GROWTH AND PRODUCTION OF MAIZE: MECHANIZED CULTIVATION

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Summary

Maize (*Zea mays*), called corn in some regions of the world, is a grass of tropical origin that has become the major grain crop in the world in terms of total production, with recent production around 800 million tons per year. Most maize grain produced is used as animal feed; in less developed countries it is, however, also a staple food.

Maize originated under warm, seasonally dry conditions of Mesoamerica, and was by human selection converted from a low-yielding progenitor species into its modern form, with a large rachis (cob) of the female inflorescence bearing up to 1,000 seeds. Maize is a C4 plant and is very efficient in water use. If subjected to water stress, however, especially during the mid-season pollination process, yields can be much decreased. Crop management needs to be attuned to this moisture sensitivity, and planting date, cultivar and husbandry should be designed to minimize the chance of water shortage in the mid-season period.

As a grain crop with high yield potential, maize needs an adequate nutrient supply, while the effects of weeds, insects, and diseases, especially during the reproductive period, should be minimized. Tillage is often performed before planting, but maize yields can be as high without tillage as they are with tillage; minimum or no tillage helps to conserve water while maintaining good yields. Planting rates need to be matched to the capability of the soil, and may range from less than 20,000 to more than 100,000 plants per hectare, depending on available soil water and nutrients.

1. Introduction

Maize (*Zea mays* L) is the most important and most widely distributed cereal in the world after wheat and rice. It is used for three main purposes: as a staple food crop for human consumption, a feed for livestock, and as raw material for many industrial uses, including bio-fuel production. The name maize is derived from the Arawak-Carib word *mahiz*. It is also known as *Indian corn*, and in North America simply as *corn* (Purse-glove, 1976).

Maize is the major crop in the United States, occupying double the area of any other crop in the country. The production in the USA covers more than 40% of the world production, and most of this is used as livestock feed, as is the case in most temperate areas. In sub-humid and semi-arid regions in Africa and Latin America maize is consumed green (boiled and roasted), boiled (dry) with beans and ground into flour, cooked and eaten as thick porridge. In these countries it is a staple crop, and a major complement of the diet based on the traditional root crops like cassava, sweet potatoes and yams. In South-East Asia the importance of maize as a food crop is overruled by rice; it is only in the areas with a relatively important dry season that maize is part of the rotation as a potential dry season crop.

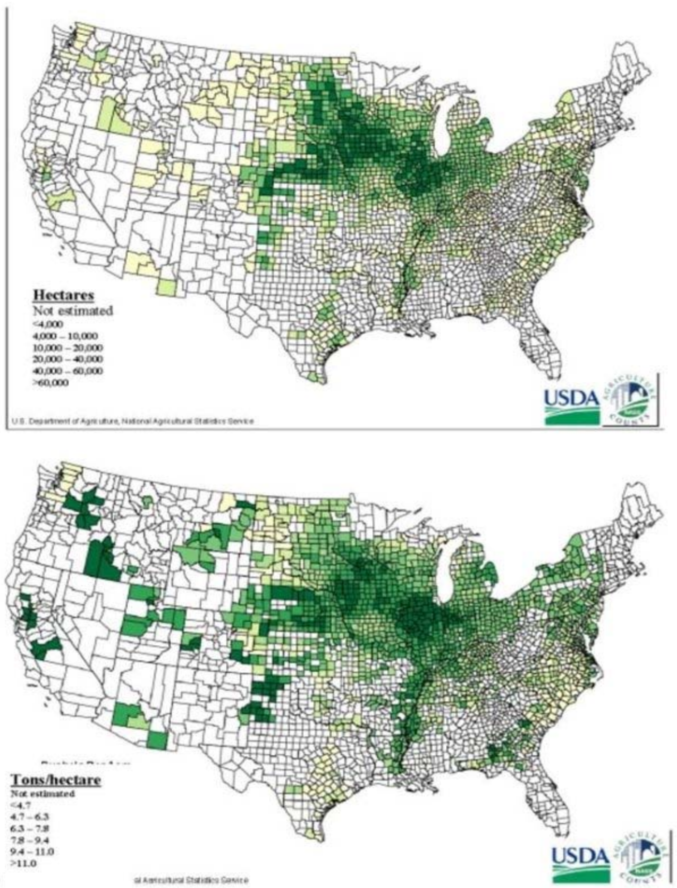

Figure 1. Distribution of maize area and yield in the Unites States in 2008
(Source: US Department of Agriculture, National Agriculture Statistics Service).

Most of the maize production in the USA is concentrated in the US Corn Belt, the largest area in the world where soils and climate are well suited to large-scale maize production due to high amounts of sunlight available, low disease development, and excellent soils. Nearly half of the cultivated area in the central part of the Corn Belt is covered by maize, and average yields in some counties exceed 11 t/ha in favorable years, with peak productions of 20 t/ha (Figure 1). This area can be considered as the type area for modern maize production, fully mechanized, using selected seeds of high-yielding hybrids, and applying modern production technologies.

This chapter deals mainly with large-scale highly mechanized maize production, with a primary goal on livestock feed. A companion paper will focus on the more traditional grain production for human consumption under traditional management, as currently applied in developing countries **(**see also: *Growth and Production of Maize under Traditional Management*).

2. Origin and Distribution

Maize was the staple food for a number of civilizations in the Americas over several millennia preceding the arrival of Europeans in the late 15th century. In pre-Columbian times it was grown from Chile to Northern Canada and from sea level to 3300m altitude. The early American civilizations were based on maize which made settled life possible. It was the basis of life for the Aztec and Maya peoples, whose life evolved around the "milpa" (cornfield).

From its origin some 7,000 years ago in the subtropics of Central America - probably in the region of the present-day border between Guatemala and Mexico - maize has spread across the globe, with production in nearly every temperate region of the world, and to a lesser extent in tropical and subtropical areas.

The major production areas in the world, in terms of cultivated area and yields, are the temperate regions of the western hemisphere and China; Brazil and several countries in Europe as well are important producers as well (Table 1). Overall, maize production in the world is dominated by relatively few countries, with the top five (US, China, Brazil, Mexico and Argentina) accounting for nearly 75% of the world production.

The highest yields are obtained in industrialized countries where the production is highly mechanized and based on well-developed crop cultivars, seed selection and adequate inputs, along with favorable climates (including irrigation) and soils: France and the United States (both 9.5 t/ha), Canada (8.5 t/ha), Argentina (7.5 t/ha).

Country	**Area**	**Yield**	**Production**
	(million ha)	(t/ha)	(million tons)
United States of America	35.0	9.5	331.2
China	29.5	5.2	151.9
Brazil	13.8	3.8	52.1
Mexico	7.3	3.2	23.5
Argentina	2.8	7.7	21.8

India	7.8	2.4	19.0
France	1.5	9.5	14.5
Indonesia	3.6	3.7	13.3
Canada	1.4	8.5	11.6
Italy	1.1	9.1	9.9
Hungary	1.3	6.7	8.4
Ukraine	1.9	3.9	7.4
Rest of World	51.0	2.5	127.2
World	**158.0**	**5.0**	**791.8**

Table 1. Maize production and yield in major maize-producing countries in the world in 2007 (Source: http://faostat.fao.org).

The major reason maize has spread so widely is its ability to produce high yields of grain under a wide variety of climatic conditions. While it lacks the compositional characteristics that make wheat and rice highly palatable to humans, maize has higher yields under good production conditions than either of these other food grain crops. Grain yields vary between 2.5 and 9 t/ha; yields in excess of 20 t/ha have locally been recorded, representing an excellent conversion of photosynthesis-linked solar radiation into utilizable biochemical energy that is among the highest of all crops.

Maize production in the European community has increased tremendously in the past 20 years, especially as a fodder crop, typically cut and chopped into fine pieces before maturity and ensiled for safe storage. This is mainly due to the introduction of short-duration cultivars which allow production of the crop at higher latitudes. The crop is also closely linked to the rapid developed of the pork meat industry and the ecological requirements to threat the enormous amounts of stable manure thereby produced. As maize has high nutrient requirements, it serves as a crop that can absorb nutrients from large quantities of animal manure applied to the field, while at the same time providing feed for animals.

3. Taxonomy

The genus *Zea*, formerly considered as monotypic with the cultigen *Zea mays* as the only species, belongs to the tribe *Maydeae*. This tribe consists of annual or perennial herbs, often with tall culms; spikelets unisexual, dissimilar, awnless; sexes in different efflorescences or in different parts of the same inflorescence, with the male flowers above the female. There are eight genera, of which five are from the Old World, from India through southeastern Asia to Australia. Two other genera, *Euchlaena* and *Tripsacum*, occur in the American tropics. Both are closely related to maize and have contributed to its ancestry (Purseglove, 1976).

Euchlaema mexicana, or teosinte, is an annual grass which grows as a weed in Mexico and Guatemala. It crosses readily with maize, and the hybrids are fertile with normal meiosis; it is considered a hybrid between maize and *Tripsacum*. It is believed that before human settlement the two species were isolated by altitudinal adaptation, maize being a plant of the higher altitudes. With domestication, maize was introduced to the lower altitudes within the natural habitats of teosinte.

Teosinte resembles maize in habit, but produces a number of basal tillers. The staminate spikelets, which occur in pairs, one sessile and the other pedicelled, are borne in a terminal tassel, which is shorter than that of maize. The grains are enclosed in an indurate husk produced by the glumes.

Tripsacum dactyloides, or gama grass, is a tufted perennial grass in tropical and subtropical North America, used as fodder. The inflorescence of *T. dactyloides* is a simplified husk-less spike, usually with two to three equivalent branches, carrying both staminate and pistillate spikelets.

4. Botany

Maize (*Zea mays*) is a thick-stemmed annual grass, usually with a single stem, one to four meters tall, with one or more tillers. It is monoecious and diclinous, with male and female inflorescences born separately on the same plant.

Maize has a high photosynthesis efficiency which is made possible by the specialized anatomical and biochemical features that enable a so-called "C4" photosynthesis. This trait is shared by only a few other crops, including sorghum and sugarcane (see also: *Growth and Production of Sorghum and Millets*)**.** Legumes and most other grass crops have what is known as C3 photosynthesis, which renders them less responsive to high light and temperature and, hence, lower-yielding. A C4 photosynthesis also confers high water use efficiency: maize can produce one kg of dry weight using only about 40 kg of water, compared to water use ratios of 60 kg or more in most C3 crops.

Maize is among the most human-modified crops on earth. Its assumed progenitor is teosinte (see above), a wild relative with a very small rachis that breaks at maturity to release 10 to 12 seeds enclosed in capsules. Selection produced a maize plant that can grow up to 5 m high, with a rachis on a single branch that contains as many as 800 - 1,000 kernels covered by modified leaves (husks) that protect the kernels from desiccation. Truly, maize would not exist in anything like its present form had it not been selected and improved upon for millennia by humans.

Human intervention in the development of maize as a crop is aided by the fact that maize is a *monoecious* crop, with separate male (the tassel) and female (the ear) flower structures borne on the same plant. Most unusually, the male and female flowers are separated by a distance of one or more meters, and pollen must travel this distance in order to effect pollination. Pollen are dispersed by wind, making maize highly cross-pollinated. At the same time, it is relatively easy to capture pollen from the tassel and to prevent pollination by covering the extended pistils before they emerge. This aids in controlling pollination and enables the making of planned crosses between or within plants.

5. Maize Improvement

Beginning in the early part of the twentieth century, geneticists initiated the process of improving maize through breeding. There are few crops in which genetic improvement has been as successful as it has been in the case of maize. One reason this has been so successful in maize is the large amount of hybrid vigor exhibited by this crop. Thus, most cultivars in commercial use today are from hybrid (F1) seed, involving two or more inbred lines. Seed yields of inbred parents are typically less than half the yields of the hybrid that results, but the increased yield of the hybrid makes this economically justified.

While hybrid maize has been widely adopted, crossing and selection of resulting off-spring can result in high-yielding cultivars that are not hybrids. These include open pol-linated varieties (OPVs) of various types, depending on the level of genetic diversity. While the best-yielding non-hybrid cultivars are not as productive as hybrids, they do offer the advantage of "breeding true," allowing producers to keep seed to grow the crop in subsequent seasons with little loss in yield potential. In contrast, producing hybrid maize requires that seeds be produced anew from inbred parents each year. Seed har-vested from a hybrid (F2 seed) can be planted to produce a crop, but the plants will show a great amount of variability, and the yield will be less.

Much of the success of maize in the North America, Europe and Australia is a result of the steady upward trend in yields, which have increased at a rate of about 120 kg/ha/year over the past three decades (Figure 2.) This increase is attributed to genetic improvement through maize breeding, combining thus better performing hybrids and improved crop management practices. Similar trends can be seen in other maize-producing areas of the world, though problems related to weather and pests might often mask the genetic gains.

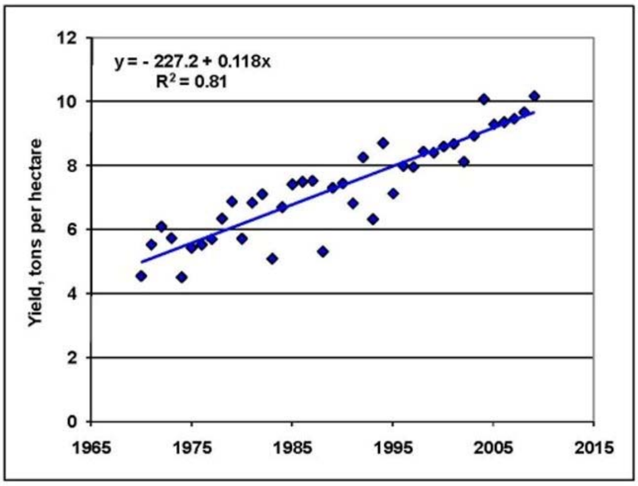

Figure 2. Maize yield trends in the United States between 1970 and 2009 (Source: http://www.nass.usda.gov)

6. Ecology and Growth Requirements

6.1. Temperature and Sunlight

Maize is a crop of subtropical origin and, though it has been altered by selection for adaptation in different environments, it always responds to higher temperatures. The threshold temperature for seed germination is about 10° C. The crop is relatively sensitive to cool temperatures, and it does not acclimatize to low temperatures as do most cool-season crops. Temperatures of 5° to 7° C may be followed by photo-inhibited physiological damage that may reduce photosynthetic rates for several days thereafter.

As a C4 plant, maize responds well to both high temperatures and intense sunlight. Well-watered maize plants reach maximum leaf photosynthesis rates at midday temperatures of 32° to 35° C. Photosynthetic rates of sun-adapted maize do not saturate until light intensity approaches full sunlight. Because photosynthetic capture of sunlight energy is the primary driving force for maize growth and yield, excessive cloudiness and short days tend to lower maize yields.

6.2. Precipitation and Water Requirements

Though maize is water-efficient, the objective to obtain high yields requires a considerable amount of water. Seasonal water use is about 500 to 600 mm in temperate areas, and up to 900 mm or more (depending upon evaporative demand) under irrigation in dry climates. Under rain fed conditions, which is the most common production system, plant water is supplied by seasonal rainfall and stored soil water. Hence, deep soils and those with high organic matter content which store much more plant-available water, are considered the most suitable for maize production.

Water uptake gradually increases from the germination into the vegetative growth stage. It reaches a peak by the time the crop canopy is complete, and more in particular from just before until just after the pollination period. Water shortages during this period may prevent successful flowering and fertilization, and thereby greatly reduce grain yield. Nearly all of the below-trend yields in the USA shown in Figure 2 were the result of such intermittent or extended dry periods.

High productivity means high demands for water. Measured water use efficiency (WUE) for maize is as high as 2.5 kg grain per m^3 of water used. At full canopy, water use rates may be 6 to 8 mm per day. The seasonal water use by a 10-ton maize crop is typically about 500mm. If good maize yields are to be anticipated this minimum amount of water should be assured.

6.3. Weather Stress in Maize Cultivation

Maize frequently suffers from weather-related problems during the growing season, the effects of which differ with the severity and duration of the stress, and the stage of crop development. Some stress conditions and their impact on crop growth and yield are discussed below.

Flooding **-** The major stress caused by flooding is the lack of oxygen needed for the proper function of the root system and the lower stem. Young plants are killed after about 5 or 6 days of being submerged. Death occurs more quickly in hot weather because high temperatures speed up biochemical processes that use oxygen, and warm water has less dissolved oxygen. Cool weather, by contrast, may allow plants to live for more than a week under flooded conditions.

Older plants at the six- to eight-leaf stage, can tolerate a week or more of standing water. Total submergence may, however, increase disease incidence and plants may suffer from reduced root growth, even for some days after the water recedes. Tolerance to flooding increases with age, but reduced root function from lack of oxygen is more detrimental to yield before and during pollination than during rapid vegetative growth or during grain fill. Submergence can also coat leaves with soil and reduce photosynthetic activity.

***Hail* -** The most common damage from hail is loss of leaf area, though stalk breakage and bruising of stalks and ears can be severe as well. Loss charts based on leaf removal studies confirm that defoliation at the time of tasseling causes the greatest yield damage, while loss of leaf area during the first month after planting or when the crop is near maturity generally causes little yield loss. Loss of leaf area in small plants usually delays development, and plants that experience hail damage may not always grow normally afterward.

***Cold injury* -** Maize is not very tolerant to cold weather. Although death of leaves from frost is the most obvious type of cold injury, other tissues can also be damaged or killed. Loss of leaves from frost is generally not serious when it happens to small plants, but it may delay plant development and postpone pollination.

Frost injury symptoms may appear on leaves even when night-time temperatures do not fall below zero degree. Radiative heat loss can lower leaf temperatures to several degrees below air temperatures on a clear, calm night. If frost kills leaves before physiological maturity in the fall, sugars usually continue to move from the stalk into the ear for some time, yields are generally lower, and harvest moisture may be high due to high grain moisture at the time of frost and slow drying rates that usually follow premature death.

***Drought* -** Maize is fairly tolerant of dry soils and moisture stress from early vegetative stages until about two weeks before pollination. Mild drought during mid-vegetative stages may even be beneficial because roots generally grow downward more strongly as surface soils are drying up. The crop also benefits from the greater amount of sunlight that accompanies dry weather.

During two weeks before, during, and two weeks following pollination, maize is very sensitive to drought, and dry soils during this period can cause serious yield losses. Most of these losses are due to failure of pollination, and the most common cause is the failure of silks to emerge. When this happens, silks do not receive pollen, and, thus, the kernels are not fertilized and do not develop. Developing kernels can also abort for several weeks after pollination. Drought later in grain-fill has a less serious effect on yield, though root function may decrease and kernels may not fill completely.

While effects of a prolonged period of drought can never be eliminated in rain fed maize production, there are some techniques that help to reduce the effect of drought on yield. Heavy soils can be drained and tilled to depth in order to improve rooting depth.

Reducing tillage, especially on lighter soils, helps to conserve water and make it more available to the crop. Depending on climatic patterns, adjusting planting date can help move the pollination period into a time period of better water supply. Using lower plant densities, and in some cases wider rows, likewise provide more water to individual plants and thereby avoid complete loss of the crop in dry areas. Finally, some modern maize cultivars tolerate or avoid water stress more effectively than others. Efforts are currently underway to identify and incorporate into commercial cultivars genes for drought resistance.

Heat **-** Because drought and heat usually occur together, many people assume that high temperatures are a serious problem for maize. In fact, temperatures up to 40° C usually cause little or no injury if soil moisture is adequate. Extended periods of hot, dry winds can cause tassel "blasting" (desiccation) and loss of pollen viability. Pollen shed usually takes place in the cooler hours of the morning, and is often finished before the high afternoon temperatures. There is evidence that hybrids vary in their sensitivity to both heat and drought, though genetic drought tolerance may mean some loss in yield potential. As a result, such hybrids may not be good choices for regions that usually have good growing conditions.

6.4. Soils

Maize thrives well in most soils, as far as they are deep (more than 1 meter) and fertile, and have a good water holding capacity. Maize grows best on sandy clay (loams), loamy and silty clay soils; it is less adapted to compact clays and sands. The major soil factor is soil water storage, and this is determined by texture and structure. Available soil moisture is a major element of success in rain-fed maize production, particularly where the rains are not uniformly distributed over the season. In this case the plant has to rely on the moisture stored in the root zone to overcome the temporary water deficit.

Sandy soils have a low moisture holding capacity; loamy and clayey soils have a high one. Sands hold less than 5% water (50mm of water over a depth of 1 meter), while loess or clay loam soils have available water up to 20% of their volume, or 200 mm of water in one meter of soil depth. The ability of the soil to hold few weeks of water in case of dry periods during the season is a most important determinant of the potential of such soil to produce maize.

In soils where this moisture retention capacity does not exist, i.e. in sandy and/or shallow soils, or when the intermediate dry spell extends beyond the time that the plant can survive on stored moisture the crop will either suffer or must be irrigated; the latter system is often part of the production system in high-tech maize production systems in the western USA, Australia and other low-rainfall areas.

Maize has a relatively deep root system, reaching as much as 2 m deep in some cases, and these roots need space to develop. For normal root development, the maize crop requires a minimum soil depth of 80-100 cm. Any soil shallower than this critical depth will give smaller yields, especially where irrigation is not practiced and where water tends to limit yields.

Maize is a relatively exacting crop in terms of plant nutrients. It requires a large quantity of nitrogen (N), which is generally applied as a top dressing when the crop is 25-30 cm high. The nutrients removed by a yield of 4 t grain/ha are estimated at 200kg N/ha, 80 kg P_2O_5/ha and 160kg K_2O/ha. In supplying the necessary nutrients for the crop, at least the same amount of these elements should be incorporated in the soil. The exact amounts of fertilizers to be added to the soil should be determined on the basis of soil analysis. Adequacy of supplies of nutrients can be assured by addition of nutrients in organic (animal or green manures) or inorganic (chemical fertilizers) forms.

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Biographical Sketch

Dr. E. Nafziger was born and raised on a livestock-grain farm in Ohio, USA. He earns degrees in agronomy from the Ohio State University, Purdue University, and the University of Illinois. Since 1982 he is Professor of Crop Production in the Crop Sciences Department at the University of Illinois, Urbana. He carries out a comprehensive research program in the management of grain crops, primarily maize and wheat, including work on crop rotations, nitrogen nutrition, tillage, and planting geometry. He develops and implements outreach/extension programs in the state and region on crop management.

Dr. Emerson serves on the Board of Directors of the Crop Science Society of America (CSSA), and is a Fellow of the American Society of Agronomy (ASA). He has won numerous awards, and holds the Ainsworth Professorship in the Crop Sciences Department at the University of Illinois. He has extensive international experience in crop research and extension, mostly in South Asia, having lived in Bangladesh for several years, and with more recent work in Pakistan and India. He has also traveled and worked in Ukraine, China, several countries in Europe, and Brazil.