.7 | 0.25 | 4.21 |
| 6 | 781 | 182 | 455 | 43 | 41.74 | 76.37 | 193 | 49.6 | 0.23 | 5.77 |
| 7 | 306 | 70 | 177 | 16 | 42.16 | 77.14 | 149 | 45.5 | 0.23 | 2.06 |
| 8 | 623 | 178 | 382 | 43 | 38.68 | 75.84 | 197 | 35.1 | 0.29 | 4.11 |
| 9 | 504 | 107 | 280 | 26 | 44.44 | 75.70 | 180 | 36.5 | 0.21 | 3.39 |
| 10 | 555 | 121 | 336 | 31 | 39.46 | 74.38 | 190 | 41.4 | 0.22 | 3.44 |
| 11 | 571 | 122 | 333 | 34 | 41.68 | 72.13 | 181 | 32.1 | 0.21 | 4.09 |
| 12 | 599 | 121 | 359 | 32 | 40.07 | 73.55 | 194 | 56.0 | 0.20 | 3.94 |
| Mean | 551.0 | 121.8 | 326.3 | 30.4 | 40.58 | 74.93 | 185.4 | 44.3 | 0.22 | 3.73 |
| SD | 131.88 | 37.61 | 75.71 | 8.85 | 2.70 | 1.64 | 12.94 | 7.17 | 0.03 | 1.03 |
| CV (%) | 23.93 | 30.87 | 23.20 | 29.09 | 6.64 | 2.19 | 6.98 | 16.20 | 14.19 | 27.62 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Height of plant measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The nitrogen content is the total nitrogen content in whole the corn plant.

Table A19. Plant characteristics from the 2002 field experiment with corn variety Dekalb 637, at the Texas A&M University Agricultural Experiment Station Farm.

| 1 † | Fresh weight | Fresh weight | Dry weight | Dry weight | Moisture | Moisture | Height | Depth | Root | Nitrogen |
|---------------|--------------|--------------|--------------|--------------|----------------|------------------|--------------|--------------|--------------|--------------|
| 163 ‡ | a.g.b. § | of roots | a.g.b. | of roots | content a.g.b. | content of roots | of plant¶ | of roots# | index | content†† |
| Plant number | | | g | | | % | | cm | | |
| 1 | 327 | 67 | 257 | 15 | 21.41 | 77.61 | 185 | 37 | 0.20 | 1.96 |
| 2 | 396 | 111 | 271 | 34 | 31.57 | 69.37 | 175 | 27 | 0.28 | 2.43 |
| 3 | 320 | 114 | 239 | 28 | 25.31 | 75.44 | 176 | 33 | 0.36 | 1.69 |
| 4 | 361 | 70 | 257 | 21 | 28.81 | 70.00 | 189 | 40 | 0.19 | 2.37 |
| 5 | 365 | 65 | 250 | 17 | 31.51 | 73.85 | 180 | 32 | 0.18 | 2.29 |
| 6 | 268 | 38 | 204 | 17 | 23.88 | 55.26 | 164 | 32 | 0.14 | 1.63 |
| 7 | 500 | 110 | 324 | 24 | 35.20 | 78.18 | 195 | 31 | 0.22 | 3.36 |
| 8 | 520 | 159 | 364 | 43 | 30.00 | 72.96 | 190 | 43 | 0.31 | 4.12 |
| 9 | 366 | 93 | 281 | 28 | 23.22 | 69.89 | 188 | 29 | 0.25 | 2.14 |
| 10 | 284 | 46 | 240 | 19 | 15.49 | 58.70 | 181 | 32 | 0.16 | 2.65 |
| 11 | 371 | 89 | 261 | 25 | 29.65 | 71.91 | 190 | 40 | 0.24 | 2.08 |
| 12 | 434 | 180 | 308 | 57 | 29.03 | 68.33 | 198 | 38 | 0.41 | 2.34 |
| 13 | 268 | 57 | 211 | 13 | 21.27 | 77.19 | 195 | 34 | 0.21 | 1.52 |
| 14 | 465 | 156 | 297 | 44 | 36.13 | 71.79 | 187 | 34 | 0.34 | 3.45 |
| Mean | 374.6 | 96.8 | 268.9 | 27.5 | 27.32 | 70.75 | 185.2 | 34.4 | 0.25 | 2.43 |
| SD | 81.13 | 44.10 | 43.45 | 12.85 | 5.80 | 6.66 | 9.24 | 4.57 | 0.08 | 0.75 |
| CV (%) | 21.66 | 45.56 | 16.16 | 46.72 | 21.22 | 9.42 | 4.99 | 13.27 | 31.77 | 30.70 |

† Sampling number.

‡ Days after planting.

§ Aboveground biomass.

¶ Height of plant measured from the root base to the base of leaf bifurcation or to the base of the tassel when present.

Depth of roots is the soil depth containing >95 % of roots on fresh-weight basis.

†† The nitrogen content is the total nitrogen content in whole the corn plant.

Table A20. Corn grain yield, ordered according to yield per plant, from lowest to highest yield, harvested in a 9 x 4.16 m area at the Agricultural Experiment Station Farm of Texas A&M University, August 2003. Block number 1.

| Grain yield | | | | | |
|---|-----|-----------------------------|----------------|------|-----------|
| Fertilized (179 kg N ha ⁻¹) | | | Non-fertilized | | |
| | | g grain plant ⁻¹ | | | |
| 12 | 107 | 198 | 4 | 81 | 153 |
| 16 | 113 | 199 | 5 | 84 | 154 |
| 17 | 115 | 201 | 6 | 86.5 | 154 |
| 20 | 116 | 205 | 8 | 87 | 157 |
| 27 | 123 | 205 | 14 | 87 | 158 |
| 41 | 129 | 210 | 15 | 89 | 160 |
| 43 | 134 | 215 | 16 | 91 | 167 |
| 43 | 134 | 216 | 18 | 93 | 169 |
| 45 | 135 | 220 | 23 | 94 | 171 |
| 47 | 135 | 322 | 30 | 95 | 172 |
| 47 | 135 | Mean:125.7 | 34 | 95 | 173 |
| 48 | 137 | SD: 59 | 35 | 97 | 173 |
| 48 | 140 | CV: 47 | 36 | 98 | 175 |
| 57 | 144 | n: 100 | 37 | 98 | 175 |
| 57 | 148 | | 37 | 99 | 176 |
| 64 | 149 | | 38 | 100 | 178 |
| 65 | 152 | | 38 | 103 | 182 |
| 65 | 157 | | 43 | 103 | 196 |
| 68 | 158 | | 44 | 105 | 201 |
| 70 | 158 | | 48 | 106 | 205 |
| 71 | 160 | | 50 | 112 | 231 |
| 73 | 162 | | 51 | 112 | Mean:98.5 |
| 74 | 162 | | 52 | 115 | SD: 51 |
| 76 | 165 | | 54 | 115 | CV: 52 |
| 79 | 167 | | 55 | 115 | n: 111 |
| 81 | 167 | | 56 | 117 | |
| 82 | 169 | | 56 | 117 | |
| 82 | 170 | | 57 | 117 | |
| 85 | 172 | | 57 | 118 | |
| 86 | 174 | | 57 | 119 | |
| 88 | 175 | | 61 | 120 | |
| 89 | 178 | | 64 | 121 | |
| 90 | 181 | | 65 | 129 | |
| 92 | 182 | | 67 | 132 | |
| 94 | 186 | | 67 | 134 | |
| 98 | 186 | | 68 | 135 | |
| 99 | 189 | | 70 | 136 | |
| 100 | 189 | | 71 | 141 | |
| 102 | 190 | | 73 | 141 | |
| 103 | 192 | | 75 | 143 | |
| 105 | 194 | | 76 | 143 | |
| 105 | 194 | | 76 | 146 | |
| 106 | 194 | | 77 | 146 | |
| 106 | 194 | | 78 | 150 | |
| 106 | 197 | | 79 | 152 | |

Table A21. Corn grain yield, ordered according to yield per plant, from lowest to highest yield, harvested in a 9 x 4.16 m area at the Agricultural Experiment Station Farm of Texas A&M University, August 2003. Block number 2.

| Grain yield | | | | | | | |
|-----------------------------|-----|-----|------------|-----------------------------|----------------|-----|------------|
| Fertilized (179 kg N ha-1) | | | | g grain plant ⁻¹ | Non-fertilized | | |
| | | | | | | | |
| 2 | 114 | 166 | 223 | | 5 | 144 | 204 |
| 3 | 115 | 169 | 271 | | 20 | 147 | 205 |
| 3 | 118 | 172 | 282 | | 30 | 148 | 209 |
| 12 | 120 | 175 | 303 | | 36 | 150 | 210 |
| 24 | 120 | 176 | 337 | | 38 | 151 | 210 |
| 25 | 120 | 176 | mean:139.6 | | 39 | 155 | 217 |
| 30 | 121 | 179 | SD: 63 | | 41 | 156 | 217 |
| 32 | 121 | 180 | CV: 45 | | 45 | 157 | 218 |
| 34 | 125 | 183 | n: 140 | | 47 | 157 | 223 |
| 36 | 125 | 183 | | | 47 | 158 | 226 |
| 37 | 127 | 183 | | | 49 | 159 | 227 |
| 38 | 130 | 184 | | | 50 | 160 | 235 |
| 48 | 130 | 185 | | | 56 | 162 | 262 |
| 48 | 134 | 186 | | | 58 | 163 | 262 |
| 51 | 135 | 187 | | | 58 | 163 | 272 |
| 51 | 136 | 187 | | | 61 | 165 | 302 |
| 56 | 139 | 190 | | | 61 | 166 | 314 |
| 59 | 139 | 190 | | | 63 | 167 | mean:147.9 |
| 59 | 140 | 191 | | | 68 | 167 | SD: 63 |
| 59 | 141 | 191 | | | 75 | 171 | CV: 42 |
| 61 | 143 | 194 | | | 79 | 172 | n: 107 |
| 65 | 144 | 194 | | | 93 | 172 | |
| 68 | 144 | 195 | | | 96 | 179 | |
| 72 | 145 | 195 | | | 96 | 180 | |
| 73 | 145 | 196 | | | 101 | 180 | |
| 75 | 145 | 201 | | | 109 | 181 | |
| 76 | 146 | 202 | | | 109 | 182 | |
| 79 | 146 | 205 | | | 110 | 183 | |
| 80 | 148 | 205 | | | 114 | 184 | |
| 80 | 149 | 206 | | | 114 | 185 | |
| 84 | 149 | 206 | | | 120 | 185 | |
| 84 | 151 | 206 | | | 120 | 187 | |
| 87 | 153 | 207 | | | 120 | 187 | |
| 99 | 155 | 209 | | | 123 | 189 | |
| 100 | 155 | 209 | | | 125 | 193 | |
| 102 | 155 | 209 | | | 127 | 194 | |
| 103 | 156 | 210 | | | 130 | 196 | |
| 103 | 156 | 210 | | | 130 | 197 | |
| 105 | 162 | 211 | | | 133 | 197 | |
| 105 | 163 | 212 | | | 135 | 197 | |
| 107 | 164 | 212 | | | 135 | 198 | |
| 107 | 164 | 213 | | | 137 | 199 | |
| 107 | 164 | 213 | | | 137 | 199 | |
| 111 | 165 | 221 | | | 139 | 200 | |
| 113 | 166 | 222 | | | 143 | 203 | |

Table A22. Corn grain yield, ordered according to yield per plant, from lowest to highest yield, harvested in a 9 x 4.16 m area at the Agricultural Experiment Station Farm of Texas A&M University, August 2003. Block number 3.

| Grain yield | | | | | | | | |
|-----------------------------|-----|-----|-----|-----------------------------|----------------|-----|-----|------------|
| Fertilized (179 kg N ha-1) | | | | g grain plant ⁻¹ | Non-fertilized | | | |
| | | | | | | | | |
| 0 | 93 | 132 | 163 | 201 | 3 | 92 | 149 | 184 |
| 4 | 93 | 133 | 163 | 202 | 11 | 93 | 150 | 185 |
| 11 | 95 | 135 | 164 | 203 | 12 | 94 | 151 | 185 |
| 19 | 96 | 136 | 164 | 203 | 13 | 96 | 151 | 185 |
| 20 | 97 | 136 | 164 | 205 | 23 | 97 | 151 | 185 |
| 23 | 98 | 136 | 166 | 208 | 29 | 99 | 151 | 185 |
| 24 | 98 | 136 | 167 | 209 | 30 | 101 | 153 | 186 |
| 29 | 98 | 137 | 167 | 209 | 33 | 104 | 156 | 187 |
| 30 | 100 | 137 | 168 | 210 | 38 | 106 | 156 | 189 |
| 31 | 101 | 138 | 168 | 213 | 39 | 106 | 156 | 190 |
| 32 | 101 | 138 | 169 | 262 | 40 | 106 | 158 | 191 |
| 36 | 102 | 138 | 170 | mean128.5 | 40 | 108 | 160 | 192 |
| 41 | 102 | 139 | 171 | SD: 51 | 40 | 108 | 160 | 192 |
| 41 | 103 | 141 | 171 | CV: 39 | 41 | 108 | 160 | 194 |
| 41 | 103 | 141 | 173 | n: 191 | 41 | 112 | 161 | 195 |
| 41 | 105 | 142 | 174 | | 45 | 112 | 162 | 198 |
| 42 | 107 | 144 | 174 | | 47 | 112 | 163 | 198 |
| 47 | 107 | 144 | 174 | | 48 | 115 | 164 | 199 |
| 50 | 109 | 146 | 175 | | 49 | 116 | 164 | 201 |
| 51 | 109 | 146 | 176 | | 51 | 117 | 166 | 202.5 |
| 52 | 110 | 147 | 176 | | 54 | 121 | 166 | 203 |
| 52 | 110 | 148 | 179 | | 54 | 122 | 166 | 203.5 |
| 55 | 110 | 148 | 179 | | 54 | 123 | 166 | 203.7 |
| 55 | 110 | 150 | 180 | | 57 | 123 | 167 | 207 |
| 67 | 111 | 151 | 180 | | 57 | 125 | 167 | 208 |
| 71 | 112 | 151 | 181 | | 62 | 126 | 167 | 210 |
| 71 | 113 | 151 | 183 | | 66 | 126 | 167 | 211 |
| 73 | 114 | 153 | 184 | | 67 | 127 | 168 | 220 |
| 73 | 115 | 153 | 186 | | 67 | 127 | 168 | 222 |
| 73 | 115 | 153 | 186 | | 68 | 128 | 169 | 223 |
| 75 | 116 | 154 | 187 | | 72 | 130 | 170 | 298 |
| 76 | 116 | 154 | 187 | | 74 | 130 | 172 | mean:130.3 |
| 77 | 118 | 155 | 187 | | 74 | 135 | 172 | SD: 56 |
| 78 | 118 | 155 | 189 | | 75 | 135 | 173 | CV: 43 |
| 78 | 118 | 156 | 189 | | 77 | 136 | 176 | n: 166 |
| 79 | 119 | 156 | 193 | | 79 | 137 | 176 | |
| 85 | 120 | 158 | 193 | | 81 | 138 | 177 | |
| 86 | 122 | 159 | 194 | | 81 | 139 | 179 | |
| 86 | 122 | 159 | 195 | | 82 | 140 | 179 | |
| 87 | 122 | 160 | 196 | | 83 | 142 | 180 | |
| 87 | 123 | 161 | 196 | | 84 | 143 | 181 | |
| 88 | 126 | 162 | 196 | | 86 | 143 | 181 | |
| 89 | 127 | 162 | 197 | | 87 | 143 | 182 | |
| 90 | 132 | 162 | 197 | | 90 | 143 | 183 | |
| 91 | 132 | 163 | 198 | | 91 | 147 | 183 | |

Table A23. Corn grain yield, ordered according to yield per plant, from lowest to highest yield, harvested in a 9 x 4.16 m area at the Agricultural Experiment Station Farm of Texas A&M University, August 2003. Block number 4.

| Grain yield | | | | | | | | | |
|-----------------------------|-------|-------|-----|-------------|-----------------------------|-------|-------|-------------|--|
| Fertilized (179 kg N ha-1) | | | | | Non-fertilized | | | | |
| | | | | | g grain plant ⁻¹ | | | | |
| 4 | 103 | 134 | 155 | 170 | 3 | 93.5 | 135 | 171.2 | |
| 24 | 104 | 134 | 155 | 170 | 5.5 | 94 | 136 | 171.5 | |
| 31 | 105 | 137 | 155 | 170 | 6 | 96.5 | 137 | 173 | |
| 34 | 107 | 137 | 155 | 170 | 15 | 97 | 140 | 173 | |
| 35 | 108 | 137 | 155 | 171 | 15 | 100 | 141 | 175 | |
| 36 | 108 | 138 | 156 | 171 | 18.5 | 101 | 141.8 | 177 | |
| 46 | 108 | 139 | 157 | 171 | 20.5 | 101 | 142 | 178 | |
| 46 | 109.5 | 139 | 157 | 172 | 25 | 101.5 | 142 | 179 | |
| 51 | 110 | 139 | 157 | 172 | 27 | 103 | 144 | 181 | |
| 52 | 112 | 140 | 158 | 172 | 27 | 103 | 144 | 181.5 | |
| 56 | 112 | 140 | 158 | 172 | 28 | 103 | 146 | 184 | |
| 58 | 113 | 141 | 158 | 172 | 31.2 | 104 | 147 | 184 | |
| 62 | 114 | 141 | 158 | 173 | 32.4 | 106 | 148 | 185 | |
| 63 | 114 | 141 | 158 | 173 | 34 | 106 | 148 | 186.8 | |
| 65 | 115 | 142 | 158 | 173 | 34.8 | 107 | 148.2 | 187 | |
| 68 | 116 | 142 | 158 | 175 | 36.5 | 108.7 | 148.6 | 187.2 | |
| 69 | 116 | 142 | 159 | 175 | 38 | 109 | 149 | 188 | |
| 70 | 118 | 142 | 159 | 175 | 38.5 | 109.5 | 149.9 | 188 | |
| 71 | 119 | 142 | 159 | 176 | 38.6 | 110 | 150 | 189 | |
| 74 | 119 | 143 | 160 | 176 | 42.2 | 110 | 152 | 191 | |
| 74 | 119 | 145 | 161 | 176 | 43 | 112 | 156 | 191 | |
| 74 | 120 | 145 | 162 | 177 | 43.2 | 113 | 156 | 192 | |
| 76 | 120 | 146 | 162 | 179 | 46.2 | 114 | 156.5 | 194 | |
| 78 | 121 | 146 | 162 | 180 | 50 | 114.8 | 157 | 195 | |
| 78 | 122 | 147 | 164 | 183 | 50.5 | 116 | 157 | 196 | |
| 78 | 122 | 147 | 164 | 183 | 54 | 116.5 | 158 | 196 | |
| 78 | 123 | 147 | 164 | 184 | 58 | 116.5 | 158 | 198 | |
| 81 | 123 | 148 | 165 | 185 | 58.5 | 118.5 | 159 | 199 | |
| 82 | 123 | 148 | 165 | 185 | 59 | 120.2 | 160 | 200 | |
| 84 | 124 | 148 | 166 | 185 | 71 | 121 | 161 | 201 | |
| 87 | 124 | 148 | 166 | 186 | 77 | 121 | 161 | 202 | |
| 87 | 124 | 149 | 166 | 186 | 77 | 121 | 162 | 202 | |
| 87 | 125 | 149 | 167 | 187 | 80.2 | 121.5 | 162 | 203 | |
| 88 | 127 | 149 | 167 | 187 | 82 | 122 | 163 | 204 | |
| 88 | 127 | 149 | 168 | 189 | 83 | 122 | 163 | 208 | |
| 91 | 128 | 150 | 168 | 190 | 83.2 | 122 | 164.5 | 210 | |
| 93 | 128 | 150 | 168 | 190 | 84 | 124 | 165 | 219 | |
| 96 | 128 | 150.5 | 168 | 191 | 85 | 128 | 166 | 224.2 | |
| 96 | 129 | 151 | 169 | 192 | 85 | 128.2 | 166 | 233 | |
| 97 | 130 | 152 | 169 | 195 | 87 | 130 | 167 | 277.5 | |
| 99 | 130 | 152 | 169 | 200 | 90 | 130.8 | 167.5 | 280 | |
| 102 | 131 | 153 | 169 | 212 | 90 | 132 | 169 | 369 | |
| 102 | 132 | 153 | 170 | mean:135.1 | 90.2 | 132 | 169 | mean:129.0 | |
| 103 | 133 | 154 | 170 | SD:39 | 91 | 133 | 171 | SD:59 | |
| 103 | 133 | 154 | 170 | CV:28,n:222 | 93 | 134 | 171 | CV:45,n:177 | |

Table A24. Bulk density of Ships clay and Weswood silt loam soil from the greenhouse experiment in 2003.

| Pot Num. | Ships clay | Weswood silt loam |
|---------------|---|--------------------------|
| | g cm ⁻³ | g cm ⁻³ |
| | Fertilized with 179 kg N ha ⁻¹ | |
| 1 | | 1.31 |
| 5 | | |
| 8 | 1.08 | 1.30 |
| 9 | | |
| 11 | | |
| 13 | 1.06 | 1.33 |
| 15 | 1.06 | 1.21 |
| 17 | 1.12 | |
| 18 | | |
| 19 | | 1.32 |
| Mean | 1.08 | 1.30 |
| SD | 0.02 | 0.04 |
| CV (%) | 2.6 | 3.7 |
| | Without fertilized | |
| 2 | | 1.32 |
| 3 | | 1.25 |
| 4 | | 1.30 |
| 6 | 1.00 | 1.36 |
| 7 | 1.00 | 1.42 |
| 10 | | 1.22 |
| 12 | | 1.29 |
| 14 | | 1.21 |
| 16 | | 1.23 |
| 20 | | 1.24 |
| Mean | 1.05 | 1.29 |
| SD | 0.04 | 0.06 |
| CV (%) | 4.2 | 4.84 |

Table A25. Meteorological data for January through March 2002 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|--------|-------------|-------|-------|-------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn.† | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| January | | °C | | mm | February | | °C | | mm | March | | °C | | mm |
| 1 | 7.8 | -0.6 | 3.9 | 0.00 | 1 | 9.4 | 2.8 | 6.1 | 0.00 | 1 | 15.6 | 8.9 | 12.2 | 0.03 |
| 2 | 6.7 | -2.8 | 2.2 | 0.00 | 2 | 11.7 | -0.6 | 5.6 | 0.00 | 2 | 14.4 | -1.7 | 6.7 | 0.03 |
| 3 | 6.7 | -7.2 | 0.0 | 0.00 | 3 | 13.9 | 5.0 | 9.4 | 0.00 | 3 | 6.1 | -6.1 | 0.0 | 0.00 |
| 4 | 11.7 | -4.4 | 3.9 | 0.00 | 4 | 12.8 | 7.2 | 10.0 | 0.18 | 4 | 14.4 | -8.3 | 3.3 | 0.00 |
| 5 | 11.7 | 5.0 | 8.3 | 2.62 | 5 | 7.2 | 3.9 | 5.6 | 2.90 | 5 | 18.3 | -3.9 | 7.2 | 0.00 |
| 6 | 16.1 | 2.8 | 9.4 | 0.00 | 6 | 5.6 | -1.1 | 2.2 | 0.00 | 6 | 25.6 | 9.4 | 17.8 | 0.00 |
| 7 | 13.9 | -2.2 | 6.1 | 0.00 | 7 | 13.9 | -2.2 | 6.1 | 0.00 | 7 | 26.7 | 15.6 | 21.1 | 0.00 |
| 8 | 19.4 | -1.1 | 9.4 | 0.00 | 8 | 16.7 | -1.1 | 7.8 | 0.00 | 8 | 23.9 | 17.2 | 20.6 | 0.00 |
| 9 | 23.9 | 5.0 | 14.4 | 0.00 | 9 | 22.2 | 5.0 | 13.9 | 0.00 | 9 | 21.7 | 7.2 | 14.4 | 0.00 |
| 10 | 22.8 | 13.3 | 18.3 | 0.00 | 10 | 11.1 | 3.3 | 7.2 | 0.00 | 10 | 16.1 | 3.9 | 10.0 | 0.00 |
| 11 | 15.0 | 8.9 | 12.2 | 0.00 | 11 | 12.8 | -1.1 | 6.1 | 0.00 | 11 | 16.1 | 10.0 | 13.3 | 0.20 |
| 12 | 18.9 | 1.7 | 10.6 | 0.00 | 12 | 17.8 | -1.7 | 8.3 | 0.00 | 12 | 21.7 | 9.4 | 15.6 | 0.00 |
| 13 | 20.0 | -1.7 | 9.4 | 0.00 | 13 | 20.0 | 1.1 | 10.6 | 0.00 | 13 | 27.8 | 6.1 | 17.2 | 0.00 |
| 14 | 20.0 | 2.2 | 11.1 | 0.00 | 14 | 19.4 | 3.9 | 11.7 | 0.00 | 14 | 30.0 | 15.6 | 22.8 | 0.00 |
| 15 | 19.4 | -1.7 | 8.9 | 0.00 | 15 | 21.7 | 6.1 | 13.9 | 0.00 | 15 | 28.3 | 13.3 | 21.1 | 0.00 |
| 16 | 22.2 | 3.3 | 12.8 | 0.00 | 16 | 17.2 | 0.0 | 8.9 | 0.00 | 16 | 18.9 | 11.7 | 15.6 | 0.00 |
| 17 | 17.2 | 10.6 | 13.9 | 0.00 | 17 | 20.6 | -1.7 | 9.4 | 0.00 | 17 | 22.8 | 16.1 | 19.4 | 0.48 |
| 18 | 11.7 | 9.4 | 10.6 | 0.13 | 18 | 23.9 | 7.8 | 16.1 | 0.00 | 18 | 28.3 | 18.3 | 23.3 | 0.00 |
| 19 | 13.3 | 2.8 | 8.3 | 0.53 | 19 | 23.3 | 9.4 | 16.7 | 1.07 | 19 | 26.7 | 16.1 | 21.7 | 0.79 |
| 20 | 15.0 | -0.6 | 7.2 | 0.00 | 20 | 22.8 | 7.2 | 15.0 | 0.00 | 20 | 17.2 | 10.0 | 13.9 | 0.30 |
| 21 | 22.8 | 4.4 | 13.9 | 0.00 | 21 | 25.6 | 6.1 | 16.1 | 0.00 | 21 | 22.2 | 7.2 | 15.0 | 0.00 |
| 22 | 23.9 | 8.3 | 16.1 | 0.00 | 22 | 18.3 | 1.7 | 10.0 | 0.00 | 22 | 13.9 | 1.7 | 7.8 | 0.00 |
| 23 | 23.3 | 20.6 | 22.2 | 0.00 | 23 | 22.2 | -0.6 | 11.1 | 0.00 | 23 | 21.7 | 1.7 | 11.7 | 0.00 |
| 24 | 22.2 | 6.1 | 14.4 | 0.13 | 24 | 25.0 | 5.0 | 15.0 | 0.00 | 24 | 25.6 | 13.9 | 20.0 | 0.00 |
| 25 | 15.6 | 0.6 | 8.3 | 0.00 | 25 | 22.2 | 6.1 | 14.4 | 0.00 | 25 | 21.7 | 7.8 | 15.0 | 0.05 |
| 26 | 15.6 | -1.1 | 7.2 | 0.00 | 26 | 7.2 | -2.8 | 2.2 | 0.00 | 26 | 17.2 | 5.0 | 11.1 | 0.00 |
| 27 | 22.2 | 2.2 | 12.2 | 0.00 | 27 | 9.4 | -8.3 | 0.6 | 0.00 | 27 | 23.3 | 5.0 | 14.4 | 0.00 |
| 28 | 26.1 | 11.1 | 18.9 | 0.00 | 28 | 13.9 | -1.7 | 6.1 | 0.00 | 28 | 27.8 | 8.9 | 18.3 | 0.00 |
| 29 | 27.2 | 18.9 | 23.3 | 0.00 | 29 | -17.8 | -17.8 | -17.8 | 0.00 | 29 | 26.7 | 20.6 | 23.9 | 0.00 |
| 30 | 26.1 | 18.9 | 22.8 | 0.00 | | | | | | 30 | 29.4 | 16.7 | 23.3 | 0.28 |
| 31 | 21.7 | 6.1 | 13.9 | 0.66 | | | | | | 31 | 22.8 | 10.0 | 16.7 | 0.00 |

†Pptn = precipitation (mm)

Table A26. Meteorological data for April through June 2002 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| April | | °C | | mm | May | | °C | | mm | June | | °C | | mm |
| 1 | 25.6 | 8.9 | 17.2 | 0.00 | 1 | 33.9 | 22.8 | 28.3 | 0.00 | 1 | 33.3 | 18.9 | 26.1 | 0.00 |
| 2 | 26.7 | 15.6 | 21.1 | 0.00 | 2 | 32.2 | 21.1 | 26.7 | 0.00 | 2 | 33.9 | 18.9 | 26.7 | 0.00 |
| 3 | 18.3 | 13.9 | 16.1 | 0.00 | 3 | 26.1 | 17.2 | 21.7 | 0.00 | 3 | 33.9 | 21.7 | 27.8 | 0.00 |
| 4 | 20.6 | 12.2 | 16.7 | 0.00 | 4 | 32.2 | 20.6 | 26.7 | 0.00 | 4 | 35.0 | 22.8 | 28.9 | 0.00 |
| 5 | 23.3 | 13.3 | 18.3 | 0.00 | 5 | 33.3 | 22.8 | 28.3 | 0.00 | 5 | 34.4 | 21.7 | 28.3 | 0.00 |
| 6 | 17.8 | 12.2 | 15.0 | 0.89 | 6 | 33.3 | 23.3 | 28.3 | 0.00 | 6 | 35.0 | 21.7 | 28.3 | 0.00 |
| 7 | 24.4 | 12.2 | 18.3 | 1.47 | 7 | 33.3 | 23.3 | 28.3 | 0.00 | 7 | 35.6 | 22.8 | 29.4 | 1.93 |
| 8 | 25.6 | 15.0 | 20.6 | 1.14 | 8 | 32.8 | 23.3 | 28.3 | 0.00 | 8 | 35.0 | 22.8 | 28.9 | 0.00 |
| 9 | 23.3 | 13.9 | 18.9 | 0.00 | 9 | 33.3 | 22.8 | 28.3 | 0.00 | 9 | 35.0 | 25.0 | 30.0 | 0.03 |
| 10 | 26.1 | 15.0 | 20.6 | 0.00 | 10 | 34.4 | 22.2 | 28.3 | 0.00 | 10 | 35.6 | 24.4 | 30.0 | 0.00 |
| 11 | 27.8 | 13.9 | 21.1 | 0.00 | 11 | 33.3 | 23.3 | 28.3 | 0.00 | 11 | 36.1 | 23.3 | 30.0 | 0.00 |
| 12 | 28.3 | 17.2 | 22.8 | 0.00 | 12 | 33.3 | 23.9 | 28.9 | 0.00 | 12 | 35.6 | 23.3 | 29.4 | 0.00 |
| 13 | 27.8 | 15.6 | 21.7 | 0.00 | 13 | 26.1 | 13.9 | 20.0 | 0.18 | 13 | 35.6 | 22.2 | 28.9 | 0.00 |
| 14 | 27.8 | 16.7 | 22.2 | 0.00 | 14 | 28.3 | 13.3 | 21.1 | 0.00 | 14 | 35.0 | 22.8 | 28.9 | 0.00 |
| 15 | 28.9 | 20.0 | 24.4 | 0.00 | 15 | 31.1 | 10.6 | 21.1 | 0.00 | 15 | 33.3 | 22.2 | 27.8 | 0.00 |
| 16 | 27.8 | 21.1 | 24.4 | 0.03 | 16 | 33.3 | 20.6 | 27.2 | 0.00 | 16 | 29.4 | 19.4 | 24.4 | 2.57 |
| 17 | 30.6 | 21.1 | 26.1 | 0.00 | 17 | 26.1 | 17.8 | 22.2 | 0.03 | 17 | 32.2 | 18.9 | 25.6 | 0.00 |
| 18 | 30.6 | 20.6 | 25.6 | 0.00 | 18 | 25.0 | 14.4 | 20.0 | 0.00 | 18 | 33.3 | 20.0 | 26.7 | 0.00 |
| 19 | 30.0 | 21.1 | 25.6 | 0.00 | 19 | 25.6 | 10.0 | 17.8 | 0.00 | 19 | 35.0 | 20.0 | 27.8 | 0.00 |
| 20 | 30.6 | 21.1 | 26.1 | 0.00 | 20 | 27.2 | 12.2 | 20.0 | 0.00 | 20 | 35.0 | 22.8 | 28.9 | 0.33 |
| 21 | 30.0 | 21.7 | 26.1 | 0.00 | 21 | 29.4 | 10.0 | 20.0 | 0.00 | 21 | 34.4 | 22.2 | 28.3 | 0.00 |
| 22 | 28.9 | 21.7 | 25.6 | 0.00 | 22 | 30.6 | 14.4 | 22.8 | 0.00 | 22 | 34.4 | 21.1 | 27.8 | 0.00 |
| 23 | 30.0 | 20.6 | 25.6 | 0.00 | 23 | 31.7 | 18.3 | 25.0 | 0.00 | 23 | 32.8 | 18.3 | 25.6 | 0.00 |
| 24 | 31.7 | 21.7 | 26.7 | 0.00 | 24 | 30.0 | 18.9 | 24.4 | 0.00 | 24 | 31.7 | 20.6 | 26.1 | 0.28 |
| 25 | 25.6 | 18.9 | 22.2 | 0.10 | 25 | 33.3 | 17.8 | 25.6 | 0.00 | 25 | 33.3 | 20.0 | 26.7 | 0.05 |
| 26 | 29.4 | 17.8 | 23.9 | 0.00 | 26 | 33.9 | 19.4 | 26.7 | 0.03 | 26 | 33.9 | 22.8 | 28.3 | 0.41 |
| 27 | 31.1 | 22.2 | 26.7 | 0.00 | 27 | 33.3 | 20.0 | 26.7 | 0.05 | 27 | 33.3 | 22.2 | 27.8 | 0.00 |
| 28 | 32.8 | 22.8 | 27.8 | 0.00 | 28 | 31.7 | 17.8 | 25.0 | 0.48 | 28 | 32.2 | 23.3 | 27.8 | 0.00 |
| 29 | 33.9 | 22.2 | 28.3 | 0.00 | 29 | 27.8 | 17.8 | 22.8 | 1.50 | 29 | 28.3 | 22.2 | 25.6 | 1.63 |
| 30 | 33.3 | 21.1 | 27.2 | 0.00 | 30 | 32.2 | 17.2 | 25.0 | 0.00 | 30 | 32.2 | 22.2 | 27.2 | 0.51 |
| | | | | | 31 | 31.1 | 20.0 | 25.6 | 0.00 | | | | | |

†Pptn = precipitation (mm)

Table A27. Meteorological data for July through September 2002 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| July | | °C | | mm | August | | °C | | mm | Sept. | | °C | | mm |
| 1 | 30.0 | 21.1 | 25.6 | 1.88 | 1 | 35.6 | 22.2 | 28.9 | 0.00 | 1 | 35.6 | 22.2 | 27.8 | 0.00 |
| 2 | 31.1 | 22.8 | 27.2 | 0.46 | 2 | 35.6 | 22.2 | 28.9 | 0.00 | 2 | 35.0 | 22.2 | 28.9 | 0.08 |
| 3 | 33.3 | 22.8 | 28.3 | 0.00 | 3 | 38.3 | 22.2 | 30.6 | 0.05 | 3 | 33.9 | 22.8 | 27.8 | 0.00 |
| 4 | 32.8 | 23.9 | 28.3 | 0.15 | 4 | 35.6 | 21.7 | 28.9 | 0.03 | 4 | 32.8 | 22.8 | 27.8 | 0.00 |
| 5 | 33.3 | 23.3 | 28.3 | 0.00 | 5 | 35.6 | 21.7 | 28.9 | 0.00 | 5 | 35.0 | 22.8 | 28.9 | 0.00 |
| 6 | 34.4 | 21.7 | 28.3 | 0.00 | 6 | 36.7 | 22.2 | 29.4 | 0.00 | 6 | 33.9 | 22.8 | 27.8 | 0.00 |
| 7 | 35.6 | 22.8 | 29.4 | 0.00 | 7 | 37.8 | 24.4 | 31.1 | 0.00 | 7 | 30.6 | 22.8 | 26.7 | 0.71 |
| 8 | 35.6 | 23.3 | 29.4 | 0.00 | 8 | 33.3 | 25.6 | 29.4 | 0.00 | 8 | 30.6 | 22.8 | 25.6 | 0.46 |
| 9 | 34.4 | 22.8 | 28.9 | 0.48 | 9 | 35.6 | 23.9 | 30.0 | 0.00 | 9 | 32.8 | 22.8 | 27.8 | 0.05 |
| 10 | 33.9 | 22.2 | 28.3 | 0.00 | 10 | 34.4 | 22.2 | 28.3 | 0.00 | 10 | 32.2 | 22.8 | 23.3 | 0.00 |
| 11 | 36.1 | 21.7 | 28.9 | 0.00 | 11 | 35.0 | 21.7 | 28.3 | 0.00 | 11 | 33.9 | 26.7 | 30.6 | 0.00 |
| 12 | 36.1 | 22.8 | 29.4 | 0.00 | 12 | 35.6 | 23.3 | 29.4 | 0.15 | 12 | 33.9 | 21.7 | 27.8 | 0.00 |
| 13 | 34.4 | 21.7 | 28.3 | 0.25 | 13 | 34.4 | 23.9 | 29.4 | 0.03 | 13 | 33.9 | 21.7 | 27.8 | 0.00 |
| 14 | 25.0 | 20.6 | 22.8 | 8.08 | 14 | 32.8 | 23.9 | 28.3 | 0.10 | 14 | 33.9 | 20.6 | 27.2 | 0.00 |
| 15 | 27.8 | 21.7 | 25.0 | 0.76 | 15 | 24.4 | 20.6 | 22.8 | 8.81 | 15 | 26.7 | 21.7 | 24.4 | 0.00 |
| 16 | 26.7 | 22.8 | 25.0 | 2.24 | 16 | 33.3 | 21.1 | 27.2 | 0.00 | 16 | 26.1 | 22.2 | 24.4 | 0.30 |
| 17 | 32.2 | 22.8 | 27.8 | 0.08 | 17 | 35.0 | 24.4 | 30.0 | 0.00 | 17 | 31.7 | 22.8 | 26.7 | 0.13 |
| 18 | 33.3 | 22.8 | 28.3 | 0.00 | 18 | 35.0 | 23.9 | 29.4 | 0.00 | 18 | 32.8 | 25.0 | 28.9 | 0.03 |
| 19 | 33.9 | 23.9 | 28.9 | 0.00 | 19 | 34.4 | 23.9 | 29.4 | 0.00 | 19 | 30.0 | 21.7 | 25.6 | 0.20 |
| 20 | 33.3 | 22.2 | 27.8 | 0.00 | 20 | 35.0 | 23.9 | 29.4 | 0.00 | 20 | 30.6 | 16.1 | 23.3 | 0.00 |
| 21 | 33.9 | 23.9 | 28.9 | 0.00 | 21 | 35.0 | 24.4 | 30.0 | 0.00 | 21 | 32.8 | 12.8 | 22.2 | 0.00 |
| 22 | 34.4 | 22.8 | 28.9 | 0.00 | 22 | 35.0 | 23.9 | 29.4 | 0.00 | 22 | 32.8 | 17.8 | 25.0 | 0.00 |
| 23 | 35.0 | 23.3 | 29.4 | 0.00 | 23 | 35.0 | 23.3 | 29.4 | 0.00 | 23 | 31.7 | 17.8 | 24.4 | 0.00 |
| 24 | 35.6 | 23.3 | 29.4 | 0.00 | 24 | 34.4 | 23.3 | 28.9 | 0.00 | 24 | 31.7 | 16.7 | 23.3 | 0.00 |
| 25 | 35.0 | 23.3 | 29.4 | 0.00 | 25 | 35.6 | 23.3 | 29.4 | 0.00 | 25 | 31.7 | 18.9 | 25.0 | 0.00 |
| 26 | 34.4 | 23.9 | 29.4 | 0.00 | 26 | 35.6 | 23.9 | 30.0 | 0.00 | 26 | 32.8 | 18.9 | 25.6 | 0.00 |
| 27 | 35.0 | 23.9 | 29.4 | 0.00 | 27 | 33.3 | 23.9 | 28.9 | 0.00 | 27 | 35.0 | 16.1 | 25.6 | 0.00 |
| 28 | 35.6 | 24.4 | 30.0 | 0.00 | 28 | 35.0 | 22.8 | 28.9 | 0.00 | 28 | 32.8 | 17.8 | 25.6 | 0.00 |
| 29 | 35.0 | 25.6 | 30.6 | 0.00 | 29 | 34.4 | 21.1 | 27.8 | 0.00 | 29 | 31.7 | 18.9 | 25.0 | 0.00 |
| 30 | 35.6 | 24.4 | 30.0 | 0.00 | 30 | 34.4 | 20.6 | 27.8 | 0.00 | 30 | 31.7 | 17.8 | 25.6 | 0.00 |
| 31 | 35.6 | 23.3 | 29.4 | 0.00 | 31 | 35.6 | 21.7 | 28.9 | 0.03 | | | | | |

†Pptn = precipitation (mm)

Table A28. Meteorological data for October through December 2002 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| Oct. | | °C | | mm | Nov. | | °C | | mm | Dec. | | °C | | mm |
| 1 | 33.9 | 21.7 | 27.2 | 1.98 | 1 | 18.9 | 11.1 | 15.6 | 0.03 | 1 | 15.0 | 5.0 | 10.0 | 0.00 |
| 2 | 32.8 | 22.8 | 27.8 | 0.00 | 2 | 13.9 | 10.6 | 12.2 | 0.89 | 2 | 22.2 | 6.1 | 14.4 | 0.00 |
| 3 | 33.9 | 22.2 | 27.8 | 0.03 | 3 | 15.0 | 11.7 | 13.3 | 0.58 | 3 | 21.1 | 16.7 | 18.9 | 0.46 |
| 4 | 33.9 | 22.2 | 27.8 | 0.00 | 4 | 11.7 | 10.6 | 11.1 | 11.58 | 4 | 20.6 | 3.9 | 12.2 | 5.97 |
| 5 | 32.8 | 21.7 | 27.2 | 0.00 | 5 | 21.1 | 8.9 | 15.0 | 0.03 | 5 | 8.9 | 2.2 | 5.6 | 0.00 |
| 6 | 33.9 | 22.8 | 27.8 | 0.00 | 6 | 18.9 | 6.7 | 12.8 | 0.00 | 6 | 11.1 | 0.0 | 5.6 | 0.00 |
| 7 | 30.0 | 21.1 | 24.4 | 6.07 | 7 | 20.0 | 5.0 | 12.2 | 0.00 | 7 | 13.9 | 2.2 | 7.8 | 0.00 |
| 8 | 23.9 | 21.7 | 22.8 | 0.18 | 8 | 23.9 | 7.8 | 15.6 | 0.00 | 8 | 16.1 | 10.0 | 13.3 | 0.41 |
| 9 | 25.0 | 17.8 | 22.2 | 1.02 | 9 | 27.8 | 16.7 | 22.2 | 0.00 | 9 | 8.9 | 6.7 | 7.8 | 2.49 |
| 10 | 22.8 | 16.7 | 20.0 | 0.00 | 10 | 30.0 | 17.2 | 23.9 | 0.03 | 10 | 10.6 | 6.7 | 8.9 | 0.03 |
| 11 | 26.7 | 17.2 | 21.7 | 0.00 | 11 | 22.8 | 12.8 | 17.8 | 0.00 | 11 | 12.8 | 2.8 | 7.8 | 0.00 |
| 12 | 27.8 | 15.0 | 21.1 | 0.00 | 12 | 18.9 | 7.8 | 13.3 | 0.00 | 12 | 12.2 | 8.9 | 11.1 | 2.67 |
| 13 | 21.1 | 13.9 | 17.8 | 0.08 | 13 | 18.9 | 5.6 | 12.2 | 0.00 | 13 | 13.9 | 3.9 | 8.9 | 0.00 |
| 14 | 15.6 | 11.7 | 13.9 | 0.15 | 14 | 23.9 | 7.8 | 15.6 | 0.00 | 14 | 17.2 | 1.1 | 8.9 | 0.00 |
| 15 | 22.2 | 8.9 | 15.6 | 0.03 | 15 | 17.8 | 8.9 | 13.3 | 0.00 | 15 | 22.2 | 6.1 | 14.4 | 0.00 |
| 16 | 22.8 | 8.9 | 15.6 | 0.00 | 16 | 15.6 | 5.0 | 10.6 | 0.00 | 16 | 22.2 | 15.0 | 18.9 | 0.00 |
| 17 | 26.1 | 8.9 | 17.2 | 0.00 | 17 | 20.6 | 3.9 | 12.2 | 0.00 | 17 | 23.9 | 15.6 | 20.0 | 0.00 |
| 18 | 26.1 | 15.6 | 20.6 | 0.00 | 18 | 23.9 | 8.9 | 16.7 | 0.00 | 18 | 23.9 | 18.9 | 21.1 | 0.00 |
| 19 | 22.8 | 17.2 | 20.0 | 4.78 | 19 | 22.2 | 7.8 | 15.0 | 0.00 | 19 | 17.8 | 8.9 | 13.9 | 1.37 |
| 20 | 23.9 | 16.1 | 19.4 | 0.00 | 20 | 22.8 | 6.7 | 14.4 | 0.00 | 20 | 17.8 | 2.2 | 10.0 | 0.00 |
| 21 | 20.6 | 15.6 | 17.8 | 2.39 | 21 | 22.8 | 7.8 | 15.6 | 0.00 | 21 | 21.7 | 5.6 | 13.3 | 0.00 |
| 22 | 21.1 | 17.2 | 18.9 | 1.98 | 22 | 18.9 | 7.2 | 13.3 | 0.00 | 22 | 18.9 | 5.6 | 12.2 | 0.00 |
| 23 | 22.8 | 17.8 | 20.0 | 0.03 | 23 | 21.1 | 6.1 | 13.3 | 0.00 | 23 | 23.9 | 7.2 | 15.6 | 3.45 |
| 24 | 20.0 | 17.8 | 18.9 | 2.95 | 24 | 23.9 | 10.0 | 16.7 | 0.00 | 24 | 7.2 | 1.7 | 5.0 | 0.00 |
| 25 | 18.9 | 13.9 | 16.7 | 0.43 | 25 | 13.9 | 7.8 | 11.1 | 0.18 | 25 | 7.8 | -2.2 | 2.8 | 0.00 |
| 26 | 17.2 | 13.9 | 15.6 | 1.37 | 26 | 7.8 | 5.0 | 6.7 | 1.96 | 26 | 10.6 | 2.8 | 6.7 | 0.00 |
| 27 | 20.6 | 17.2 | 18.3 | 0.00 | 27 | 8.9 | 3.9 | 6.7 | 0.00 | 27 | 17.2 | 2.2 | 10.0 | 0.00 |
| 28 | 21.1 | 16.7 | 18.9 | 1.47 | 28 | 13.9 | 1.1 | 7.8 | 0.00 | 28 | 18.9 | 2.8 | 11.1 | 0.00 |
| 29 | 22.8 | 13.9 | 18.3 | 0.03 | 29 | 16.7 | 1.7 | 8.9 | 0.00 | 29 | 22.2 | 8.9 | 15.6 | 0.00 |
| 30 | 26.1 | 12.2 | 18.9 | 0.00 | 30 | 20.6 | 7.8 | 14.4 | 0.00 | 30 | 21.1 | 12.8 | 17.8 | 2.36 |
| 31 | 18.9 | 12.8 | 15.6 | 0.00 | | | | | | 31 | 15.6 | 5.6 | 11.7 | 0.05 |

†Pptn = precipitation (mm)

Table A29. Meteorological data for January through March 2003 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|-------|-------|-------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| January | | °C | | mm | February | | °C | | mm | March | | °C | | mm |
| 1 | 20.6 | 2.2 | 11.1 | 0.00 | 1 | 20.6 | 3.9 | 12.2 | 0.00 | 1 | 12.2 | 7.8 | 10.0 | 0.08 |
| 2 | 11.7 | 2.8 | 7.2 | 0.00 | 2 | 22.8 | 11.7 | 17.2 | 0.00 | 2 | 15.6 | 10.0 | 12.8 | 0.00 |
| 3 | 16.1 | 0.6 | 8.3 | 0.00 | 3 | 22.8 | 7.8 | 15.6 | 0.00 | 3 | 12.8 | 7.8 | 10.0 | 1.32 |
| 4 | 18.9 | 2.8 | 11.1 | 0.00 | 4 | 13.9 | 1.1 | 7.8 | 0.00 | 4 | 13.9 | 8.9 | 11.1 | 0.00 |
| 5 | 20.0 | 5.0 | 12.2 | 0.00 | 5 | 10.6 | 7.8 | 10.0 | 0.00 | 5 | 13.9 | 5.0 | 9.4 | 0.05 |
| 6 | 18.9 | 7.2 | 13.3 | 0.00 | 6 | 7.8 | 5.0 | 6.7 | 2.01 | 6 | 17.2 | 2.2 | 10.0 | 0.00 |
| 7 | 11.1 | 1.7 | 6.7 | 0.00 | 7 | 5.6 | 2.2 | 3.9 | 0.00 | 7 | 23.9 | 3.9 | 13.9 | 0.00 |
| 8 | 21.7 | 2.8 | 12.2 | 0.00 | 8 | 5.6 | 1.7 | 3.3 | 0.05 | 8 | 17.8 | 10.0 | 13.9 | 0.00 |
| 9 | 25.6 | 10.0 | 17.8 | 0.00 | 9 | 17.2 | 3.9 | 10.6 | 0.13 | 9 | 22.8 | 11.1 | 16.7 | 0.00 |
| 10 | 12.8 | 5.6 | 8.9 | 0.00 | 10 | 15.6 | 6.1 | 11.1 | 0.00 | 10 | 22.8 | 8.9 | 15.6 | 0.00 |
| 11 | 7.2 | 2.8 | 5.6 | 0.51 | 11 | 20.0 | 5.6 | 12.8 | 0.00 | 11 | 22.8 | 13.9 | 18.3 | 0.00 |
| 12 | 3.9 | 1.7 | 2.8 | 1.42 | 12 | 22.2 | 11.7 | 16.7 | 0.03 | 12 | 25.6 | 17.8 | 21.7 | 0.00 |
| 13 | 7.8 | 1.7 | 4.4 | 0.00 | 13 | 20.0 | 16.1 | 17.8 | 0.13 | 13 | 27.8 | 17.2 | 22.8 | 0.00 |
| 14 | 12.8 | 3.9 | 8.3 | 0.00 | 14 | 22.2 | 17.8 | 20.0 | 0.08 | 14 | 26.1 | 12.2 | 18.9 | 0.03 |
| 15 | 11.7 | 2.8 | 7.2 | 0.00 | 15 | 20.0 | 7.8 | 13.9 | 0.00 | 15 | 25.0 | 12.8 | 18.9 | 0.00 |
| 16 | 11.1 | 0.6 | 6.1 | 0.00 | 16 | 6.7 | -1.1 | 3.3 | 0.00 | 16 | 25.0 | 16.1 | 20.6 | 0.00 |
| 17 | 7.2 | -2.2 | 2.2 | 0.00 | 17 | 16.1 | -2.2 | 6.7 | 0.00 | 17 | 25.0 | 12.8 | 18.9 | 0.03 |
| 18 | 12.8 | -3.3 | 4.4 | 0.00 | 18 | 20.0 | 6.1 | 13.3 | 0.00 | 18 | 18.9 | 12.2 | 15.6 | 1.02 |
| 19 | 16.7 | -1.1 | 7.8 | 0.00 | 19 | 21.7 | 11.1 | 16.7 | 0.61 | 19 | 25.0 | 11.7 | 18.3 | 0.00 |
| 20 | 22.2 | 12.8 | 17.8 | 0.00 | 20 | 13.9 | 10.0 | 12.2 | 10.82 | 20 | 17.2 | 11.1 | 14.4 | 0.00 |
| 21 | 26.7 | 8.9 | 18.9 | 0.00 | 21 | 13.9 | 10.0 | 12.2 | 2.69 | 21 | 18.9 | 7.2 | 13.3 | 0.00 |
| 22 | 12.8 | 5.6 | 9.4 | 0.00 | 22 | 18.9 | 10.0 | 14.4 | 0.28 | 22 | 16.1 | 7.8 | 12.2 | 0.30 |
| 23 | 3.9 | -2.2 | 1.1 | 0.00 | 23 | 23.9 | 5.0 | 15.6 | 0.00 | 23 | 22.2 | 6.1 | 14.4 | 0.00 |
| 24 | 7.8 | -3.3 | 2.2 | 0.00 | 24 | 6.1 | 0.0 | 3.3 | 0.15 | 24 | 23.9 | 10.6 | 17.2 | 0.03 |
| 25 | 7.8 | 3.9 | 5.6 | 0.03 | 25 | 0.6 | -2.2 | -1.1 | 0.13 | 25 | 22.8 | 13.9 | 18.3 | 1.35 |
| 26 | 6.7 | 1.7 | 4.4 | 0.74 | 26 | 2.8 | -1.1 | 1.1 | 0.00 | 26 | 17.8 | 11.7 | 14.4 | 0.15 |
| 27 | 11.7 | 3.9 | 7.8 | 0.00 | 27 | 8.9 | 1.7 | 5.6 | 0.00 | 27 | 25.0 | 10.6 | 17.8 | 0.03 |
| 28 | 21.1 | 8.9 | 15.0 | 0.05 | 28 | 10.6 | 5.6 | 7.8 | 0.00 | 28 | 17.2 | 8.9 | 13.3 | 0.00 |
| 29 | 17.2 | 8.9 | 13.3 | 0.00 | 29 | -17.8 | -17.8 | -17.8 | 0.00 | 29 | 13.9 | 3.9 | 8.9 | 0.00 |
| 30 | 10.6 | 7.8 | 8.9 | 0.00 | | | | | | 30 | 17.8 | 0.6 | 8.9 | 0.00 |
| 31 | 17.8 | 8.9 | 13.3 | 0.00 | | | | | | 31 | 22.2 | 6.1 | 14.4 | 0.00 |

†Pptn = precipitation (mm)

Table A30. Meteorological data for April through June 2003 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| April | | °C | | mm | May | | °C | | mm | June | | °C | | mm |
| 1 | 23.9 | 10.0 | 16.7 | 0.00 | 1 | 31.1 | 17.8 | 24.4 | 0.05 | 1 | 35.0 | 21.1 | 27.8 | 0.00 |
| 2 | 23.9 | 12.8 | 18.3 | 0.00 | 2 | 30.6 | 17.2 | 23.3 | 0.00 | 2 | 33.9 | 22.8 | 28.3 | 0.13 |
| 3 | 23.9 | 15.6 | 20.0 | 0.00 | 3 | 27.8 | 22.8 | 25.6 | 0.00 | 3 | 35.6 | 22.2 | 27.8 | 0.00 |
| 4 | 27.2 | 18.9 | 23.3 | 0.00 | 4 | 30.0 | 22.8 | 26.7 | 0.00 | 4 | 28.9 | 20.6 | 24.4 | 0.33 |
| 5 | 28.9 | 18.9 | 23.9 | 0.00 | 5 | 30.6 | 22.8 | 26.7 | 0.00 | 5 | 26.1 | 18.9 | 22.2 | 2.16 |
| 6 | 25.6 | 18.9 | 22.2 | 0.08 | 6 | 30.6 | 23.9 | 27.2 | 0.05 | 6 | 28.9 | 20.0 | 24.4 | 0.00 |
| 7 | 28.9 | 17.8 | 23.3 | 0.03 | 7 | 32.8 | 23.9 | 28.3 | 0.00 | 7 | 31.7 | 17.8 | 24.4 | 0.00 |
| 8 | 17.8 | 7.8 | 13.9 | 0.00 | 8 | 32.8 | 25.0 | 28.9 | 0.00 | 8 | 30.0 | 20.0 | 25.0 | 0.03 |
| 9 | 18.9 | 2.8 | 11.1 | 0.00 | 9 | 32.8 | 22.8 | 27.8 | 0.00 | 9 | 33.9 | 20.0 | 26.7 | 0.00 |
| 10 | 22.8 | 2.2 | 12.8 | 0.00 | 10 | 32.2 | 22.8 | 27.2 | 0.00 | 10 | 32.8 | 25.0 | 28.9 | 0.00 |
| 11 | 25.0 | 10.6 | 17.8 | 0.00 | 11 | 28.9 | 17.8 | 23.3 | 0.03 | 11 | 36.1 | 25.6 | 30.6 | 0.00 |
| 12 | 27.8 | 11.1 | 18.9 | 0.00 | 12 | 25.0 | 18.9 | 22.2 | 0.15 | 12 | 33.9 | 20.0 | 26.7 | 1.91 |
| 13 | 27.8 | 12.2 | 20.0 | 0.00 | 13 | 32.8 | 17.8 | 25.6 | 0.00 | 13 | 32.8 | 20.0 | 25.6 | 5.08 |
| 14 | 27.8 | 15.0 | 21.7 | 0.00 | 14 | 32.8 | 22.2 | 27.8 | 0.00 | 14 | 31.7 | 18.9 | 25.6 | 0.53 |
| 15 | 27.8 | 17.8 | 22.2 | 0.00 | 15 | 32.8 | 22.8 | 27.8 | 0.00 | 15 | 27.8 | 17.8 | 22.8 | 2.62 |
| 16 | 30.0 | 17.8 | 23.9 | 0.00 | 16 | 35.0 | 20.6 | 27.8 | 1.09 | 16 | 31.1 | 21.7 | 26.7 | 0.08 |
| 17 | 28.9 | 17.2 | 22.2 | 0.00 | 17 | 30.6 | 17.8 | 23.3 | 0.03 | 17 | 30.6 | 20.6 | 25.6 | 0.00 |
| 18 | 28.9 | 18.9 | 23.3 | 0.00 | 18 | 32.2 | 16.7 | 24.4 | 0.00 | 18 | 31.7 | 21.1 | 26.7 | 0.00 |
| 19 | 23.9 | 20.0 | 22.2 | 0.03 | 19 | 33.9 | 21.1 | 27.8 | 0.00 | 19 | 32.8 | 22.2 | 27.8 | 0.00 |
| 20 | 23.9 | 17.2 | 20.0 | 0.00 | 20 | 32.2 | 17.2 | 23.9 | 0.00 | 20 | 30.6 | 22.8 | 24.4 | 0.00 |
| 21 | 27.2 | 17.2 | 22.2 | 0.00 | 21 | 26.7 | 17.2 | 22.2 | 0.08 | 21 | 32.8 | 23.9 | 28.3 | 0.00 |
| 22 | 22.8 | 13.9 | 17.8 | 0.33 | 22 | 28.9 | 17.8 | 23.3 | 0.00 | 22 | 33.9 | 23.9 | 28.9 | 0.00 |
| 23 | 26.7 | 17.8 | 21.7 | 0.00 | 23 | 31.1 | 17.8 | 24.4 | 0.00 | 23 | 35.0 | 25.6 | 30.0 | 0.00 |
| 24 | 32.8 | 21.7 | 27.2 | 0.00 | 24 | 32.2 | 20.6 | 26.1 | 0.00 | 24 | 33.9 | 23.9 | 28.9 | 0.00 |
| 25 | 27.8 | 16.1 | 22.8 | 0.00 | 25 | 30.6 | 18.9 | 24.4 | 0.00 | 25 | 35.0 | 23.9 | 29.4 | 0.00 |
| 26 | 28.9 | 13.9 | 21.1 | 0.00 | 26 | 31.1 | 21.7 | 26.1 | 0.00 | 26 | 32.8 | 22.8 | 27.8 | 3.71 |
| 27 | 30.6 | 15.6 | 22.8 | 0.00 | 27 | 28.9 | 20.6 | 24.4 | 0.00 | 27 | 32.2 | 22.8 | 26.7 | 0.00 |
| 28 | 27.8 | 16.7 | 22.2 | 0.00 | 28 | 30.0 | 15.6 | 23.3 | 0.00 | 28 | 32.8 | 22.2 | 27.8 | 0.00 |
| 29 | 27.8 | 17.2 | 22.2 | 0.00 | 29 | 33.9 | 16.1 | 25.0 | 0.00 | 29 | 32.8 | 22.8 | 27.8 | 0.00 |
| 30 | 28.9 | 18.9 | 23.9 | 0.00 | 30 | 37.2 | 20.6 | 31.7 | 0.00 | 30 | 32.8 | 22.8 | 27.8 | 0.00 |
| | | | | | 31 | 36.1 | 21.7 | 28.9 | 0.00 | | | | | |

†Pptn = precipitation (mm)

Table A31. Meteorological data for July through September 2003 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| July | | °C | | mm | August | | °C | | mm | Sept. | | °C | | mm |
| 1 | 33.9 | 23.9 | 28.9 | 0.00 | 1 | 35.6 | 23.9 | 29.4 | 0.00 | 1 | 30.0 | 23.9 | 26.7 | 0.00 |
| 2 | 33.9 | 22.2 | 27.8 | 0.00 | 2 | 35.6 | 23.9 | 30.0 | 0.00 | 2 | 30.0 | 22.8 | 26.7 | 0.56 |
| 3 | 32.8 | 22.8 | 27.8 | 0.84 | 3 | 35.0 | 25.0 | 29.4 | 0.00 | 3 | 30.0 | 22.8 | 25.6 | 7.11 |
| 4 | 30.0 | 22.2 | 25.6 | 2.72 | 4 | 36.7 | 22.8 | 29.4 | 0.00 | 4 | 32.8 | 22.8 | 27.8 | 0.03 |
| 5 | 31.1 | 22.8 | 26.7 | 0.05 | 5 | 36.1 | 23.9 | 30.0 | 0.00 | 5 | 31.7 | 22.8 | 27.2 | 0.00 |
| 6 | 32.8 | 23.9 | 28.3 | 0.51 | 6 | 36.7 | 23.9 | 30.0 | 0.00 | 6 | 31.1 | 17.8 | 24.4 | 0.00 |
| 7 | 32.2 | 22.8 | 27.2 | 0.30 | 7 | 38.9 | 23.9 | 31.1 | 0.00 | 7 | 30.6 | 16.1 | 23.3 | 0.00 |
| 8 | 32.2 | 22.8 | 27.2 | 0.33 | 8 | 38.9 | 25.6 | 32.2 | 0.00 | 8 | 30.0 | 17.8 | 23.9 | 0.00 |
| 9 | 32.2 | 22.8 | 26.7 | 0.48 | 9 | 33.9 | 23.9 | 28.9 | 0.00 | 9 | 32.2 | 18.9 | 25.6 | 0.00 |
| 10 | 32.8 | 22.8 | 27.8 | 0.03 | 10 | 36.7 | 23.9 | 30.0 | 0.00 | 10 | 32.8 | 22.8 | 27.8 | 0.28 |
| 11 | 32.8 | 21.1 | 27.2 | 3.61 | 11 | 33.9 | 20.6 | 27.2 | 1.55 | 11 | 32.8 | 20.0 | 25.6 | 4.93 |
| 12 | 32.8 | 22.2 | 27.8 | 0.03 | 12 | 30.0 | 20.6 | 25.6 | 0.25 | 12 | 27.8 | 20.0 | 23.3 | 1.40 |
| 13 | 33.9 | 23.9 | 28.3 | 0.00 | 13 | 31.7 | 20.0 | 25.6 | 0.00 | 13 | 32.2 | 18.9 | 25.6 | 0.00 |
| 14 | 33.9 | 23.9 | 28.9 | 0.00 | 14 | 32.2 | 22.8 | 27.2 | 0.08 | 14 | 28.9 | 20.6 | 24.4 | 0.00 |
| 15 | 28.9 | 23.9 | 26.7 | 0.20 | 15 | 35.6 | 22.8 | 28.9 | 0.00 | 15 | 30.6 | 17.8 | 23.9 | 0.00 |
| 16 | 31.7 | 23.9 | 27.8 | 0.84 | 16 | 36.7 | 25.0 | 30.6 | 0.00 | 16 | 31.7 | 20.6 | 26.7 | 0.00 |
| 17 | 33.9 | 22.8 | 27.8 | 0.00 | 17 | 36.1 | 23.9 | 30.0 | 0.00 | 17 | 31.1 | 18.9 | 24.4 | 0.03 |
| 18 | 33.9 | 22.8 | 27.8 | 0.00 | 18 | 36.7 | 25.0 | 30.0 | 0.00 | 18 | 26.7 | 21.1 | 24.4 | 0.25 |
| 19 | 32.8 | 23.9 | 28.3 | 0.00 | 19 | 36.1 | 23.9 | 30.0 | 0.00 | 19 | 28.9 | 20.6 | 24.4 | 0.00 |
| 20 | 33.9 | 22.8 | 28.3 | 0.00 | 20 | 36.1 | 23.9 | 30.0 | 0.00 | 20 | 27.8 | 20.0 | 23.9 | 0.00 |
| 21 | 35.6 | 23.9 | 30.0 | 0.00 | 21 | 36.7 | 22.2 | 28.9 | 5.38 | 21 | 22.8 | 20.0 | 21.7 | 1.32 |
| 22 | 35.6 | 23.9 | 29.4 | 0.00 | 22 | 32.2 | 22.2 | 26.7 | 0.00 | 22 | 28.9 | 18.9 | 23.9 | 0.00 |
| 23 | 30.6 | 21.7 | 26.1 | 0.41 | 23 | 33.9 | 22.8 | 28.9 | 0.00 | 23 | 30.6 | 17.2 | 23.9 | 0.03 |
| 24 | 32.8 | 23.9 | 27.8 | 0.00 | 24 | 35.6 | 22.8 | 28.9 | 0.00 | 24 | 27.8 | 20.0 | 24.4 | 0.00 |
| 25 | 33.9 | 22.8 | 28.3 | 0.00 | 25 | 35.6 | 23.9 | 30.0 | 0.00 | 25 | 30.6 | 20.0 | 25.0 | 0.00 |
| 26 | 35.0 | 22.8 | 28.3 | 0.00 | 26 | 35.0 | 23.9 | 29.4 | 0.00 | 26 | 23.9 | 20.0 | 22.2 | 0.00 |
| 27 | 33.9 | 22.8 | 28.3 | 0.00 | 27 | 35.6 | 23.9 | 29.4 | 0.00 | 27 | 31.7 | 18.9 | 25.0 | 0.00 |
| 28 | 35.0 | 22.8 | 28.3 | 0.00 | 28 | 35.6 | 25.0 | 30.0 | 0.00 | 28 | 28.9 | 17.8 | 23.9 | 0.00 |
| 29 | 35.6 | 22.8 | 28.9 | 0.00 | 29 | 35.0 | 23.9 | 29.4 | 0.00 | 29 | 26.7 | 15.0 | 21.1 | 0.00 |
| 30 | 35.6 | 23.9 | 29.4 | 0.00 | 30 | 33.9 | 23.9 | 28.9 | 0.00 | 30 | 26.1 | 12.8 | 20.0 | 0.00 |
| 31 | 35.6 | 23.9 | 29.4 | 0.00 | 31 | 26.1 | 22.8 | 24.4 | 3.76 | | | | | |

†Pptn = precipitation (mm)

Table A32. Meteorological data for October through December 2003 for College Station, Texas.

| Temperature | | | | | Temperature | | | | | Temperature | | | | |
|-------------|------|------|------|---------|-------------|------|------|------|-------|-------------|------|------|------|-------|
| Date | Max | Min | Avg | Pptn. † | Date | Max | Min | Avg | Pptn. | Date | Max | Min | Avg | Pptn. |
| Oct. | | °C | | mm | Nov. | | °C | | mm | Dec. | | °C | | mm |
| 1 | 27.2 | 13.9 | 20.6 | 0.00 | 1 | 27.2 | 18.9 | 23.3 | 0.00 | 1 | 22.8 | 12.8 | 17.8 | 0.00 |
| 2 | 25.0 | 16.1 | 20.0 | 0.00 | 2 | 27.8 | 20.0 | 23.9 | 0.00 | 2 | 20.6 | 9.4 | 15.0 | 0.00 |
| 3 | 26.7 | 12.8 | 19.4 | 0.00 | 3 | 26.7 | 20.0 | 23.3 | 0.00 | 3 | 23.9 | 10.0 | 17.2 | 0.00 |
| 4 | 28.9 | 12.8 | 21.1 | 0.00 | 4 | 26.7 | 20.0 | 23.3 | 0.00 | 4 | 18.3 | 6.1 | 12.2 | 0.00 |
| 5 | 30.0 | 18.9 | 23.9 | 5.99 | 5 | 27.8 | 18.9 | 23.3 | 0.00 | 5 | 13.9 | 3.3 | 8.9 | 0.00 |
| 6 | 27.2 | 18.9 | 22.2 | 2.06 | 6 | 20.0 | 11.7 | 16.1 | 0.00 | 6 | 11.1 | -1.7 | 5.0 | 0.00 |
| 7 | 27.8 | 18.9 | 23.3 | 0.00 | 7 | 12.2 | 10.6 | 11.7 | 0.00 | 7 | 17.8 | 1.1 | 9.4 | 0.00 |
| 8 | 28.9 | 21.7 | 24.4 | 0.00 | 8 | 13.9 | 10.0 | 12.2 | 0.08 | 8 | 23.9 | 8.9 | 16.7 | 0.00 |
| 9 | 23.9 | 20.6 | 22.2 | 7.65 | 9 | 15.6 | 11.1 | 13.3 | 0.15 | 9 | 22.2 | 7.8 | 15.0 | 0.23 |
| 10 | 25.6 | 18.9 | 22.2 | 0.03 | 10 | 26.1 | 10.0 | 18.3 | 0.00 | 10 | 13.9 | 1.1 | 7.8 | 0.00 |
| 11 | 27.8 | 17.8 | 23.3 | 0.00 | 11 | 27.8 | 20.6 | 24.4 | 0.69 | 11 | 15.6 | 0.0 | 7.8 | 0.00 |
| 12 | 27.8 | 20.6 | 23.3 | 0.00 | 12 | 28.9 | 20.6 | 25.0 | 0.00 | 12 | 15.0 | 9.4 | 12.2 | 1.91 |
| 13 | 28.9 | 21.7 | 24.4 | 0.00 | 13 | 22.2 | 13.9 | 18.3 | 0.08 | 13 | 9.4 | 1.1 | 5.6 | 0.00 |
| 14 | 25.6 | 12.8 | 20.0 | 0.03 | 14 | 22.2 | 9.4 | 16.1 | 0.00 | 14 | 16.1 | -2.2 | 7.2 | 0.00 |
| 15 | 25.0 | 11.7 | 18.3 | 0.00 | 15 | 27.2 | 15.6 | 21.7 | 0.10 | 15 | 22.8 | 7.8 | 15.6 | 0.00 |
| 16 | 28.9 | 13.9 | 21.1 | 0.00 | 16 | 27.8 | 18.3 | 23.3 | 5.31 | 16 | 17.2 | 2.8 | 10.0 | 0.00 |
| 17 | 27.8 | 15.6 | 22.2 | 0.00 | 17 | 23.3 | 20.0 | 21.7 | 3.35 | 17 | 17.2 | -2.2 | 7.8 | 0.00 |
| 18 | 25.6 | 12.8 | 18.9 | 0.00 | 18 | 22.2 | 10.6 | 16.7 | 0.13 | 18 | 18.3 | 0.6 | 9.4 | 0.00 |
| 19 | 26.7 | 12.8 | 20.0 | 0.00 | 19 | 22.2 | 6.7 | 14.4 | 0.00 | 19 | 17.8 | 0.6 | 9.4 | 0.00 |
| 20 | 27.8 | 12.8 | 20.0 | 0.00 | 20 | 23.9 | 7.2 | 15.6 | 0.00 | 20 | 17.8 | 0.0 | 8.9 | 0.00 |
| 21 | 28.9 | 13.9 | 21.1 | 0.00 | 21 | 25.0 | 11.1 | 18.3 | 0.00 | 21 | 22.2 | 7.8 | 15.0 | 0.00 |
| 22 | 31.7 | 12.8 | 22.8 | 0.00 | 22 | 26.7 | 16.1 | 21.7 | 0.00 | 22 | 23.9 | 11.1 | 17.8 | 0.15 |
| 23 | 32.2 | 15.0 | 22.8 | 0.00 | 23 | 22.2 | 4.4 | 13.3 | 0.08 | 23 | 16.1 | 3.3 | 10.0 | 0.03 |
| 24 | 28.9 | 16.7 | 22.8 | 0.00 | 24 | 11.1 | 0.6 | 6.1 | 0.00 | 24 | 16.1 | -1.1 | 7.8 | 0.00 |
| 25 | 27.8 | 15.0 | 22.2 | 1.30 | 25 | 17.8 | 0.6 | 9.4 | 0.00 | 25 | 16.7 | 5.0 | 11.1 | 0.00 |
| 26 | 15.6 | 11.7 | 13.3 | 0.25 | 26 | 22.8 | 13.9 | 18.3 | 0.00 | 26 | 21.1 | 11.1 | 16.1 | 0.00 |
| 27 | 21.7 | 10.0 | 15.6 | 0.00 | 27 | 22.8 | 8.9 | 16.1 | 0.00 | 27 | 25.0 | 16.7 | 21.1 | 0.00 |
| 28 | 26.7 | 8.9 | 17.8 | 0.00 | 28 | 16.1 | 2.8 | 9.4 | 0.00 | 28 | 18.9 | 6.7 | 12.8 | 0.79 |
| 29 | 26.7 | 12.2 | 19.4 | 0.00 | 29 | 17.2 | -0.6 | 8.3 | 0.00 | 29 | 14.4 | 1.1 | 7.8 | 0.00 |
| 30 | 28.9 | 16.7 | 22.8 | 0.00 | 30 | 22.2 | 5.6 | 13.9 | 0.00 | 30 | 16.1 | -0.6 | 7.8 | 0.00 |
| 31 | 28.9 | 21.7 | 25.6 | 0.03 | | | | | | 31 | 20.0 | 5.0 | 12.8 | 0.00 |

†Pptn = precipitation (mm)

Table A33. Long-term meteorological data for January for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| Jan. | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 7:23 | 17:36 | 15 | 4 | 9 | 27 | 1952 | -8 | 1979 |
| 2 | 7:23 | 17:36 | 15 | 4 | 9 | 26 | 1982 | -11 | 1979 |
| 3 | 7:23 | 17:37 | 15 | 4 | 9 | 27 | 1971 | -7 | 1979 |
| 4 | 7:23 | 17:38 | 14 | 4 | 9 | 26 | 1957 | -9 | 1959 |
| 5 | 7:24 | 17:39 | 14 | 4 | 9 | 24 | 1956 | -7 | 1972 |
| 6 | 7:24 | 17:39 | 14 | 4 | 9 | 28 | 1989 | -6 | 1970 |
| 7 | 7:24 | 17:40 | 14 | 4 | 9 | 28 | 1978 | -9 | 1970 |
| 8 | 7:24 | 17:41 | 14 | 3 | 9 | 27 | 1957 | -9 | 1976 |
| 9 | 7:24 | 17:42 | 14 | 3 | 9 | 27 | 1957 | -7 | 1962 |
| 10 | 7:24 | 17:43 | 14 | 3 | 9 | 27 | 1963 | -10 | 1962 |
| 11 | 7:24 | 17:43 | 14 | 3 | 9 | 27 | 1971 | -13 | 1982 |
| 12 | 7:24 | 17:44 | 14 | 3 | 9 | 25 | 1952 | -14 | 1973 |
| 13 | 7:24 | 17:45 | 14 | 3 | 9 | 26 | 1952 | -8 | 1982 |
| 14 | 7:24 | 17:46 | 14 | 3 | 9 | 26 | 1971 | -12 | 1982 |
| 15 | 7:23 | 17:47 | 14 | 3 | 9 | 26 | 1952 | -5 | 1963 |
| 16 | 7:23 | 17:48 | 14 | 3 | 9 | 26 | 1952 | -6 | 1982 |
| 17 | 7:23 | 17:49 | 14 | 3 | 9 | 26 | 1952 | -9 | 1982 |
| 18 | 7:23 | 17:49 | 14 | 3 | 9 | 26 | 1952 | -6 | 1957 |
| 19 | 7:23 | 17:50 | 14 | 3 | 9 | 26 | 1952 | -8 | 1984 |
| 20 | 7:22 | 17:51 | 14 | 3 | 9 | 27 | 1954 | -7 | 1963 |
| 21 | 7:22 | 17:52 | 14 | 3 | 9 | 26 | 1982 | -9 | 1985 |
| 22 | 7:22 | 17:53 | 14 | 3 | 9 | 27 | 1969 | -8 | 1954 |
| 23 | 7:21 | 17:54 | 14 | 3 | 9 | 30 | 1972 | -7 | 1963 |
| 24 | 7:21 | 17:55 | 14 | 3 | 9 | 27 | 1971 | -9 | 1963 |
| 25 | 7:20 | 17:55 | 15 | 4 | 9 | 29 | 1971 | -4 | 1963 |
| 26 | 7:20 | 17:56 | 15 | 4 | 9 | 27 | 1952 | -2 | 1988 |
| 27 | 7:20 | 17:57 | 15 | 4 | 9 | 28 | 1972 | -6 | 1963 |
| 28 | 7:19 | 17:58 | 15 | 4 | 9 | 26 | 1982 | -4 | 1979 |
| 29 | 7:19 | 17:59 | 15 | 4 | 9 | 27 | 1975 | -6 | 1966 |
| 30 | 7:18 | 18:00 | 15 | 4 | 10 | 29 | 1971 | -8 | 1966 |
| 31 | 7:17 | 18:01 | 15 | 4 | 10 | 27 | 1975 | -7 | 1985 |

Table A34. Long-term meteorological data for February for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| Feb. | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 7:17 | 18:02 | 15 | 4 | 10 | 28 | 1963 | -7 | 1985 |
| 2 | 7:16 | 18:02 | 16 | 4 | 10 | 27 | 1974 | -10 | 1985 |
| 3 | 7:16 | 18:03 | 16 | 4 | 10 | 25 | 1976 | -6 | 1985 |
| 4 | 7:15 | 18:04 | 16 | 4 | 10 | 28 | 1957 | -9 | 1996 |
| 5 | 7:14 | 18:05 | 16 | 4 | 10 | 27 | 1957 | -6 | 1989 |
| 6 | 7:13 | 18:06 | 16 | 4 | 11 | 27 | 1969 | -7 | 1989 |
| 7 | 7:13 | 18:07 | 16 | 4 | 11 | 26 | 1957 | -6 | 1967 |
| 8 | 7:12 | 18:07 | 16 | 4 | 11 | 28 | 1994 | -6 | 1971 |
| 9 | 7:11 | 18:08 | 16 | 4 | 11 | 30 | 1960 | -6 | 1979 |
| 10 | 7:10 | 18:09 | 16 | 4 | 11 | 30 | 1954 | -5 | 1973 |
| 11 | 7:09 | 18:10 | 16 | 5 | 11 | 27 | 1976 | -8 | 1981 |
| 12 | 7:09 | 18:11 | 17 | 5 | 11 | 27 | 1962 | -7 | 1988 |
| 13 | 7:08 | 18:12 | 17 | 5 | 11 | 27 | 1962 | -6 | 1958 |
| 14 | 7:07 | 18:12 | 17 | 5 | 11 | 28 | 1956 | -2 | 1963 |
| 15 | 7:06 | 18:13 | 17 | 5 | 11 | 28 | 1957 | 0 | 1958 |
| 16 | 7:05 | 18:14 | 17 | 6 | 12 | 29 | 1982 | -3 | 1958 |
| 17 | 7:04 | 18:15 | 17 | 6 | 12 | 32 | 1982 | -4 | 1980 |
| 18 | 7:03 | 18:16 | 17 | 6 | 12 | 32 | 1986 | -3 | 1978 |
| 19 | 7:02 | 18:16 | 18 | 6 | 12 | 32 | 1986 | -6 | 1978 |
| 20 | 7:01 | 18:17 | 18 | 6 | 12 | 35 | 1986 | 0 | 1955 |
| 21 | 7:00 | 18:18 | 18 | 6 | 12 | 37 | 1996 | -2 | 1978 |
| 22 | 6:59 | 18:19 | 18 | 6 | 12 | 36 | 1996 | -3 | 1978 |
| 23 | 6:58 | 18:19 | 18 | 6 | 13 | 32 | 1996 | -2 | 1967 |
| 24 | 6:57 | 18:20 | 18 | 7 | 13 | 29 | 1977 | -5 | 1965 |
| 25 | 6:56 | 18:21 | 18 | 7 | 13 | 29 | 1954 | -6 | 1974 |
| 26 | 6:55 | 18:22 | 19 | 7 | 13 | 31 | 1954 | -4 | 1960 |
| 27 | 6:54 | 18:22 | 19 | 7 | 13 | 27 | 1996 | -1 | 1977 |
| 28 | 6:53 | 18:23 | 19 | 7 | 13 | 29 | 1978 | -2 | 1962 |
| 29 | 6:52 | 18:24 | 19 | 7 | 13 | 28 | 1988 | -3 | 1984 |

Table A35. Long-term meteorological data for March for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|-------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| March | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:52 | 18:24 | 19 | 7 | 14 | 28 | 1953 | -4 | 1980 |
| 2 | 6:50 | 18:24 | 19 | 8 | 14 | 30 | 1956 | -7 | 1980 |
| 3 | 6:49 | 18:25 | 19 | 8 | 14 | 28 | 1976 | -5 | 1980 |
| 4 | 6:48 | 18:26 | 20 | 8 | 14 | 28 | 1976 | -4 | 1965 |
| 5 | 6:47 | 18:27 | 20 | 8 | 14 | 32 | 1991 | -4 | 1989 |
| 6 | 6:46 | 18:27 | 20 | 8 | 14 | 32 | 1991 | -4 | 1989 |
| 7 | 6:45 | 18:28 | 21 | 8 | 14 | 29 | 1974 | -4 | 1989 |
| 8 | 6:44 | 18:29 | 21 | 8 | 15 | 30 | 1974 | -2 | 1996 |
| 9 | 6:42 | 18:29 | 21 | 9 | 15 | 28 | 1974 | -3 | 1996 |
| 10 | 6:41 | 18:30 | 21 | 9 | 15 | 31 | 1954 | -5 | 1996 |
| 11 | 6:40 | 18:31 | 21 | 9 | 15 | 32 | 1955 | 1 | 1969 |
| 12 | 6:39 | 18:31 | 21 | 9 | 16 | 31 | 1967 | 1 | 1983 |
| 13 | 6:38 | 18:32 | 21 | 9 | 16 | 31 | 1971 | -1 | 1968 |
| 14 | 6:36 | 18:33 | 22 | 9 | 16 | 32 | 1967 | -3 | 1993 |
| 15 | 6:35 | 18:33 | 22 | 10 | 16 | 29 | 1977 | -1 | 1999 |
| 16 | 6:34 | 18:34 | 22 | 10 | 16 | 28 | 1971 | 1 | 1962 |
| 17 | 6:33 | 18:35 | 22 | 10 | 16 | 31 | 1972 | 2 | 1959 |
| 18 | 6:31 | 18:35 | 22 | 10 | 16 | 31 | 1982 | 1 | 1960 |
| 19 | 6:30 | 18:36 | 22 | 11 | 17 | 32 | 1974 | -2 | 1965 |
| 20 | 6:29 | 18:37 | 22 | 11 | 17 | 32 | 1982 | -4 | 1965 |
| 21 | 6:28 | 18:37 | 22 | 11 | 17 | 28 | 1953 | -1 | 1996 |
| 22 | 6:26 | 18:38 | 23 | 11 | 17 | 34 | 1971 | -1 | 1970 |
| 23 | 6:25 | 18:38 | 23 | 11 | 17 | 33 | 1995 | -1 | 1968 |
| 24 | 6:24 | 18:39 | 23 | 11 | 17 | 29 | 1954 | -1 | 1952 |
| 25 | 6:23 | 18:40 | 23 | 11 | 17 | 29 | 1955 | 1 | 1955 |
| 26 | 6:22 | 18:40 | 23 | 12 | 18 | 28 | 1956 | -4 | 1955 |
| 27 | 6:20 | 18:41 | 23 | 12 | 18 | 31 | 1984 | -1 | 1955 |
| 28 | 6:19 | 18:42 | 23 | 12 | 18 | 33 | 1971 | -1 | 1955 |
| 29 | 6:18 | 18:42 | 23 | 12 | 18 | 31 | 1960 | 2 | 1975 |
| 30 | 6:17 | 18:43 | 24 | 12 | 18 | 32 | 1996 | 1 | 1975 |
| 31 | 6:15 | 18:44 | 24 | 12 | 18 | 33 | 1982 | -2 | 1987 |

Table A36. Long-term meteorological data for April for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date |
|-------|---------|--------|-------------|----------|------|-------------|----------------|------------|------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| April | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:14 | 18:44 | 24 | 12 | 18 | 31 | 1974 | 3 | 1961 |
| 2 | 6:13 | 18:45 | 24 | 13 | 18 | 31 | 1982 | 4 | 1970 |
| 3 | 6:12 | 18:45 | 24 | 13 | 19 | 31 | 1988 | -1 | 1987 |
| 4 | 6:11 | 18:46 | 24 | 13 | 19 | 32 | 1958 | 3 | 1987 |
| 5 | 6:09 | 18:47 | 24 | 13 | 19 | 32 | 1955 | 3 | 1973 |
| 6 | 6:08 | 18:47 | 24 | 13 | 19 | 33 | 1960 | 3 | 1970 |
| 7 | 6:07 | 18:48 | 24 | 13 | 19 | 32 | 1960 | 2 | 1996 |
| 8 | 7:06 | 19:49 | 25 | 13 | 19 | 32 | 1989 | 5 | 1973 |
| 9 | 7:05 | 19:50 | 25 | 13 | 19 | 34 | 1963 | 1 | 1973 |
| 10 | 7:04 | 19:50 | 25 | 14 | 19 | 33 | 1963 | -2 | 1973 |
| 11 | 7:03 | 19:51 | 25 | 14 | 20 | 31 | 1987 | 3 | 1989 |
| 12 | 7:01 | 19:51 | 25 | 14 | 20 | 31 | 1966 | 6 | 1957 |
| 13 | 7:00 | 19:52 | 26 | 14 | 20 | 33 | 1996 | 3 | 1959 |
| 14 | 6:59 | 19:53 | 26 | 14 | 20 | 32 | 1996 | 1 | 1980 |
| 15 | 6:58 | 19:53 | 26 | 14 | 20 | 31 | 1954 | 4 | 1983 |
| 16 | 6:57 | 19:54 | 26 | 14 | 21 | 32 | 1987 | 2 | 1961 |
| 17 | 6:56 | 19:55 | 26 | 14 | 21 | 33 | 1987 | 2 | 1999 |
| 18 | 6:55 | 19:55 | 26 | 15 | 21 | 34 | 1996 | 6 | 1999 |
| 19 | 6:53 | 19:56 | 26 | 15 | 21 | 33 | 1987 | 4 | 1953 |
| 20 | 6:52 | 19:56 | 26 | 15 | 21 | 33 | 1987 | 4 | 1953 |
| 21 | 6:51 | 19:57 | 26 | 15 | 21 | 32 | 1996 | 8 | 1953 |
| 22 | 6:50 | 19:58 | 26 | 15 | 21 | 31 | 1955 | 6 | 1959 |
| 23 | 6:49 | 19:58 | 27 | 16 | 21 | 33 | 1958 | 7 | 1959 |
| 24 | 6:48 | 19:59 | 27 | 16 | 21 | 32 | 1955 | 7 | 1968 |
| 25 | 6:47 | 20:00 | 27 | 16 | 22 | 33 | 1996 | 8 | 1968 |
| 26 | 6:46 | 20:00 | 27 | 16 | 22 | 33 | 1988 | 8 | 1952 |
| 27 | 6:45 | 20:01 | 27 | 16 | 22 | 33 | 1987 | 8 | 1952 |
| 28 | 6:44 | 20:02 | 27 | 16 | 22 | 34 | 1987 | 8 | 1973 |
| 29 | 6:43 | 20:02 | 27 | 16 | 22 | 32 | 1959 | 8 | 1965 |
| 30 | 6:42 | 20:03 | 27 | 16 | 22 | 32 | 1955 | 7 | 1996 |

Table A37. Long-term meteorological data for May for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| May | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:41 | 20:04 | 27 | 17 | 22 | 32 | 1955 | 9 | 1994 |
| 2 | 6:40 | 20:04 | 27 | 17 | 22 | 35 | 1964 | 9 | 1967 |
| 3 | 6:40 | 20:05 | 27 | 17 | 22 | 32 | 1971 | 7 | 1954 |
| 4 | 6:39 | 20:06 | 28 | 17 | 23 | 35 | 1984 | 6 | 1954 |
| 5 | 6:38 | 20:06 | 28 | 17 | 23 | 34 | 1984 | 8 | 1953 |
| 6 | 6:37 | 20:07 | 28 | 17 | 23 | 36 | 1984 | 10 | 1957 |
| 7 | 6:36 | 20:07 | 28 | 17 | 23 | 34 | 1984 | 9 | 1992 |
| 8 | 6:35 | 20:08 | 28 | 17 | 23 | 33 | 1956 | 9 | 1982 |
| 9 | 6:35 | 20:09 | 28 | 17 | 23 | 33 | 1952 | 8 | 1984 |
| 10 | 6:34 | 20:09 | 28 | 18 | 23 | 33 | 1963 | 9 | 1961 |
| 11 | 6:33 | 20:10 | 28 | 18 | 23 | 34 | 1967 | 7 | 1981 |
| 12 | 6:32 | 20:11 | 28 | 18 | 23 | 34 | 1978 | 8 | 1960 |
| 13 | 6:32 | 20:11 | 28 | 18 | 23 | 34 | 1984 | 9 | 1960 |
| 14 | 6:31 | 20:12 | 29 | 18 | 24 | 34 | 1955 | 9 | 1971 |
| 15 | 6:30 | 20:13 | 29 | 18 | 24 | 34 | 1978 | 11 | 1973 |
| 16 | 6:30 | 20:13 | 29 | 18 | 24 | 34 | 1996 | 10 | 1967 |
| 17 | 6:29 | 20:14 | 29 | 18 | 24 | 35 | 1996 | 11 | 1967 |
| 18 | 6:29 | 20:15 | 29 | 18 | 24 | 34 | 1978 | 13 | 1976 |
| 19 | 6:28 | 20:15 | 29 | 19 | 24 | 34 | 1960 | 12 | 1976 |
| 20 | 6:28 | 20:16 | 29 | 19 | 24 | 35 | 1996 | 12 | 1981 |
| 21 | 6:27 | 20:17 | 29 | 19 | 24 | 36 | 1996 | 12 | 1960 |
| 22 | 6:27 | 20:17 | 29 | 19 | 24 | 36 | 1996 | 14 | 1967 |
| 23 | 6:26 | 20:18 | 29 | 19 | 25 | 36 | 1996 | 13 | 1967 |
| 24 | 6:26 | 20:18 | 30 | 19 | 25 | 36 | 1955 | 16 | 1967 |
| 25 | 6:25 | 20:19 | 30 | 19 | 25 | 36 | 1996 | 15 | 1979 |
| 26 | 6:25 | 20:20 | 30 | 19 | 25 | 36 | 1996 | 16 | 1979 |
| 27 | 6:24 | 20:20 | 30 | 19 | 25 | 37 | 1958 | 13 | 1961 |
| 28 | 6:24 | 20:21 | 31 | 20 | 26 | 37 | 1958 | 12 | 1961 |
| 29 | 6:24 | 20:21 | 31 | 20 | 26 | 38 | 1996 | 14 | 1984 |
| 30 | 6:24 | 20:22 | 31 | 20 | 26 | 35 | 1956 | 12 | 1984 |
| 31 | 6:23 | 20:22 | 31 | 20 | 26 | 36 | 1958 | 13 | 1984 |

Table A38. Long-term meteorological data for June for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| June | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:23 | 20:23 | 31 | 20 | 26 | 36 | 1958 | 13 | 1964 |
| 2 | 6:23 | 20:24 | 31 | 21 | 26 | 36 | 1960 | 14 | 1964 |
| 3 | 6:23 | 20:24 | 31 | 21 | 26 | 38 | 1960 | 12 | 1970 |
| 4 | 6:22 | 20:25 | 31 | 21 | 26 | 38 | 1960 | 14 | 1970 |
| 5 | 6:22 | 20:25 | 31 | 21 | 26 | 37 | 1960 | 13 | 1970 |
| 6 | 6:22 | 20:26 | 31 | 21 | 26 | 38 | 1958 | 15 | 1970 |
| 7 | 6:22 | 20:26 | 32 | 21 | 27 | 36 | 1958 | 17 | 1970 |
| 8 | 6:22 | 20:26 | 32 | 21 | 27 | 37 | 1985 | 16 | 1983 |
| 9 | 6:22 | 20:27 | 32 | 21 | 27 | 37 | 1958 | 14 | 1996 |
| 10 | 6:22 | 20:27 | 32 | 21 | 27 | 37 | 1958 | 13 | 1955 |
| 11 | 6:22 | 20:28 | 32 | 21 | 27 | 38 | 1953 | 14 | 1955 |
| 12 | 6:22 | 20:28 | 32 | 21 | 27 | 38 | 1958 | 15 | 1955 |
| 13 | 6:22 | 20:28 | 32 | 21 | 27 | 38 | 1996 | 16 | 1979 |
| 14 | 6:22 | 20:29 | 32 | 22 | 27 | 38 | 1996 | 17 | 1979 |
| 15 | 6:22 | 20:29 | 32 | 22 | 27 | 39 | 1960 | 16 | 1989 |
| 16 | 6:22 | 20:29 | 32 | 22 | 27 | 38 | 1996 | 14 | 1989 |
| 17 | 6:22 | 20:30 | 32 | 22 | 27 | 38 | 1996 | 16 | 1989 |
| 18 | 6:22 | 20:30 | 32 | 22 | 27 | 39 | 1996 | 19 | 1988 |
| 19 | 6:23 | 20:30 | 33 | 22 | 27 | 39 | 1996 | 19 | 1955 |
| 20 | 6:23 | 20:31 | 33 | 22 | 28 | 39 | 1996 | 17 | 1976 |
| 21 | 6:23 | 20:31 | 33 | 22 | 28 | 38 | 1960 | 16 | 1976 |
| 22 | 6:23 | 20:31 | 33 | 22 | 28 | 38 | 1953 | 18 | 1961 |
| 23 | 6:23 | 20:31 | 33 | 22 | 28 | 39 | 1953 | 18 | 1955 |
| 24 | 6:24 | 20:31 | 33 | 22 | 28 | 38 | 1980 | 19 | 1974 |
| 25 | 6:24 | 20:31 | 33 | 22 | 28 | 38 | 1958 | 15 | 1974 |
| 26 | 6:24 | 20:32 | 33 | 22 | 28 | 39 | 1953 | 16 | 1974 |
| 27 | 6:25 | 20:32 | 33 | 22 | 28 | 40 | 1980 | 16 | 1974 |
| 28 | 6:25 | 20:32 | 33 | 22 | 28 | 38 | 1980 | 17 | 1974 |
| 29 | 6:25 | 20:32 | 33 | 22 | 28 | 38 | 1980 | 17 | 1985 |
| 30 | 6:26 | 20:32 | 33 | 22 | 28 | 38 | 1980 | 16 | 1985 |

Table A39. Long-term meteorological data for July for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| July | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:26 | 20:32 | 33 | 22 | 28 | 39 | 1980 | 20 | 1985 |
| 2 | 6:26 | 20:32 | 33 | 22 | 28 | 39 | 1980 | 21 | 1964 |
| 3 | 6:27 | 20:32 | 33 | 22 | 28 | 38 | 1990 | 21 | 1961 |
| 4 | 6:27 | 20:32 | 33 | 22 | 28 | 38 | 1952 | 21 | 1968 |
| 5 | 6:28 | 20:31 | 33 | 23 | 28 | 39 | 1957 | 18 | 1968 |
| 6 | 6:28 | 20:31 | 34 | 23 | 28 | 39 | 1956 | 18 | 1968 |
| 7 | 6:29 | 20:31 | 34 | 23 | 28 | 39 | 1971 | 18 | 1968 |
| 8 | 6:29 | 20:31 | 34 | 23 | 28 | 39 | 1956 | 19 | 1983 |
| 9 | 6:30 | 20:31 | 34 | 23 | 28 | 38 | 1956 | 21 | 1968 |
| 10 | 6:30 | 20:31 | 34 | 23 | 28 | 38 | 1954 | 21 | 1968 |
| 11 | 6:31 | 20:30 | 34 | 23 | 28 | 40 | 1954 | 21 | 1972 |
| 12 | 6:31 | 20:30 | 34 | 23 | 29 | 43 | 1954 | 21 | 1959 |
| 13 | 6:32 | 20:30 | 34 | 23 | 29 | 38 | 1954 | 21 | 1953 |
| 14 | 6:32 | 20:29 | 34 | 23 | 29 | 39 | 1980 | 17 | 1990 |
| 15 | 6:33 | 20:29 | 34 | 23 | 29 | 39 | 1969 | 16 | 1967 |
| 16 | 6:33 | 20:29 | 34 | 23 | 29 | 39 | 1978 | 14 | 1967 |
| 17 | 6:34 | 20:28 | 34 | 23 | 29 | 39 | 1980 | 19 | 1990 |
| 18 | 6:34 | 20:28 | 34 | 23 | 29 | 39 | 1980 | 19 | 1967 |
| 19 | 6:35 | 20:27 | 34 | 23 | 29 | 39 | 1996 | 21 | 1974 |
| 20 | 6:36 | 20:27 | 34 | 23 | 29 | 39 | 1996 | 20 | 1989 |
| 21 | 6:36 | 20:26 | 34 | 23 | 29 | 39 | 1996 | 18 | 1989 |
| 22 | 6:37 | 20:26 | 34 | 23 | 29 | 39 | 1996 | 18 | 1988 |
| 23 | 6:37 | 20:25 | 34 | 23 | 29 | 41 | 1996 | 18 | 1988 |
| 24 | 6:38 | 20:25 | 34 | 23 | 29 | 41 | 1954 | 21 | 1970 |
| 25 | 6:39 | 20:24 | 34 | 23 | 29 | 39 | 1954 | 21 | 1989 |
| 26 | 6:39 | 20:24 | 34 | 23 | 29 | 41 | 1954 | 21 | 1959 |
| 27 | 6:40 | 20:23 | 34 | 23 | 29 | 40 | 1954 | 22 | 1975 |
| 28 | 6:41 | 20:22 | 34 | 23 | 29 | 41 | 1995 | 18 | 1994 |
| 29 | 6:41 | 20:22 | 35 | 23 | 29 | 39 | 1960 | 18 | 1994 |
| 30 | 6:42 | 20:21 | 35 | 23 | 29 | 39 | 1957 | 21 | 1954 |
| 31 | 6:42 | 20:20 | 35 | 23 | 29 | 39 | 1958 | 20 | 1971 |

Table A40. Long-term meteorological data for August for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|--------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| August | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:43 | 20:19 | 35 | 23 | 29 | 39 | 1958 | 19 | 1971 |
| 2 | 6:44 | 20:19 | 35 | 23 | 29 | 39 | 1958 | 20 | 1994 |
| 3 | 6:44 | 20:18 | 35 | 23 | 29 | 40 | 1951 | 20 | 1973 |
| 4 | 6:45 | 20:17 | 35 | 23 | 29 | 42 | 1951 | 19 | 1976 |
| 5 | 6:46 | 20:16 | 35 | 23 | 29 | 41 | 1951 | 19 | 1973 |
| 6 | 6:46 | 20:15 | 35 | 23 | 29 | 41 | 1951 | 21 | 1957 |
| 7 | 6:47 | 20:15 | 35 | 23 | 29 | 41 | 1988 | 19 | 1961 |
| 8 | 6:47 | 20:14 | 35 | 23 | 29 | 41 | 1988 | 20 | 1990 |
| 9 | 6:48 | 20:13 | 35 | 23 | 29 | 42 | 1962 | 17 | 1989 |
| 10 | 6:49 | 20:12 | 35 | 23 | 29 | 42 | 1962 | 16 | 1989 |
| 11 | 6:49 | 20:11 | 35 | 23 | 29 | 41 | 1969 | 19 | 1989 |
| 12 | 6:50 | 20:10 | 35 | 23 | 29 | 40 | 1951 | 18 | 1967 |
| 13 | 6:50 | 20:09 | 34 | 23 | 29 | 41 | 1951 | 16 | 1967 |
| 14 | 6:51 | 20:08 | 34 | 23 | 29 | 41 | 1951 | 16 | 1967 |
| 15 | 6:52 | 20:07 | 34 | 23 | 29 | 41 | 1951 | 19 | 1967 |
| 16 | 6:52 | 20:06 | 34 | 23 | 29 | 42 | 1951 | 18 | 1992 |
| 17 | 6:53 | 20:05 | 34 | 23 | 29 | 42 | 1951 | 17 | 1992 |
| 18 | 6:54 | 20:04 | 34 | 22 | 29 | 39 | 1978 | 16 | 1992 |
| 19 | 6:54 | 20:03 | 34 | 22 | 29 | 40 | 1999 | 21 | 1976 |
| 20 | 6:55 | 20:02 | 34 | 22 | 28 | 42 | 1999 | 18 | 1953 |
| 21 | 6:55 | 20:01 | 34 | 22 | 28 | 39 | 1995 | 19 | 1961 |
| 22 | 6:56 | 20:00 | 34 | 22 | 28 | 41 | 1980 | 18 | 1956 |
| 23 | 6:57 | 19:59 | 34 | 22 | 28 | 41 | 1980 | 17 | 1961 |
| 24 | 6:57 | 19:58 | 34 | 22 | 28 | 40 | 1980 | 17 | 1966 |
| 25 | 6:58 | 19:57 | 34 | 22 | 28 | 39 | 1952 | 17 | 1961 |
| 26 | 6:58 | 19:55 | 34 | 22 | 28 | 39 | 1999 | 18 | 1958 |
| 27 | 6:59 | 19:54 | 33 | 22 | 28 | 40 | 1990 | 18 | 1970 |
| 28 | 6:59 | 19:53 | 33 | 22 | 28 | 39 | 1995 | 16 | 1992 |
| 29 | 7:00 | 19:52 | 33 | 22 | 28 | 39 | 1999 | 16 | 1992 |
| 30 | 7:01 | 19:51 | 33 | 22 | 28 | 42 | 1954 | 17 | 1986 |
| 31 | 7:01 | 19:50 | 33 | 22 | 28 | 41 | 1954 | 19 | 1986 |

Table A41. Long-term meteorological data for September for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|-------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| Sept. | A.M. | P.M. | | | °C | | Year | °C | Year |
| 1 | 7:02 | 19:48 | 33 | 22 | 28 | 41 | 1985 | 19 | 1968 |
| 2 | 7:02 | 19:47 | 33 | 22 | 27 | 40 | 1951 | 19 | 1955 |
| 3 | 7:03 | 19:46 | 33 | 22 | 27 | 41 | 1951 | 16 | 1974 |
| 4 | 7:04 | 19:45 | 33 | 21 | 27 | 39 | 1995 | 14 | 1974 |
| 5 | 7:04 | 19:44 | 32 | 21 | 27 | 38 | 1963 | 13 | 1974 |
| 6 | 7:05 | 19:42 | 32 | 21 | 27 | 38 | 1963 | 13 | 1974 |
| 7 | 7:05 | 19:41 | 32 | 21 | 27 | 39 | 1963 | 17 | 1953 |
| 8 | 7:06 | 19:40 | 32 | 21 | 27 | 37 | 1955 | 15 | 1957 |
| 9 | 7:06 | 19:39 | 32 | 21 | 27 | 37 | 1985 | 15 | 1957 |
| 10 | 7:07 | 19:37 | 32 | 21 | 27 | 38 | 1963 | 16 | 1957 |
| 11 | 7:07 | 19:36 | 32 | 21 | 26 | 37 | 1963 | 16 | 1959 |
| 12 | 7:08 | 19:35 | 31 | 21 | 26 | 37 | 1982 | 14 | 1959 |
| 13 | 7:09 | 19:34 | 31 | 21 | 26 | 37 | 1965 | 13 | 1954 |
| 14 | 7:09 | 19:32 | 31 | 20 | 26 | 37 | 1965 | 15 | 1960 |
| 15 | 7:10 | 19:31 | 31 | 20 | 26 | 37 | 1954 | 12 | 1989 |
| 16 | 7:10 | 19:30 | 31 | 20 | 26 | 37 | 1954 | 12 | 1989 |
| 17 | 7:11 | 19:29 | 31 | 19 | 26 | 39 | 1995 | 13 | 1981 |
| 18 | 7:11 | 19:27 | 31 | 19 | 26 | 37 | 1956 | 11 | 1981 |
| 19 | 7:12 | 19:26 | 31 | 19 | 25 | 38 | 1956 | 10 | 1981 |
| 20 | 7:13 | 19:25 | 30 | 19 | 25 | 38 | 1999 | 13 | 1981 |
| 21 | 7:13 | 19:23 | 30 | 19 | 25 | 37 | 1957 | 12 | 1983 |
| 22 | 7:14 | 19:22 | 30 | 19 | 24 | 36 | 1993 | 9 | 1983 |
| 23 | 7:14 | 19:21 | 30 | 19 | 24 | 36 | 1993 | 8 | 1994 |
| 24 | 7:15 | 19:20 | 29 | 18 | 24 | 36 | 1993 | 11 | 1975 |
| 25 | 7:15 | 19:18 | 29 | 18 | 24 | 36 | 1954 | 7 | 1989 |
| 26 | 7:16 | 19:17 | 29 | 18 | 24 | 37 | 1954 | 11 | 1975 |
| 27 | 7:17 | 19:16 | 29 | 18 | 24 | 38 | 1953 | 12 | 1952 |
| 28 | 7:17 | 19:14 | 29 | 18 | 24 | 38 | 1953 | 9 | 1967 |
| 29 | 7:18 | 19:13 | 29 | 17 | 23 | 36 | 1953 | 8 | 1967 |
| 30 | 7:18 | 19:12 | 29 | 17 | 23 | 37 | 1953 | 9 | 1984 |

Table A42. Long-term meteorological data for October for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | | | |
| Oct. | A.M. | P.M. | °C | | | Year | °C | Year |
| 1 | 7:19 | 19:11 | 28 | 17 | 23 | 36 | 6 | 1984 |
| 2 | 7:20 | 19:09 | 28 | 17 | 23 | 36 | 8 | 1984 |
| 3 | 7:20 | 19:08 | 28 | 17 | 23 | 35 | 8 | 1961 |
| 4 | 7:21 | 19:07 | 28 | 17 | 23 | 37 | 8 | 1975 |
| 5 | 7:21 | 19:06 | 28 | 16 | 22 | 35 | 8 | 1975 |
| 6 | 7:22 | 19:05 | 28 | 16 | 22 | 36 | 8 | 1953 |
| 7 | 7:23 | 19:03 | 28 | 16 | 22 | 34 | 8 | 1999 |
| 8 | 7:23 | 19:02 | 28 | 16 | 22 | 35 | 2 | 1952 |
| 9 | 7:24 | 19:01 | 27 | 16 | 22 | 33 | 4 | 1952 |
| 10 | 7:25 | 19:00 | 27 | 16 | 22 | 34 | 6 | 1990 |
| 11 | 7:25 | 18:59 | 27 | 15 | 21 | 34 | 7 | 1990 |
| 12 | 7:26 | 18:57 | 27 | 15 | 21 | 36 | 8 | 1977 |
| 13 | 7:27 | 18:56 | 27 | 14 | 21 | 35 | 4 | 1977 |
| 14 | 7:27 | 18:55 | 27 | 14 | 21 | 33 | 7 | 1969 |
| 15 | 7:28 | 18:54 | 26 | 14 | 21 | 33 | 7 | 1978 |
| 16 | 7:29 | 18:53 | 26 | 14 | 21 | 34 | 6 | 1954 |
| 17 | 7:29 | 18:52 | 26 | 14 | 20 | 33 | 6 | 1954 |
| 18 | 7:30 | 18:51 | 26 | 14 | 20 | 33 | 7 | 1976 |
| 19 | 7:31 | 18:50 | 26 | 13 | 20 | 32 | 3 | 1989 |
| 20 | 7:31 | 18:49 | 26 | 13 | 20 | 32 | 1 | 1989 |
| 21 | 7:32 | 18:48 | 26 | 13 | 19 | 33 | 2 | 1976 |
| 22 | 7:33 | 18:46 | 25 | 13 | 19 | 33 | 4 | 1952 |
| 23 | 7:33 | 18:45 | 25 | 13 | 19 | 33 | 4 | 1990 |
| 24 | 7:34 | 18:44 | 25 | 13 | 19 | 32 | 3 | 1952 |
| 25 | 7:35 | 18:44 | 24 | 13 | 19 | 33 | 3 | 1980 |
| 26 | 7:36 | 18:43 | 24 | 12 | 19 | 33 | 3 | 1957 |
| 27 | 7:36 | 18:42 | 24 | 12 | 18 | 33 | 1 | 1957 |
| 28 | 7:37 | 18:41 | 24 | 12 | 18 | 31 | 0 | 1957 |
| 29 | 7:38 | 18:40 | 24 | 12 | 18 | 31 | 4 | 1954 |
| 30 | 7:39 | 18:39 | 24 | 12 | 18 | 32 | 0 | 1993 |
| 31 | 7:39 | 18:38 | 23 | 12 | 18 | 32 | -2 | 1993 |

Table A43. Long-term meteorological data for November for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | Record High | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | | | | |
| Nov. | A.M. | P.M. | °C | | | | Year | °C | Year |
| 1 | 6:40 | 17:38 | 23 | 12 | 18 | 31 | 1955 | 1 | 1991 |
| 2 | 6:41 | 17:37 | 23 | 11 | 17 | 32 | 1955 | -1 | 1951 |
| 3 | 6:41 | 17:36 | 23 | 11 | 17 | 30 | 1987 | -3 | 1951 |
| 4 | 6:42 | 17:35 | 23 | 11 | 17 | 31 | 1987 | -3 | 1991 |
| 5 | 6:43 | 17:35 | 23 | 11 | 17 | 31 | 1963 | -1 | 1991 |
| 6 | 6:44 | 17:34 | 22 | 11 | 17 | 31 | 1989 | -1 | 1959 |
| 7 | 6:45 | 17:33 | 22 | 11 | 17 | 31 | 1988 | -2 | 1993 |
| 8 | 6:45 | 17:32 | 22 | 11 | 17 | 32 | 1989 | -1 | 1959 |
| 9 | 6:46 | 17:32 | 22 | 10 | 16 | 31 | 1988 | -2 | 1991 |
| 10 | 6:47 | 17:31 | 22 | 10 | 16 | 30 | 1995 | 1 | 1953 |
| 11 | 6:48 | 17:31 | 22 | 10 | 16 | 30 | 1962 | -1 | 1952 |
| 12 | 6:49 | 17:30 | 21 | 9 | 16 | 30 | 1955 | -1 | 1968 |
| 13 | 6:50 | 17:29 | 21 | 9 | 16 | 31 | 1955 | -1 | 1986 |
| 14 | 6:51 | 17:29 | 21 | 9 | 16 | 31 | 1988 | -2 | 1969 |
| 15 | 6:51 | 17:28 | 21 | 9 | 16 | 31 | 1952 | -3 | 1969 |
| 16 | 6:52 | 17:28 | 21 | 9 | 15 | 30 | 1957 | -3 | 1970 |
| 17 | 6:53 | 17:27 | 21 | 9 | 15 | 28 | 1964 | -2 | 1959 |
| 18 | 6:54 | 17:27 | 20 | 9 | 15 | 29 | 1986 | -4 | 1959 |
| 19 | 6:55 | 17:27 | 20 | 9 | 14 | 30 | 1970 | -2 | 1959 |
| 20 | 6:56 | 17:26 | 20 | 8 | 14 | 29 | 1977 | -3 | 1969 |
| 21 | 6:57 | 17:26 | 20 | 8 | 14 | 28 | 1996 | 0 | 1975 |
| 22 | 6:57 | 17:26 | 19 | 8 | 14 | 30 | 1955 | 0 | 1975 |
| 23 | 6:58 | 17:25 | 19 | 8 | 14 | 28 | 1973 | -5 | 1975 |
| 24 | 6:59 | 17:25 | 19 | 8 | 14 | 29 | 1965 | -3 | 1970 |
| 25 | 7:00 | 17:25 | 19 | 8 | 14 | 30 | 1981 | -2 | 1999 |
| 26 | 7:01 | 17:25 | 19 | 8 | 13 | 30 | 1965 | -3 | 1993 |
| 27 | 7:02 | 17:24 | 19 | 7 | 13 | 28 | 1994 | -7 | 1993 |
| 28 | 7:02 | 17:24 | 18 | 7 | 13 | 28 | 1975 | -4 | 1976 |
| 29 | 7:03 | 17:24 | 18 | 7 | 13 | 27 | 1975 | -7 | 1976 |
| 30 | 7:04 | 17:24 | 18 | 7 | 13 | 26 | 1970 | -6 | 1976 |

Table A44. Long-term meteorological data for December for College Station, Texas.

| Date | Sunrise | Sunset | Temperature | | | | Date of Record | Record Low | Date of Record |
|------|---------|--------|-------------|----------|------|-------------|----------------|------------|----------------|
| | | | Avg. High | Avg. Low | Mean | Record High | | | |
| Dec. | A.M. | P.M. | | | °C | | Year | °C | Year |
| 1 | 7:05 | 17:24 | 18 | 7 | 13 | 27 | 1954 | -4 | 1979 |
| 2 | 7:06 | 17:24 | 18 | 7 | 13 | 28 | 1995 | -16 | 1971 |
| 3 | 7:07 | 17:24 | 18 | 7 | 12 | 30 | 1995 | -2 | 1974 |
| 4 | 7:07 | 17:24 | 18 | 6 | 12 | 28 | 1954 | -2 | 1989 |
| 5 | 7:08 | 17:24 | 18 | 6 | 12 | 29 | 1995 | -3 | 1990 |
| 6 | 7:09 | 17:24 | 17 | 6 | 12 | 28 | 1951 | -3 | 1999 |
| 7 | 7:10 | 17:24 | 17 | 6 | 12 | 28 | 1933 | -3 | 1984 |
| 8 | 7:10 | 17:24 | 17 | 6 | 12 | 28 | 1994 | -4 | 1990 |
| 9 | 7:11 | 17:25 | 17 | 6 | 12 | 26 | 1985 | -4 | 1978 |
| 10 | 7:12 | 17:25 | 17 | 6 | 12 | 27 | 1983 | -7 | 1978 |
| 11 | 7:13 | 17:25 | 17 | 6 | 11 | 28 | 1987 | -5 | 1957 |
| 12 | 7:13 | 17:25 | 17 | 5 | 11 | 27 | 1956 | -7 | 1957 |
| 13 | 7:14 | 17:26 | 16 | 5 | 11 | 27 | 1995 | -7 | 1989 |
| 14 | 7:15 | 17:26 | 16 | 5 | 11 | 27 | 1995 | -7 | 1985 |
| 15 | 7:15 | 17:26 | 16 | 4 | 11 | 26 | 1995 | -7 | 1989 |
| 16 | 7:16 | 17:27 | 16 | 4 | 11 | 26 | 1957 | -11 | 1989 |
| 17 | 7:16 | 17:27 | 16 | 4 | 11 | 26 | 1990 | -6 | 1972 |
| 18 | 7:17 | 17:27 | 16 | 4 | 10 | 26 | 1980 | -4 | 1979 |
| 19 | 7:18 | 17:28 | 16 | 4 | 10 | 26 | 1957 | -4 | 1975 |
| 20 | 7:18 | 17:28 | 15 | 4 | 10 | 27 | 1951 | -4 | 1973 |
| 21 | 7:19 | 17:29 | 15 | 4 | 10 | 26 | 1970 | -6 | 1973 |
| 22 | 7:19 | 17:29 | 15 | 4 | 9 | 27 | 1981 | -13 | 1989 |
| 23 | 7:20 | 17:30 | 15 | 3 | 9 | 27 | 1955 | -17 | 1989 |
| 24 | 7:20 | 17:30 | 14 | 3 | 9 | 28 | 1955 | -12 | 1989 |
| 25 | 7:21 | 17:31 | 14 | 3 | 9 | 29 | 1955 | -12 | 1983 |
| 26 | 7:21 | 17:31 | 14 | 3 | 9 | 27 | 1988 | -11 | 1983 |
| 27 | 7:21 | 17:32 | 14 | 3 | 9 | 26 | 1971 | -3 | 1983 |
| 28 | 7:22 | 17:33 | 14 | 3 | 9 | 27 | 1984 | -3 | 1983 |
| 29 | 7:22 | 17:33 | 14 | 3 | 8 | 27 | 1984 | -8 | 1983 |
| 30 | 7:22 | 17:34 | 14 | 2 | 8 | 27 | 1951 | -11 | 1983 |
| 31 | 7:23 | 17:35 | 14 | 2 | 8 | 28 | 1951 | -7 | 1976 |

Table A45. Localization of sites for the 2002 and 2003 field experiments. The coordinates for the four point of each site were established using a GPS Trimble Pathfinder Pro XRS with satellite differential corrections (DGPS). The accuracy is about 1m.

| 2002 Field Experiment | |
|--|------------------|
| TAMU [†] Experiment Station Farm | |
| 30° 33' 09.421 N [‡] | 96° 25' 23.575 W |
| 30° 33' 08.872 N | 96° 25' 25.649 W |
| 30° 33' 06.725 N | 96° 25' 24.961 W |
| 30° 33' 07.353 N | 96° 25' 23.021 W |
| TAMU Experiment Station Farm with Dekalb 687 | |
| 30° 32' 07.147 N | 96° 25' 13.523 W |
| 30° 32' 08.952 N | 96° 25' 11.518 W |
| 30° 32' 09.922 N | 96° 25' 13.025 W |
| 30° 32' 09.881 N | 96° 25' 13.013 W |
| Field Experiment at Farmer's Field | |
| 30° 32' 24.404 N | 96° 28' 49.625 W |
| 30° 32' 25.830 N | 96° 28' 51.214 W |
| 30° 32' 24.615 N | 96° 28' 52.615 W |
| 30° 32' 23.198 N | 96° 28' 51.048 W |
| 2003 Field Experiment | |
| TAMU Experiment Station Farm | |
| 30° 32' 56.693 N | 96° 25' 55.887 W |
| 30° 32' 55.361 N | 96° 25' 57.486 W |
| 30° 32' 54.426 N | 96° 25' 56.461 W |
| 30° 32' 55.881 N | 96° 25' 54.857 W |

[†] Texas A&M University.

[‡] Data are in grade, minutes and seconds, latitude north (N) and longitude west (W).

VITA

I, Catalino Jorge López Collado was born in Veracruz, Veracruz, México on April 30 in 1964. Parents are Galdina Collado García and Francisco López Sánchez, from Chazumba and San Miguel Tulancingo Oaxaca, State, respectively. I have three brothers and four sisters. I grew up in Veracruz until the age of 16, when I decided to study at Universidad Autónoma Chapingo, in Chapingo, State of Mexico. I received my Bachelor of Science as an Agronomist Engineer Specialist in Soil Science in 1988; the title of my thesis was “Amendment of a saline-sodic soil from the Texcoco ex-lake using gypsum, calcium chloride and hen manure”. After that I worked in Campus Tabasco, a regional center of Colegio de Postgraduados in Cardenas, Tabasco, Mexico, as a researcher in soil fertility and plant nutrition. I worked there for 2 years, and then I studied in Colegio de Postgraduados in Montecillo, State of Mexico, where I received a Master of Science degree in Edaphology in May 1993. The title of my thesis was “Free amino acids to evaluate the nutritional status in apple trees cv. Rayada”. I returned as a researcher to Campus Veracruz, in Veracruz State.

My decision to come to Texas A&M University was because this is one of the best universities in agriculture in the United States and its soil science faculty are recognized around the world; the most important reason why I came here was to work with Dr. Lloyd Richard Hossner and Dr. Frank Michael Hons. I am proud that they were my advisors. Less important reasons were the climate and the closeness to my country and home state.

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