3.4 Herbaceous crops

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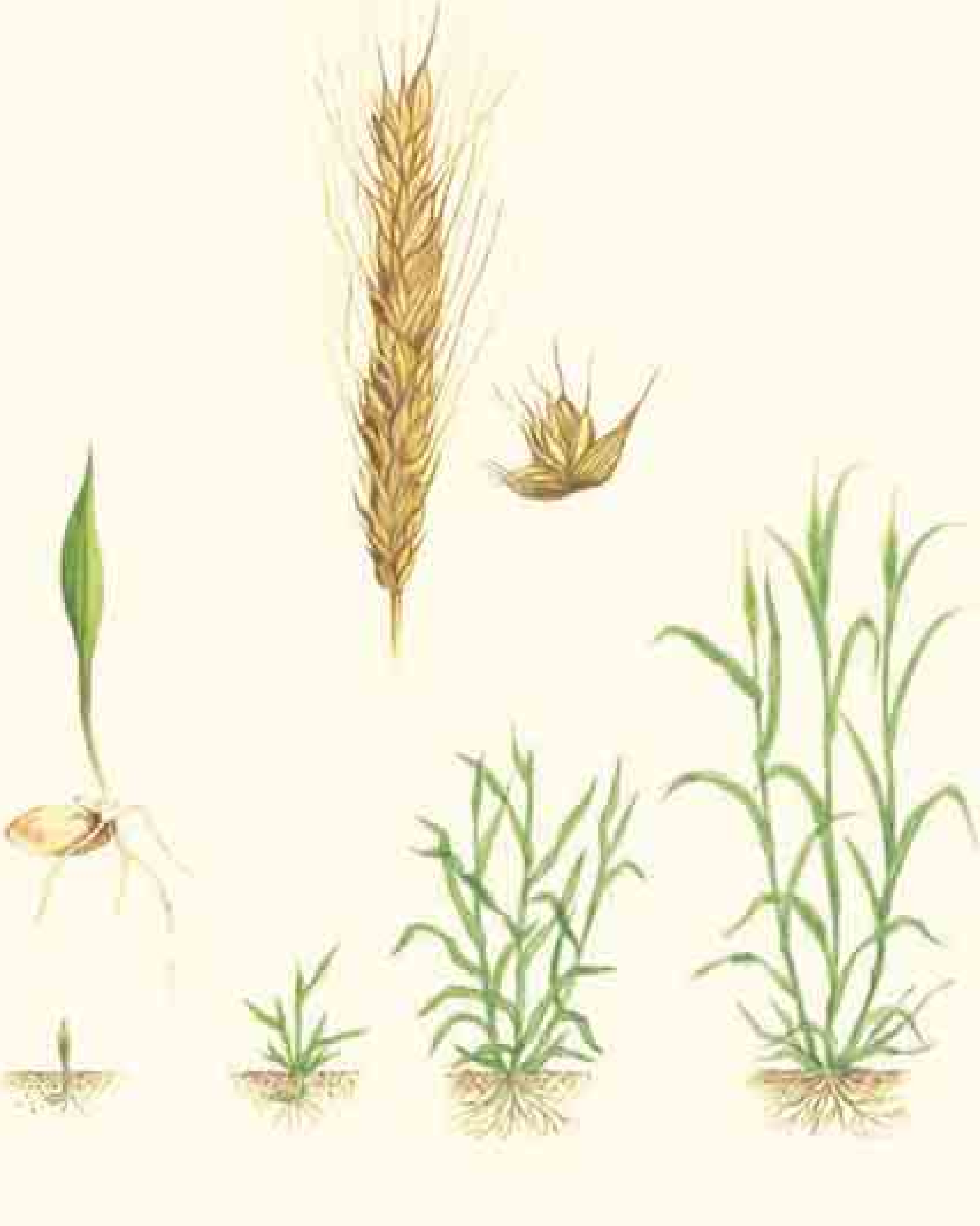

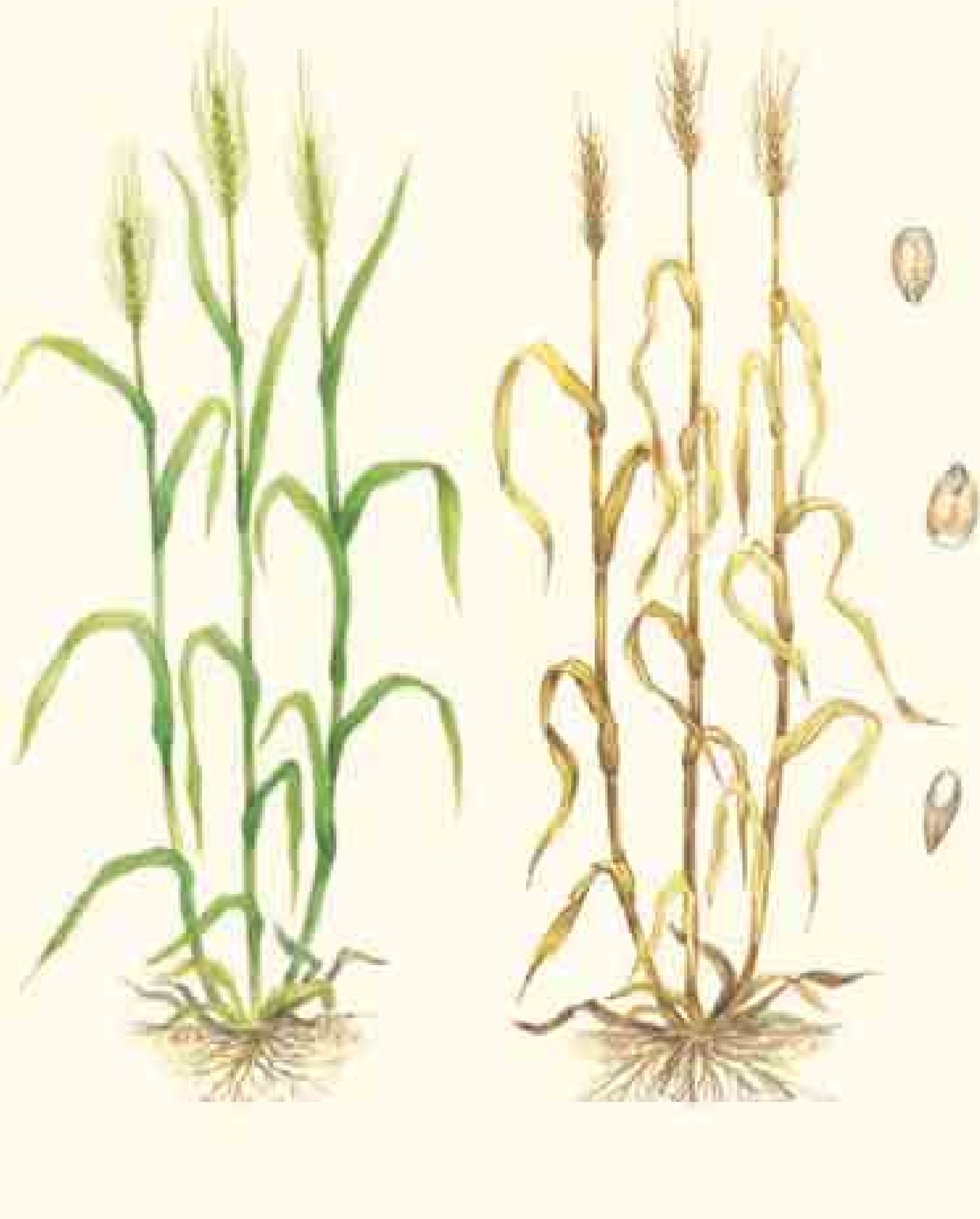

Wheat

Wheat

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GENERAL DESCRIPTION

Bread and durum wheat (*Triticum aestivum* and *Triticum turgidum durum*, respectively) comprise the third largest crop in the world. In 2009, 226 million ha were sown to wheat, producing 685 million tonne of grain at an average grain yield of 3 tonne/ha (FAO, 2011). Over the last 50 years, the average yield per hectare has increased dramatically, particularly between the 1950s and 1980s. Since the area cropped has remained relatively constant, global production has reflected the increase in yield (Figure 1).

Wheat is a cool season crop originating in the Fertile Crescent but now widely spread around the world. It is grown in arctic and humid regions as well as the tropical highlands and from sea level on the Dutch Polders to 4 500 m altitude in Tibet. The growing conditions are very diverse, not only because of the widespread climatic regions and altitudes, but also because of variability of soil types and crop management. Currently, the countries with the largest wheat production are China, India, the Russian Federation, the United States, France, Canada, Germany, Pakistan, Australia and Ukraine in that order. These countries totally cover more than two-thirds of the global wheat production (Figure 2).

In many annual cropping areas, wheat is grown in rotation with a variety of other winter annuals such as other cereals, oilseed crops, and pulses, although wheat following wheat often occurs. In other cases it is sown as a second crop after summer cereals or cotton. Two systems of particular importance are the rice-wheat and maize-wheat systems.

GROWTH AND DEVELOPMENT

Winter wheat is sown in autumn, while spring wheat is sown in autumn or spring. Winter wheat requires a cold period or chilling (vernalization) during early growth for normal heading under long days. Wheat is usually sown at a depth of around 5 cm, although greater depths may be used under dry conditions, to attempt to place the seed into moist soil. While this can be successful, it delays emergence and growth and in extreme situations may reduce stand density. Sowing is usually into moist soil but in some dry environments 'dry sowing' may be practised shortly before the expected start of the rainy season. Plant densities range from 50 to over 500 plant/m^2

with the lower densities being used in drier environments. Row spacing ranges typically from 0.15 to 0.25 m, depending on the production system. Sowing is by broadcasting in some cases. In many developing countries the use of reduced tillage and stubble retention systems is increasing but in developed countries multiple pre-sowing cultivations are more common. Stubble retention and the degree of cultivation influence the rates of infiltration, evaporation, and runoff. The impact of soil type and management, particularly cultivation and irrigation, on soil compaction has a profound effect on the depth of root exploration, and hence access to soil water, and the frequency of anaerobic conditions resulting from waterlogging.

The length of the total growing period (life cycle) of spring wheat (sown in spring) ranges from 100 to 170 days while winter wheat needs about 180 to 300 days to mature. In some exceptional cases, season lengths of more than 300 days have been recorded. Day length and temperature requirements are key factors in cultivar selection. Cultivars can be grouped as winter or spring types according to chilling requirements, winter hardiness and day length sensitivity. Some winter wheat cultivars in early stages of development exhibit a strong resistance to cold temperature, surviving down to -20 °C. The resistance is lost in the active growth period in spring, and during the head development and flowering period frost may lead to loss of spikelets, and in extreme circumstances, loss of the whole head.

In areas with severe winters, cold winds and little snow, spring wheat cultivars are planted after winter. Spring wheat is also sown in the autumn to over-winter in regions with winter dominant rainfall and mild winter temperatures such as some arid and Mediterranean regions, as well as in the cool season of high lands in the tropics. Spring wheat requires little or no chilling to initiate head development. Winter wheat and some spring wheat cultivars are also photoperiod sensitive, which delays the end of the tillering phase to long sunshine days.

Crop development or phenology is dependent on temperature (Porter and Gawith, 1999). For crop growth, minimum mean daily temperature for measurable growth is about 5°C for winter and spring wheat. Mean daily temperature for optimum growth is between 15 and 23 °C. In *AquaCrop*, the growing degree day (GDD) for wheat is calculated with a base temperature of 0°C and an upper temperature of 26 °C. This means crop development speeds up as the mean daily temperature increases from 0 °C to 26 °C, and further increase above 26 °C does not enhance growth and development. Maximum canopy is often reached before heading at booting stage while flowering of individual heads can last between one and 10 days. Grain filling usually occurs into the warming part of the year when average maximum temperatures are between 20-30 °C. Prolonged periods below 5 °C can cause dormancy in winter wheat. Vernalization requirements and photoperiod sensitivity vary substantially between cultivars and alter the duration of the tillering phase. Table 1 shows the duration from sowing to

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FIGURE 1 World wheat harvested area and average yield over the period 1961-2009 (FAO, 2011).

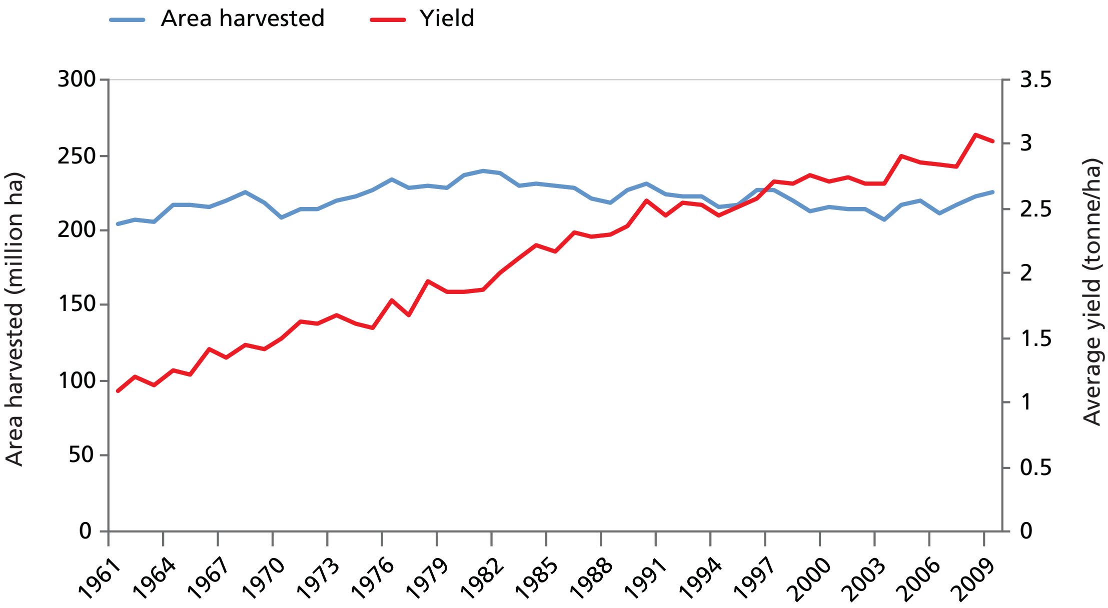

FIGURE 2 Wheat harvested area (GAEZ, 2011).

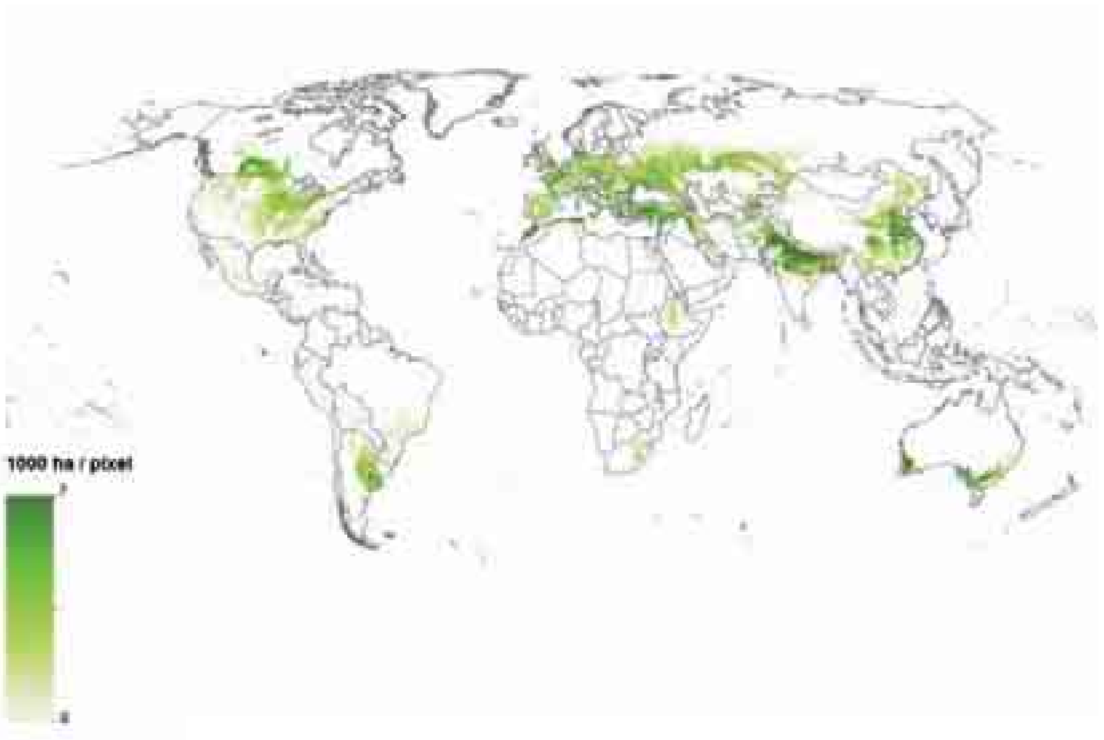

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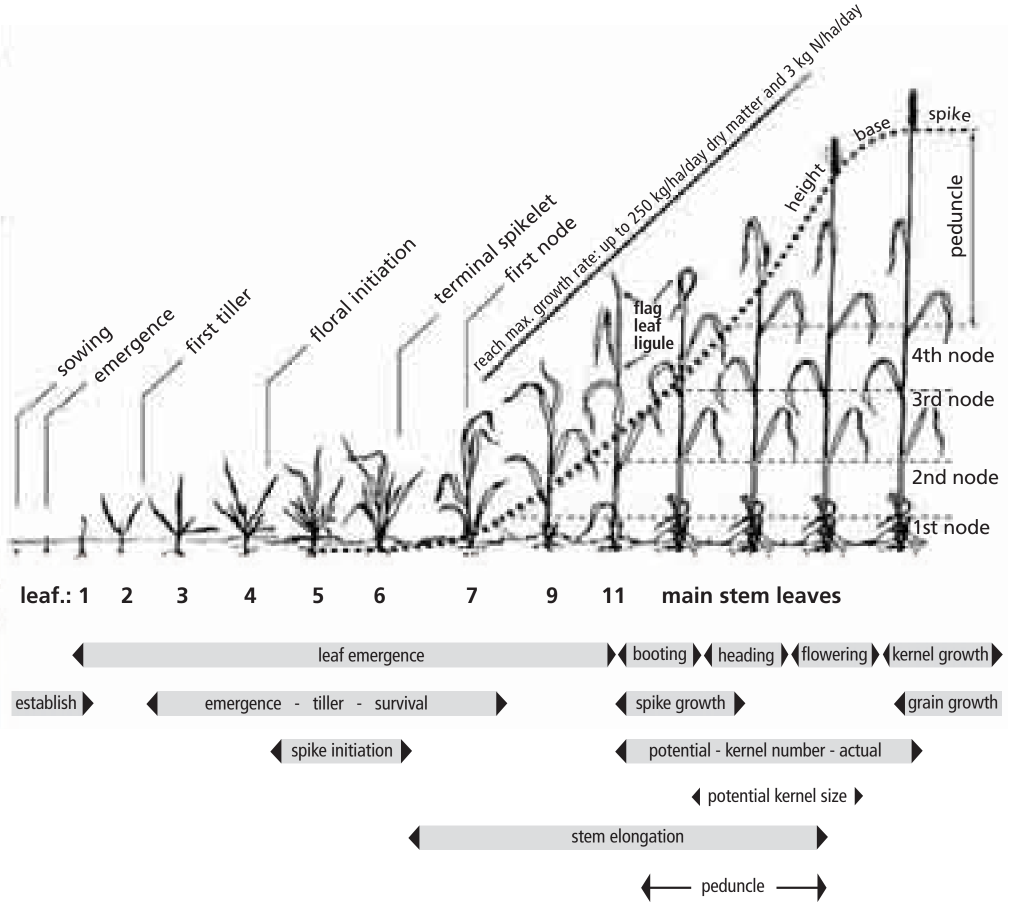
TABLE 1 Duration of the main phenological phases of wheat in days from sowing (S) for various wheat producing areas.

Wheat areas	S-Emergence	S-Heading	S-Anthesis	S-Maturity	Cultivar type
Central and Northern Europe	12-48		54-250	71-280	spring, winter
Italy	12-19	62-166	67-170	100-213	spring
China		67-	-217	83-251	spring, winter
India	4-	ca. 77	70-103	85-145	spring
Russia		39-		76-305	spring, winter
North Africa and West Asia	6-16	116-138		158-178	spring
USA		55-210		113-310	spring, winter
Canada	5-15	50-250		90-300	spring, winter
South America	6-12		70-135	112-186	spring
Australia	7-17	35-90	60-170	90-215	spring, winter

FIGURE 3 Typical developmental stages of wheat.



various developmental phases for wheat in different wheat growing regions. Figure 3 shows typical development of a wheat plant.

Wheat can be grown on a very wide range of soils from deep sands and shallow soils to loams to heavy clays. Maximum rooting depth can vary from 0.30 m in duplex soils of Western Australia with impermeable B horizons or other soils with high or low pH, high salinity or toxicities such as boron in the subsoil, through to 2.80 m on deep sands with root deepening rates of 0.7 to 2.0 cm/day.

WATER USE & PRODUCTIVITY

Total cumulative evapotranspiration (ET) of wheat crops typically ranges from 200 to 500 mm, although it can be less in non-irrigated semi-arid areas and reach 600-800 mm under heavy irrigation. The slope of the plot of grain yield vs. ET can be taken as the water productivity in terms of yield and consumptive use ($WP_{Y/ET}$). If the x-intercept of this relationship is taken as a measure of cumulative soil evaporation, then the slope can be interpreted as the water productivity in terms of transpiration ($WP_{Y/Tr}$). On this basis, $WP_{Y/Tr}$ is typically reported to be around 1.0-1.2 kg/m^3 (10-12 kg/ha per mm) for grain production (French and Schultz, 1984). An international analysis has indicated the maximum achievable efficiency (for grain) in current wheat systems is likely to be around 2.2 kg/m^3 (Sadras and Angus, 2006).

The proportion of water used as transpiration varies widely. When crops are grown on stored soil moisture with little in-season rainfall, soil evaporation can fall to as little as 20 percent of ET. With frequent, small, in-season rainfall events, soil evaporation can increase to as high as 75 percent, in cases of very sparse crop cover. Soil type, stubble cover, weather and early crop vigour also influence the proportion of soil evaporation.

Cultivars vary little in terms of dry matter production per unit ET. Cultivar variation in yield is typically related more to differences in total water use, mostly through changes in crop duration, or to changes in harvest index.

Early in the growing season, daily water usage can be very low (< 2 mm/day) because of cool temperatures and, in Mediterranean conditions, high humidity. Transpiration as a proportion of total ET is also low because of the small canopy size. For winter wheat in temperate environments, this situation can continue for some months. As the canopy enlarges during tillering and stem elongation, the rate of water usage increases and typically peaks around anthesis at rates between 5 and 8 mm/day. The ratio of actual to reference ET peaks at around 1.0 to 1.2 during the period from stem elongation to anthesis and declines during grain filling and maturation. As the canopy senesces markedly towards maturity, the ratio falls rapidly.

RESPONSE TO WATER STRESS

As for all cereals, wheat yield can be considered as the product of three components: the number of ears per unit area, the number of grains per ear, and the size of the grains. Both the number of ears and the number of grains are the product of the number produced and the proportion surviving. To a large extent, the components are developed sequentially and the timing of moisture stress dictates which of the components are affected. The potential number of tillers, and hence ears per unit area, is determined earliest followed by the number of grains per ear and finally grain size. So, broadly speaking, early stress limits tiller number and stress after anthesis reduces the size of the individual grains and the grain number through abortion of the developing grains (Passioura and Angus, 2010).

Studies to determine the developmental stage at which yield is most sensitive to water stress have produced inconsistent results. However, in most situations, yield is correlated to grains per m^2. Hence, the number of grains per unit area and thus tillers per unit is generally the most important determinant of yield. Consistent with this, the periods during which wheat yield is usually considered to be most responsive to moisture stress are (a) the period when tillers are developing and their abortion rates are highest; (b) when florets are being formed and grains are set; and (c) from early to mid-grain filling when young developing grains can be aborted due to a lack of assimilate (Turner, 1997).

In broad terms, apart from the seedling stage, sensitivity to water stress generally appears to decline with development. However, it is important to maintain a degree of balance throughout growth, particularly in terms of pre- and post-anthesis water use (Fischer, 1979). If all the water is used before anthesis, when limited rainfall is expected later in growth, severe terminal drought can result in a serious impact on grain filling with reduced yield, grain number, grain size and grain quality; with a consequent reduction in harvest index (HI) (Passioura, 1977). Further, the plants can acclimate to water stress to some degree. So, low levels of stress during the pre-anthesis phase appear to reduce the impact of stress around anthesis and shortly after.

Excess water can cause waterlogging during vegetative growth and can reduce yield substantially. Reduced levels of soil oxygen for as little as three days can damage roots, reduce nutrient uptake and reduce tiller numbers. The capacity to recover depends on the timing of the waterlogging event and the subsequent growth conditions. Serious damage to roots can limit the depth of soil explored and can therefore reduce the access to mineral nutrition and soil water. This exacerbates the impact of any subsequent water limitation.

SOIL FERTILITY

Soil fertility levels can only be determined in relation to yield potential and also depend on soil type. As a rough guide, for each tonne of yield per hectare, wheat needs to take up about 25-40 kg/ha N, 3-5 kg/ha P and 15-30 kg/ha K. The uptake of N not only influences yield but also grain protein percentage which affects the suitability of the grain for different end uses. To meet a specific uptake demand for a targeted yield, 150-200 percent of the required crop N uptake has to be available for the crop from the combined amount of soil mineralization and fertilizer application. Note that soil N content is highly dynamic and N can easily be lost through nitrate leaching particularly on sandy soils with low water-holding capacity. Soil N content can therefore change several fold during a growing season. P and K are less dynamic, but uptake efficiency is often less than for N. Therefore, similar amounts of plant-available P and K (150-200 percent of uptake requirements) might be required to achieve potential yield for specific growing conditions.

When nutrition is limiting, yield potential and canopy expansion are constrained, reducing the total water requirement of the crop. Excessively high nutrient levels, particularly N, result in luxuriant vegetative growth and high water consumption but usually without a commensurate increase in grain yield. A possible cause is reduced HI since an excessive number of tillers are formed and many of them either do not have time to form heads or die off as a result of heavy shading by older tillers.

TEMPERATURE

Temperature requirements of wheat, especially with respect to cold temperature, have already been discussed under Growth and Development. Temperatures above 34 °C are possible in most wheat-growing regions during grain filling. Such temperatures accelerate senescence and can cause significant reduction in grain yield through reduced grain size and increase the proportions of shrivelled and undersized grain. Cultivars are available that can tolerate high temperatures to some degree, to minimize heat stress damage.

SALINITY

Wheat is considered moderately tolerant to soil salinity. The reduction in shoot growth with increasing sodium concentration in a sand or solution culture is approximately linear with a concentration of 100 mM (about 10 dS/m) reducing shoot growth by around 45 percent in bread wheat and about 50 percent in durum. By comparison, the reduction in barley is around 40 percent and in rice about 75 percent. Wheat cultivars with higher salt tolerance are becoming available.

IRRIGATION PRACTICE

While much wheat is grown solely under rainfall and stored soil water, the importance of fully or partially irrigated production is very high in some countries. Irrigation practices for wheat production are diverse. In arid areas, or when grown in the dry season of monsoonal regions, wheat may be grown under full irrigation. In Mediterranean and semi-arid systems, supplemental irrigation may be used to alleviate intermittent drought or to reduce the impact of increasing water deficits as spring progresses (Oweis, *et al.*, 1999).

On a global scale the most common method of application is flood irrigation in bordered basins. Furrow application and overhead application by a variety of sprinkler methods are also used. Irrigation is frequently applied to wheat with little knowledge of its moisture requirements or the available soil moisture at the time of application. Because wheat is so widely grown, a variety of scheduling systems and tools have been developed including methods based on water budgets, in-field soil moisture measurement and canopy temperature. However the extent of their use in commercial production is very limited, particularly in less economically developed countries. Where rainfall is low and irrigation water supply is limited, the preceding crop and the interval between the crops, in combination with the rainfall pattern and soil water characteristics, dictate whether there is a need for irrigation at or before seeding to establish a crop stand. Subsequently, generally speaking, irrigation should be managed to avoid or minimize water deficits during the three periods already mentioned: (a) tillering to stem elongation, (b) time of flowering, and (c) early to mid-grain filling. After the development of a reasonable canopy, subsequent irrigations may be scheduled such that up to 50-60 percent of total available soil water (TAW) is depleted between applications without a notable negative impact on yield (Geerts and Raes, 2009).

Over irrigation is common in wheat, even under supplemental irrigation: two or three irrigations are sometimes applied in a short interval with little consideration of soil water status or crop demand. Excessive water supply results in lower water productivity in terms of yield per unit of water applied. In extreme situations, excessive water (from rainfall or irrigation) results in waterlogging which, as mentioned earlier, can substantially depress growth and yield. Over-generous water supply during the vegetative period, particularly in combination with high fertility, produces luxuriant vegetation and may result in lodging after head formation. Lodging may also occur if an excessive amount of water is applied in a single irrigation late in development, particularly with sprinkler irrigation.

YIELD

Wheat grain yields (at 11 percent moisture) can vary from crop failures in seasons with less than 100 to 150 mm available water, to 1-3 tonne/ha in water limited rainfed conditions (Mediterranean, arid, dry-season subtropical environments) and 4-10 tonne/ha in rainfed temperate (western and northern Europe) climates or irrigated systems (China). Exceptionally, grain yields can reach a maximum of 15 tonne/ha in cool, long season (life cycle of over 300 days) environments with high solar radiation input such as southern New Zealand, Southern Chile, Ireland, England and some regions of China. In 2009, average country yields ranged from less than 0.5 tonne/ha in Honduras, Lesotho, Somalia, Venezuela and Eritrea to more than 9 tonne/ha in Belgium.

A major factor contributing to the improvement in yield over the last century is the increases of HI brought about by breeding for shorter statue. Under favourable conditions with no stress, HI ranges between 0.45 and 0.55 for modern wheat cultivars (Austin, 1999). However, when there is water stress after flowering or when the cultivar is poorly matched to the production environment, HI can fall to as low as 0.20 to 0.30.

The balance of water supply before and after flowering can have a substantial effect on grain quality. Water stress during grain filling leads to shrivelled grain with a low milling percentage (flour produced per grain input). On the other hand, high water supply late in the season leads to increased yield with low protein concentration. These changes alter the suitability of the grain for various end uses.

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Rice

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Rice

GENERAL DESCRIPTION

Cultivated rice is represented by two main species: (i) *Oryza sativa*, grown worldwide, with its two ecogeographic races *indica*, adapted to the tropics, and *japonica*, adapted to temperate regions and tropical uplands; and (ii) *Oryza glaberrima*, grown in parts of West Africa. In the mid-nineties, a new rice called NERICA (New Rice for Africa) was developed from crosses between *O. glaberrima* and *O. sativa* species specifically targeted at the upland and dryland areas of sub-Sahara Africa (Jones *et al.* 1997). Two main rice growing environments are distinguished: lowland (or paddy) rice, where fields have saturated soils with ponded water during crop growth, and upland rice, where fields have well-drained, nonsaturated soils without ponded water. Rice is grown throughout the year in the tropics, and in the summer in the subtropics and temperate regions.

Rice represents the food of 3 billion people worldwide. The global annual production of rough (unmilled) rice is about 650-700 million tonne, of which 90 percent is produced and consumed in Asia (Figure 1). Main cropping countries are China, India, Indonesia, Bangladesh, Viet Nam, Myanmar, Thailand and Philippines (FAO, 2011). Worldwide, there are about 158 million ha of lowland rice (including double cropping), of which 101 million ha are harvested for irrigated rice and provide 75 percent of the world's rice production, while the remaining 57 million ha of rainfed lowland rice contribute 19 percent to the world's rice production. Some 11 million ha of lowland rice area is prone to uncontrolled flooding. These include deepwater areas, low-lying coastal areas subject to daily tidal submergence, and areas affected by flash floods of 1-2 weeks, where the problem is often excess water but not necessarily prolonged submergence. About 14 million ha of upland rice are usually not equipped with irrigation facilities, and contribute 6 percent to the world's rice production. (Figure 2).

In most tropical irrigated areas, rice is grown as a monoculture with two crops per year, while three crops per year occur in places like the Mekong Delta in Vietnam. In Pakistan, India, Nepal, Bangladesh, and central China, rice is often grown under irrigation over the summer, in rotation with a range of other crops in winter, including 15-20 million ha of rice-wheat systems. In China, some 19 of the 30 million ha rice are planted to modern hybrid rice cultivars, which usually outyield the best parent. Rainfed lowland rice is mainly grown in the monsoon season, with large areas in Eastern India, northeast Thailand, Laos, and Cambodia. Upland rice was

FIGURE 1 World rice harvested area and average yield over the period 1961-2009 (FAO, 2011).

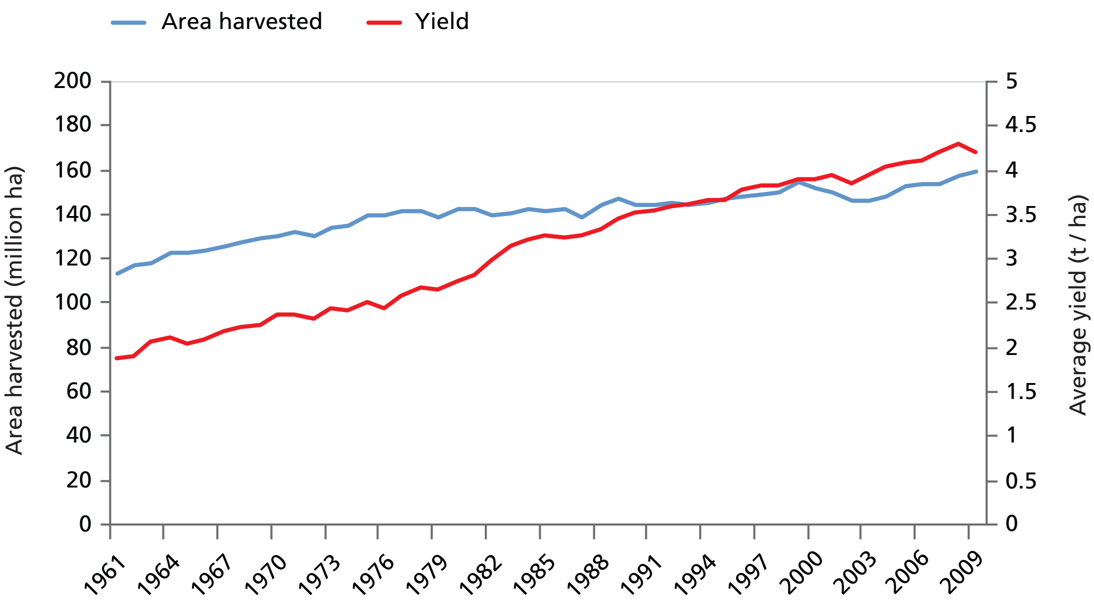
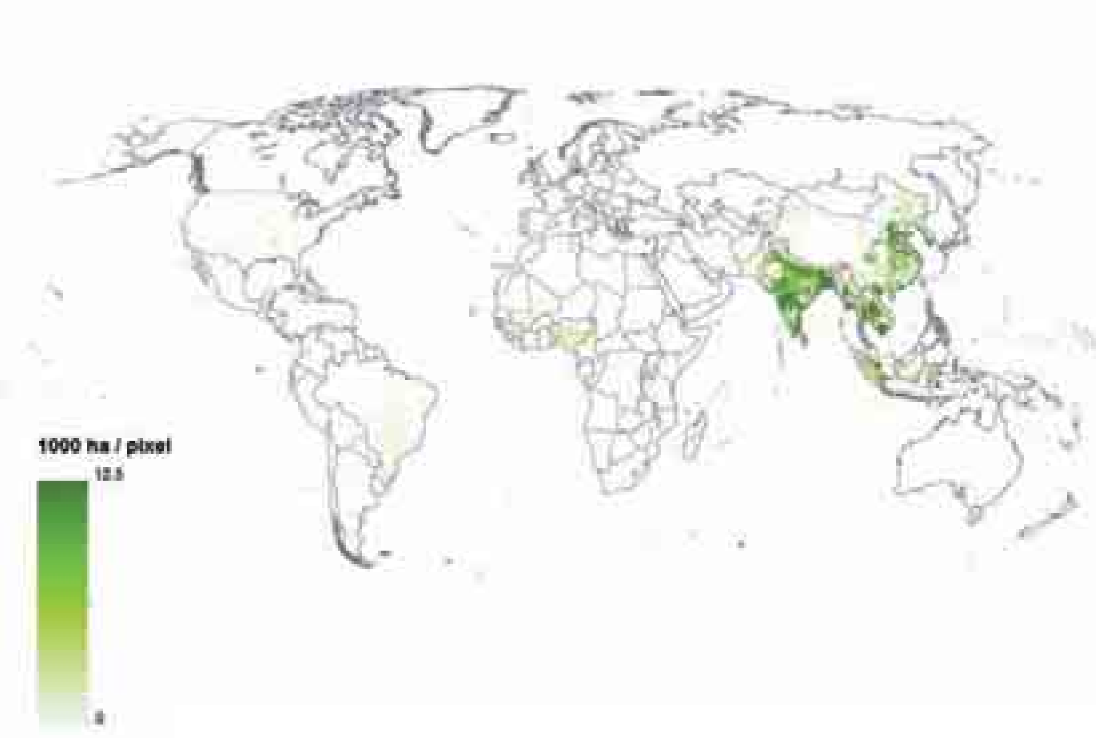


FIGURE 2 Rice harvested area (GAEZ, 2011).



Reference year 2000

historically grown under shifting cultivation with long fallow periods (more than 15 years). At the turn of the twentieth century, most of Asia's upland rice areas have made the transition to permanent systems where rice is grown every year, while 14 percent of the Asian upland rice area still practises shifting cultivation with shorter fallow periods (3-5 years). In Central and West Africa, the rice belt of Africa, upland areas represent about 40 percent of the area under rice cultivation but involve about 70 percent of the region's rice farmers.

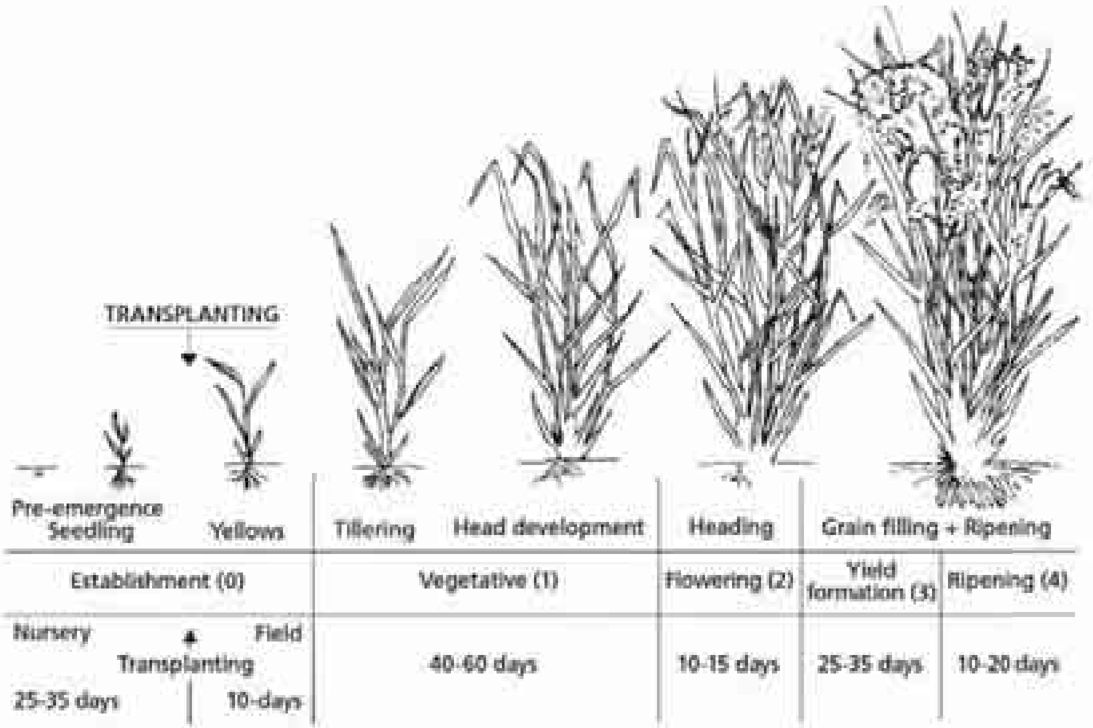
GROWTH AND DEVELOPMENT

Lowland rice is usually grown in 'puddled' fields. Puddling consists of harrowing or rototilling under shallow submerged conditions, and is done to control weeds, to reduce soil permeability, and to ease transplanting. After puddling, land is levelled under wet conditions. A typical vertical cross-section through a puddled rice field shows a layer of 0-0.10 m ponded water, a puddled, muddy topsoil of 0.10-0.20 m, a plow pan that is formed by decades or centuries of puddling, and an undisturbed subsoil. Rice roots are usually contained within the puddled layer and are quite shallow.

The dominant method of crop establishment in most rice areas is by transplanting. Rice is first raised in a separate seedbed. Seeds are pre-germinated and are broadcast into either a flooded or wet soil surface in the nursery at a rate of 500 to 800 kg/ha. At transplanting (12-25 days after establishment for modern cultivars, whereas it takes 40 days or more for traditional cultivars), the plant densities are equivalent to seeding rates of 40-50 kg/ha. Two to three seedlings are normally hand transplanted in hills 0.15 to 0.30 m apart. Hybrid rice is usually transplanted as one seedling per hill, while some local cultivars are planted with 5-6 seedlings per hill. Each plant develops three to seven tillers, dependent on nutrient status, cultivar, and seedling density. In a good crop stand, the number of grain-bearing panicles will reach 400-600/ m^2 in the dry season, and 300-400/m^2 in the wet season (for common *indica* cultivars in the tropics).

Rice can also be established directly in the field by wet or dry seeding (broadcasting pre-germinated seeds onto wet or flooded soil or sowing dry seeds in dry or moist soil). Seeds are broadcast or sown in rows of 20-30 cm spacing, at the rate of 80 to 250 kg/ha (Rice Knowledge Bank, IRRI). In recent years the trend in Asia is toward more direct seeding. In commercial production fields of the United States and Spain, seeds are commonly broadcast from airplanes. The duration of the growing cycle (from germination to maturity) of rice depends on cultivar and location, ranging from 90 days for short-duration modern tropical cultivars, to 180 days for traditional or modern cultivars in subtropical and temperate environments. Cultivar differences in growth duration are determined by changes in the time from germination to beginning flowering (60 to 150 days), while the time from beginning flowering to maturity is pretty constant and lasts about 30 days in the tropics but can go up to 65 days in cool, temperate regions The growth and development of rice is temperature dependent (Kropff *et al.*, 1994), stopping at average temperatures below the base temperature, which is tentatively set at 8 °C for rice in *AquaCrop*. Most tropical cultivars die when, in the early vegetative growth phase, the average daytime temperature drops below 12 °C for more than three consecutive days. Generally, damage to the pollen occurs when the temperature at flowering is outside the range of 8 to 35 °C. Though many traditional rice cultivars are photoperiod sensitive (shortening day lengths induce flowering), most modern high-yielding ones are not. (See Figure 3 for typical development).

FIGURE 3 Typical developmental stages of rice.



WATER USE & PRODUCTIVITY

Because of the flooded nature of lowland rice, its water use and water productivity are different from those of upland rice and other cereals. Irrigated rice receives 34-43 percent of the total world's irrigation water, or about 24-30 percent of the entire world's developed fresh water resources (Bouman *et al.*, 2006). Water is used for land preparation and to match the outflows from the field by seepage, percolation, evaporation and transpiration. The amount of water used for wet land preparation can be as low as 100-150 mm but can approach 1000 mm in large-scale irrigation systems. Typical percolation rates vary from 1-5 mm/day in heavy clay soils to 25-30 mm/day in sandy and sandy loam soils (Bouman *et al.*, 2007). In midseason when there is complete canopy cover of the ground, rice evapotranspires at a rate slightly higher than the reference evapotranspiration (ET_o). Common daily ET rates from rice fields average 4-5 mm/day in a tropical wet season and 6-7 mm/day in a tropical dry season, but on some days can reach as high as 10-11 mm/day in subtropical regions before the onset of the monsoon, and in semiarid regions. Seasonal ET vary from 400 to 700 mm in the tropics and from 800 to 1 100 mm in temperate regions. The total estimated ET of world rice fields (including both lowland and upland rice) is some 860 km^3/year.

Modern rice cultivars, when grown under flooded conditions, have a water productivity with respect to transpiration for grain yield ($WP_{Y/Tr}$), of about 2 kg/m^3 (Bouman *et al.*, 2006). The water productivity with respect to evapotranspiration ($WP_{Y/ET}$) ranges from 0.6 to 1.6 kg/m^3, with a mean of 1.1 kg/m^3 (similar to that of wheat). Water productivity with respect to total water input (irrigation plus rainfall) is around 0.4 kg/m^3 (range from 0.2 to 1.2).

RESPONSE TO STRESSES

Because rice evolved from a semi-aquatic ancestor, it is extremely sensitive to water shortage. The main reason is its shallow root system; in terms of sensitivity of rice organs to low water potential, it is actually not that different from many other crops (Hsiao *et al.,* 1984). Leaf and canopy expansion are reduced soon after the soil dries below saturation in most cultivars; even in upland cultivars, expansion begins to be inhibited when only a small fraction of the total available water (TAW) has been depleted (Lilley and Fukai, 1994; Wopereis *et al.*, 1996). Rice is susceptible to large yield losses at the time of flowering because of reduced water availability. The spikelets scheduled to pollinate on a day when panicle water potential is low (e.g. -1.8 MPa) do not open to shed pollens, causing spikelet sterility and reducing the harvest index (HI). Another stress is combined high temperature and strong wind at flowering time. Spikelets of newly emerged panicles have low epidermal resistance to water vapour apparently related to the slow formation of epicuticular wax. On days of high temperature and wind, such spikelets desiccate and die and turn white (O'Toole *et al.*, 1984), symptom referred to as 'white heads' or 'blasting'. This again reduces HI. A large part of rainfed lowlands are frequently affected by drought, the largest and most frequently and severely affected areas being eastern India (about 20 million ha) and northeastern Thailand and Laos (7 million ha).

Although rice is adapted to waterlogging, complete submergence can be lethal. Most rice varieties can survive complete submergence of only 3-4 days though some rainfed lowland rice varieties can survive up to 14 days (depending on depth, temperature, and turbidity of the water). Recently, a gene has been discovered (sub1) that confers tolerance to submergence in the early vegetative growth stage of up to 14 days, and which has successfully been introduced into a number of popular lowland varieties using marker-assisted breeding techniques. Tall plants tend to lodge when the water level recedes, resulting in additional yield losses and poor grain quality.

Rice is salt-sensitive (Shannon, 1997). Some 9-12 million ha of lowland rice area in South Asia is estimated to be affected by salinity and/or alkalinity (Bouman *et al.*, 2006) either from sea water intrusion in the coastal areas or from water and/or soil salinity inland. The threshold for yield reduction is 3 dS/m of soil electric conductivity (EC_e), with 90 percent yield loss at 10 dS/m EC_e. Rice is relatively salt tolerant during germination, tillering, and toward maturity, but is sensitive during early seedling and at flowering and grain filling.

Fertilizer needs depend on targeted yield, the fertility of the soil, residue management, and the amount of nutrients coming into the rice field by irrigation water and atmospheric deposition. The rice crop needs the following uptake of major nutrients to produce 1 tonne of grain per hectare: 15-20 kg N/ha, 2-3 kg P/ha, and 15-20 kg K/ha (Rice Knowledge Bank, IRRI).

IRRIGATION PRACTICE

Lowland rice

Irrigated lowland rice is mostly grown with supplementary irrigation in the wet season (monsoon), and is entirely reliant on irrigation in the dry season. Fields are bunded with small dykes about 0.20 m high and 0.20-0.30 m wide to keep ponded water in the field (basin). Farmers with access to irrigation aim to maintain 50-100 mm of ponded water ('floodwater') as this assures the crop of optimal water supply and helps control weeds and pests. The soil is usually kept ponded until a week or two before harvest. Total seasonal water input to rice fields (rainfall plus irrigation) depends heavily on percolation rate of the soil, and is up to 2-3 times more than for other cereals. It varies from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2 000 mm in coarse-textured soils with deep groundwater tables. Around 1 300-1 500 mm is a typical value for irrigated rice in Asia (Bouman *et al.*, 2006).

Farmers faced with water scarcity are unable to keep their fields continuously flooded and adopt various water-saving technologies such as alternate wetting and drying (AWD) (Bouman *et al.*, 2007). In AWD, the field is flooded intermittently; hence, the field is alternately flooded and drained. The number of days of drained soil between irrigations can vary from one to more than 10 days. AWD is also the water-management practice used in the system of rice intensification (SRI). SRI is a cultivation system based on the use of young seedlings, wide row spacing, careful transplanting of single seedlings, transplanting in squares, alternate wetting and drying, manual or mechanical weed control, and large amounts of organic fertilizer use (Stoop *et al.*, 2002). Under rainfed conditions, lowland rice fields are intermittently flooded in an uncontrolled manner.

Upland rice

The management of upland rice generally resembles that of other cereals. Land preparation is under dry conditions, no puddling takes place, and the soil is not saturated or flooded during crop growth. Typical traditional upland rice fields may be flat or sloping without provision of irrigation facilities. After dry land preparation, seeds are hand-dibbled. Usually, no fertilizers, herbicides, or pesticides are applied.

An emerging production system is aerobic rice, in which especially developed high-yielding cultivars are grown in flat, well-drained, non-puddled, and non-saturated soils. The aerobic rice systems are practised in Brazil (250 000 ha) and on the North China Plain (80 000 ha) (Bouman *et al.*, 2007). The usual establishment method is dry direct seeding, either broadcast or seeded in rows of 0.20-0.30 m spacing. Irrigation is applied by flood or furrow irrigation (or raised beds), or sprinklers. Unlike irrigated lowland rice, the applied water does not flood the soil, but just brings the soil of the root zone to field capacity.

YIELD

Rice yield is usually expressed as rough rice with 14 percent moisture content. Rough rice includes a hull (about 20 percent by weight) and the whole grain. ‘Brown rice’ is the least processed form of rice in which the outer hull is removed, but the outer bran layers of the grain (11 percent by weight of rough rice) are still there. Milling removes all or part of the bran and germ from the rough rice, and results in ‘white rice’ (69 percent by weight of rough rice) which consists of the germ and starchy endosperm.

Country-average irrigated lowland rice yields in Asia range from 3 to 9 tonne/ha (rough rice), with an overall average of about 5 tonne/ha. Under continuously flooded conditions, short-duration (100-115 days) modern tropical cultivars can yield 8-10 tonne/ha in the dry season and 6-8 tonne/ha in the wet season. Good yields of long duration (120-150 days) cultivars in subtropical and temperate climates are around 12 tonne/ha, while maximum yields of up to 17 tonne/ha have been reported (Yunnan province in China, and in Australia), although such reported record yields are often open to question. Significant yield improvement has recently come only from the development of hybrid rice, which has increased yield potential by 5-15 percent over inbred cultivars in the same environment (Peng *et al.*, 1999). Lowland rice with uncontrolled flooding has average yields of around 1.5 tonne/ha, most likely the result of occasional water deficit, as well as deprivation of oxygen supply when flooded excessively. For good conditions yields of rainfed lowland rice average 4-5 tonne/ha. With frequent abiotic stresses (mainly drought), however, yields are considerably lower, only around 2 tonne/ha. Average upland rice yields are around 1 tonne/ha, while aerobic rice with application of around 90 kg N/ha can reach 4-6 tonne/ha.

HI varies with cultivar, location, season, and growth conditions. HI of modern, short-duration tropical cultivars is about 0.45 to 0.5 (45 to 50 percent) in the dry season and 0.35 to 0.4 in the wet season. The HI of many long-duration cultivars used in rainfed lowlands is about 0.35. HI of modern hybrid rice in China range from 0.4 to 0.5. With drought, HI decreases and can reach close to zero in extreme situations.

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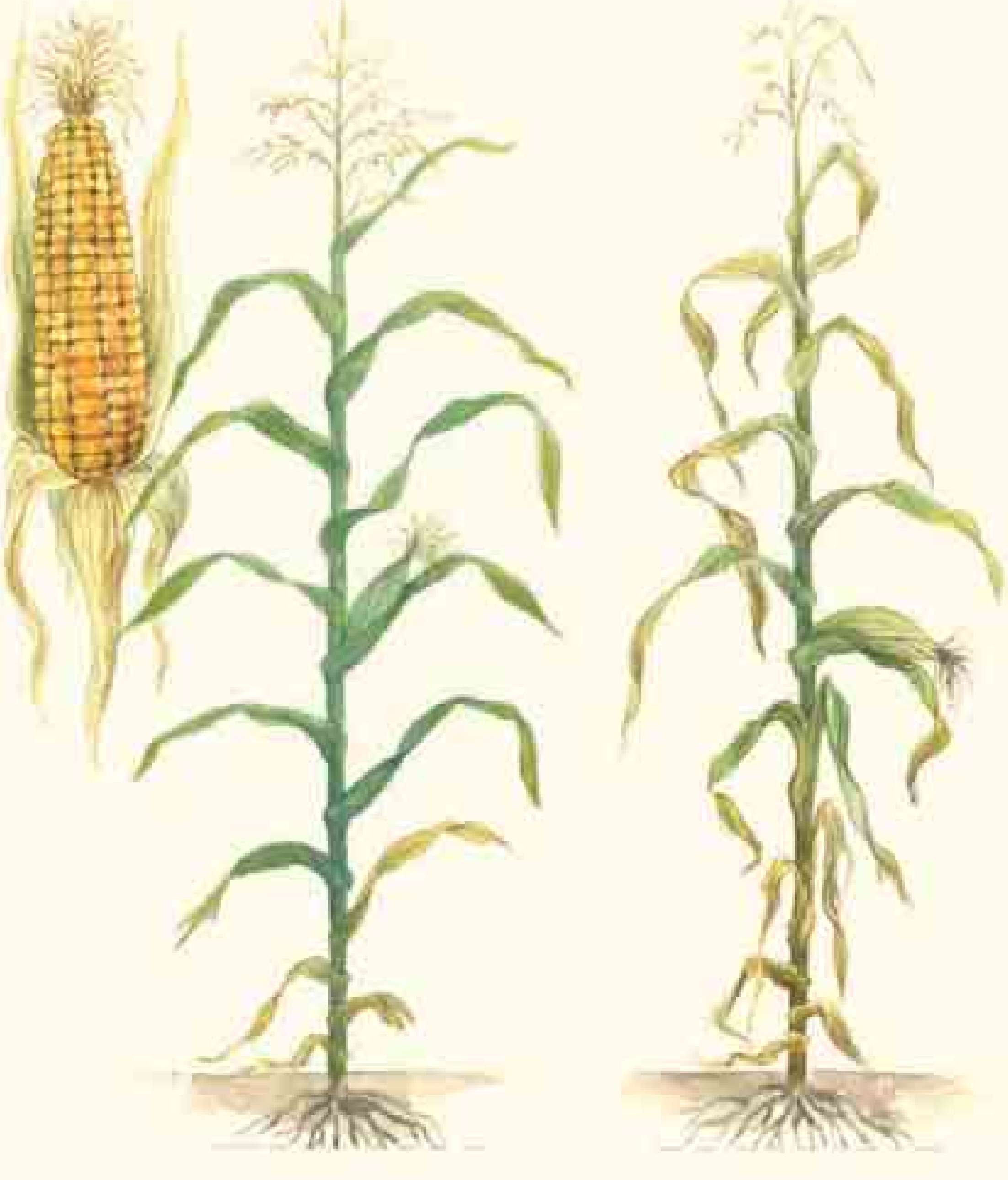

Maize

Maize

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GENERAL DESCRIPTION

Maize (*Zea mays* L.) ranks as the most important crop worldwide in terms of grain production; although wheat and rice are the most important for direct human consumption. Maize seeds are consumed by humans directly or after processing, and are often the main component of animal feed. Vegetable oil, sugar syrup, alcohol as biofuel, and feedstock for the manufacturing of plastic are commonly derived from maize seeds. The area devoted to maize and the yield per hectare have been increasing over time (Figure 1), total production was 819 million tonne in 2009 (FAO, 2011), the last year of available statistics. The grain production of wheat and paddy rice that year were each about 16 percent less than that of maize, with rice planted on about the same of area as maize and wheat planted on 30 percent more than maize. Nearly all the high-yielding maize cultivars are hybrids. The increasing use of hybrids in the 1930s led to a clear acceleration in the yield increase over time. Maize is a C_4 species, which originated in a climate with warm summers. It is grown, however, extensively in temperate regions for grain (Figure 2) as well as for silage. For the latter, the crop is harvested before full maturity, when the grains are in the late phase of filling and the vegetative material still mostly green, is coarsely chopped and partially fermented as animal feed. Even in areas with a growing season too short for grain to mature, maize is popular as a crop for silage and forage. The dominant producer of grain maize is the United States, with about 41 percent of the world's total, followed by other top producing countries China (20 percent), Brazil (6 percent), Mexico, Indonesia and India (2 percent).

The crop originated in Central America, where it is traditionally planted in hills. Nonetheless, most of the world's maize is grown as a row crop and as single crop. In Mexico and some subtropical countries in Africa and America, maize is frequently grown intercropped with beans. In the corn belt of the United States, it is often grown in rotation with soybean. On the northern plain of China, it is commonly grown in rotation with winter wheat. Other crops grown in rotation with maize include other winter cereals, and several forage and grain legumes.

GROWTH AND DEVELOPMENT

Maize germplasm is very diverse (Duncan, 1975), with a wide range of seed size, plant height, tillering habit, number of leaves per stem, number of

FIGURE 1 World maize harvested area and average yield over the period 1961-2009 (FAO, 2011).

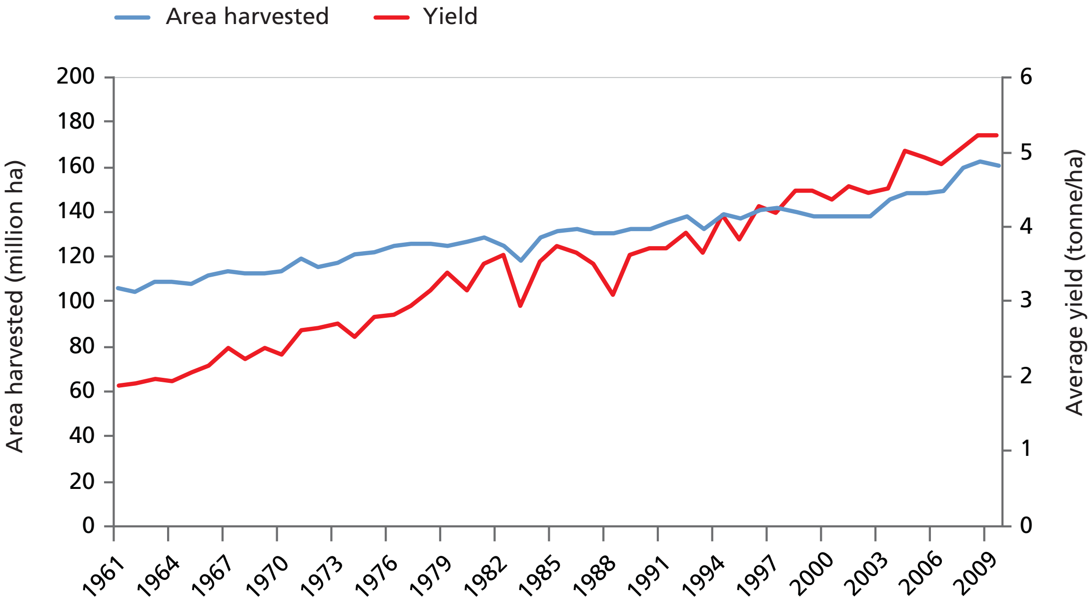
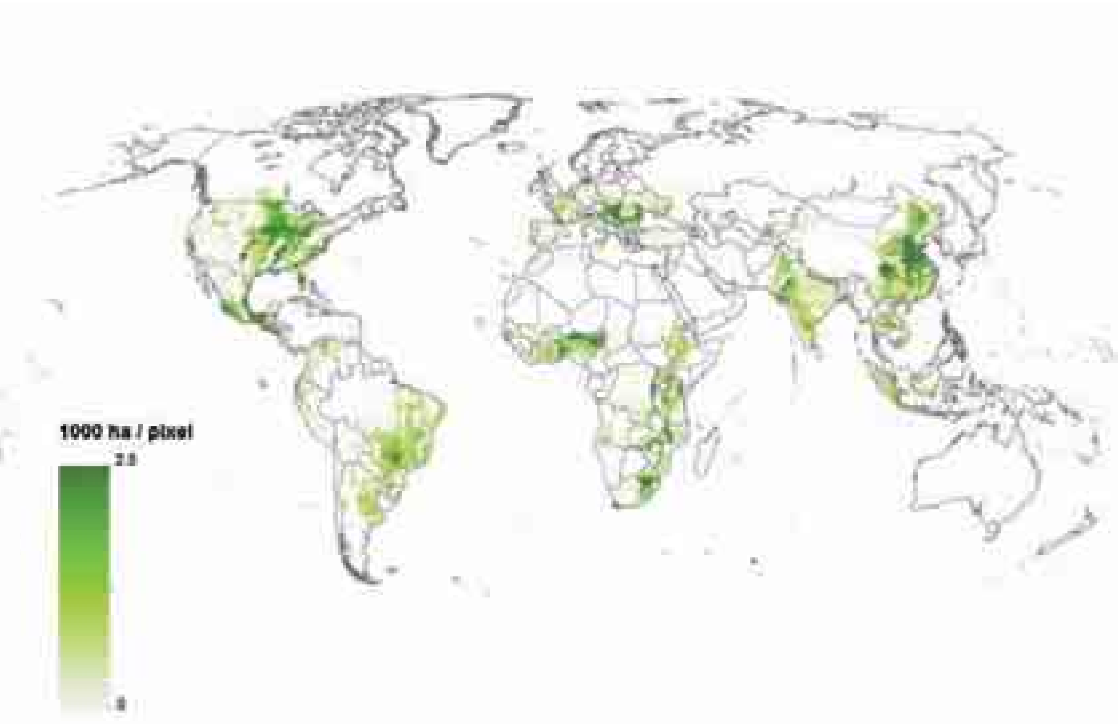


FIGURE 2 Maize harvested area (GAEZ, 2011).



Reference year 2000

ears per plant and ear size. Breeding and selection for high yield, however, have drastically narrowed the ranges, making the crop highly determinant. The description here is confined to modern well-developed cultivars, virtually all hybrids. Some land races and open-pollinated material may not fall within the range of this description.

Maize seed is large (0.2 to 0.3 g per seed) and with this large reserve the seedling is able to develop a relatively large leaf area a few days after emergence. This accounts for the large initial canopy size per seedling (large cc_o). Modern maize cultivars do not tiller when planted at sufficient density for high production, although many do tiller at much reduced density. Only one ear is produced per plant when planted at high density. The exceptions are plants at the edge of the field, which often produce two ears because more radiation is available for photosynthesis, and prolific cultivars, which produce more than one ear (but smaller in size) per plant.

Maize leaves develop and expand according to their sequential position on the nodes of the stem. Cultivars vary in the total number of leaves (number of nodes on the stem) largely according to their life-cycle length, with more nodes and leaves for the longer-season cultivars. The more common number of high-yielding cultivars varies from 18 to 22 leaves (Rhoads and Bennett, 1990). Because fewer leaves usually means a smaller total leaf area per plant, shorter season cultivars need to be planted at a higher density to reach the same maximum canopy cover (CC_x) as a longer-season cultivar. Density of commercial plantings varies from 40 000 to 110 000 plant/ha, and high yields are achieved at densities no less than 70 000 plant/ha. In areas of limited rainfall and no irrigation, or when soil nutrients are limiting, plant density should be reduced to match the available resources. As a C_4 crop, the relative growth rate of leaves is high, leading to a high canopy growth coefficient (CGC). During the early part of canopy development, the typical rate of canopy growth is about 16 percent (of existing canopy cover) per day for optimal conditions. As is the case for most other crops, expansive growth of leaves and hence canopy growth is highly sensitive to water stress.

On good soils, the root deepening rate of maize can average 2.5 cm per day, with effective rooting reaching a depth of 2.8 m or deeper near the time of maturity (Hsiao *et al.*, 1976). The more commonly observed rooting depth, especially in regions with cold winter temperatures, however, is less; in the order of 1.5 to 2 m. Rate of deepening can be markedly restricted by impeding (either physically or chemically) layers in the soil, poor aeration and cold soil temperature. The rate of deepening is important in situations where there is substantial amount of water stored in the deeper layers during periods when there is little or no rainfall and irrigation.

Maize is monoecious, with its male organ (tassel-bearing anthers) located separately from the female organ (ears with stigmas called silks) on the tall (1.6 to 3.4 m) plant. Tassel is located terminally on the stem and emerges from the flag leaf (last leaf on the stem) enclosing it, when the leaf area of the plant has reached near maximum with only the flag leaf and possibly the next leaf below still expanding. The ear is formed at the leaf axil many nodes below (e.g., node number 11) and ahead of the tassel. However, silks emerge from the husk of the ear after tassel emergence, and after the tassel begins to shed pollen. Because tasselling occurs only after all the leaves are grown, the cultivars have a higher number of leaves would flower and pollinate later than those with fewer leaf number, other things being equal. For current cultivars with a 120 to 135 day life cycle under favourable conditions, the time interval from emergence to flowering is about 65 to 70 days; the start of canopy senescence is about 105 days. Short-season cultivars for more northern latitudes flower 10 to 15 days earlier. Maximum canopy cover (CC_x) is achieved at flowering if plant density is 70 000 plant/ha or less; and under good conditions full canopy cover is achieved sooner if the density is substantially higher, because the leaf area per unit land area (leaf area index, LAI) needed to close the canopy is reached earlier, before flowering.

The emergence of all the silks on an ear and their pollination may take 7 or 8 days when temperature and water regimes are favourable. Because of heterogeneity of a field plant population, the overall pollination time for a field may last at least twice as long as that for a single ear.

Kernel weight increases after pollination (Duncan, 1975) follows the classical time course curve for cereal grains. The grain maturation process is associated with declines in kernel water content and full maturity is generally considered to be at the time when a 'black layer' forms at the base of the germ of the kernel (Daynard, 1972). At full maturity and under favourable conditions, the grain of modern cultivars comprises around 50 percent of the above-ground biomass produced by the crop, that is, the harvest index is close to 0.50 (or 50 percent). For unimproved cultivars or land races, the harvest index may be as low as 0.3. The *AquaCrop* simulation recommends that HI be set to increase until the time of full maturity, with the latter taken to be the time when green canopy cover declines to 10 percent of the maximum canopy cover reached. As for many other crops (Evans, 1993), maize grain yield is often correlated with green leaf area duration (Wolfe *et al.,* 1988a). Reduced green leaf area duration may be the result of the leaf growth rate being reduced and/or premature leaf senescence, caused by water stress or the nitrogen or other nutrients deficiency, as discussed below.

IRRIGATION, WATER USE AND PRODUCTIVITY

In the United States corn belt, where rainfall amount and distribution are usually favourable and the soil is deep with a high water-holding capacity, maize is grown without irrigation or only with supplemental irrigation. In the more arid areas of the United States, maize is irrigated. In northern China, where rainfall coincides with the maize-growing season, the crop can be rainfed or grown with supplemental irrigation. The common application methods include furrow and centre pivot irrigation. Seasonal maize water use varies according to evaporative demand of the atmosphere, and hence according to climate, time of season when the crop is grown, life cycle length of the crop, and water availability. For well-watered situations, seasonal ET ranges from less than 500 to more than 800 mm, the typical seasonal ET of a cultivar of medium-season length grown in a temperate climate at latitude of 35° to 40° being around 650 mm.

At midseason, when there is complete canopy cover of the ground and water and mineral nutrients are not limiting, maize transpires at a rate slightly higher than the reference ET (ET_o). Detailed data (Steduto and Hsiao, 1998) show the crop coefficient (K_c) is slightly less than the values used earlier, only in the range of 1.07 to 1.12. This presumably is the result of lower stomatal conductance of maize leaves relative to most broad-leaf crop species. As a C_4 crop, maize water use efficiency is high (de Wit, 1958*;* Steduto *et al.*, 2007), mostly because of the high rate of photosynthesis, with only a minor contribution from the slightly more restricted transpiration rate. Contrary to earlier opinions, maize under favourable conditions responds positively to increases in atmospheric CO_2, as shown by increases in leaf area (Hsiao and Jackson, 1999) and biomass at least up to 520 ppm CO_2. Hence, *AquaCrop* adjustments normalize water productivity (WP*) according to atmospheric CO_2 concentration, year-by-year. For example, maize WP* was adjusted from 32.4 g/m^2 in 1990 to 33.7 g/m^2 in 2000.

RESPONSES TO STRESSES

Water stress develops when rain and irrigation are absent and the water stored in the root zone is depleted to the point where plant processes are affected. In *AquaCrop*, the threshold level that triggers stress responses are set for different key processes. As for virtually all crops, leaf expansive growth of maize is the most sensitive of all the stress responses (Bradford and Hsiao, 1982; Hsiao and Xu, 2000) and its stress response threshold in *AquaCrop* is set not far below soil field capacity. Very mild water stress, lasting for many days can lead to a much smaller canopy cover during the vegetative stage. If stress is sufficiently more severe, stomatal conductance are also reduced, and at a similar stress level senescence of older leaves begins to accelerate. Crop transpiration and photosynthesis would be reduced both as the result of less green canopy cover (because of reduced growth or more senescence) and lower stomatal conductance. This of course leads directly to reduced rate of biomass production, and hence reduced grain yield. An added negative effect is that the acceleration of canopy senescence would reduce the canopy duration and shorten the grain-filling period. There would not be sufficient time for the harvest index to build up and reach its normal maximum. The end result is that the percentage reduction of grain yield would be even more than the percentage reduction of biomass.

As a result of the monoecious nature of maize, fairly severe to severe water stress can cause a peculiar problem of reproduction. In addition to expansive growth of leaves, expansive growth of stems as well as silk and tassel are also inhibited by the stress. The slower silk growth or elongation leads to delayed emergence of silk from the husk. Tassel emergence is also delayed by water stress, but the delay is less than that for silk (T.C. Hsiao, personal observation). This difference in delay can cause pollination failure as, by the time the silk emerges, there may not be sufficient pollen left to fully pollinate the crop. On the other hand, the failure to pollinate the late silks on an ear and the very late ears of a plant population must be substantial to negatively impact yield because in dense plantings the number of grains (kernels) a plant is able to mature is only 65 to 75 percent of its number of silks, and the late emerging silks do not form mature kernels even when pollens are ample (Duncan, 1975; T.C. Hsiao, unpublished). Also, the very late ears are formed by the smallest plants in the population and their contribution to yield is minimal even when pollinated. The time interval between tassel emergence and silk emergence appears to vary with different genetic lines (Bolaños and Edmeades, 1996), but is minimal for lines well-adapted to the local environment. As the severity of water stress increases, however, this interval is lengthened more and more and grain yield can be drastically reduced as a result of pollination failure (Bolaños and Edmeades, 1996). As mentioned, modern maize is highly determinant with a narrow time interval for pollination. This means there is no opportunity to make up for reduced pollination with later flowers when rain or irrigation comes.

Overall, and relative to other crops, maize is considered to be sensitive to water stress. Maize does not osmotically adjust as well as cotton, sorghum or wheat to low water status. In addition and as already discussed, its high determinancy makes it harder to make up for the loss in productivity after the period of water stress is released by irrigation or rain.

With respect to salinity, maize is considered to have medium sensitivity (Ayers and Westcot, 1985). Its responses to salinity stress are similar to its responses to water stress, namely, slowing of leaf expansive growth, reduction of stomatal conductance and photosynthesis, and acceleration of leaf (hence canopy) senescence, with the same relative ranking of sensitivity of these parameters similar to that of water stress.

Deficiency of mineral nutrients can markedly impact maize productivity. The most common deficiency is nitrogen, although potassium or phosphorus deficiency can be equally or more important in some soils. Maize grain contains about 1.3 to 1.8 percent nitrogen. With a fair grain yield of 10 tonne/ha, 130 to 180 kg of nitrogen would be removed from the soil by the grain alone. For maize to produce reasonably good to high yields, nitrogen removal by the whole crop for the season is in the range of 180 to 340 kg/ha (Wolfe *et al.,* 1988a; Rhoads and Bennett, 1990). As for all crops, the photosynthesis rate of maize leaves in favourable environments are linearly related to leaf nitrogen content (Evans, 1993). The photosynthesis rate is reduced by about two-thirds as leaf nitrogen content drops to less than 1.5 percent, and approaches zero as the content decreases below 1 percent (Wolfe *et al.*, 1988b). The common fertilization rate in countries such as the United States (Rhoads and Bennett, 1990) and China are in the order of 200 kg of nitrogen per ha or somewhat higher. For many developing countries the rate of fertilization is usually less than half that amount. This is almost certainly one major reason for the low world average yield. In the field the effects of water stress are often confounded by nitrogen deficiency. The reason is that fertilizer nitrogen is applied to the top layer of the soil, which dries up first when water stress develops and essentially nitrogen becomes unavailable (Wolfe *et al.*, 1988a).

Being a C_4 and warm-season crop, maize is sensitive to cold. In *AquaCrop*, for the calculation of growing degree day (GDD), the base temperature (T_{base}) for maize is set at 8 °C, and the upper temperature threshold (T_{upper}), the temperature above which crop development no longer increases with an increase in temperature, is set at 30 °C. The minimum GDD for full biomass production per unit of transpiration is tentatively set at 10.

YIELD

Over the last few decades grain yield for maize has continued to increase. Much of this increase is because of higher planting density, improved fertilization, optimal canopy structure, and late-maturing cultivars with longer life-cycles. Yields around 17 tonne/ha for late-maturing maize cultivars, grown with optimal water and mineral nutrients supply under ideal conditions and excellent pest and weed control, have been reported in experimental studies and in farm tests. Farm yields between 11 and 14 tonne/ha are normally achieved under full irrigation and high fertility. The average country yields are generally much lower, except for a few countries; for instance, it was slightly over 10 tonne/ha for the United States, and over 9 tonne/ha for France, in 2009. Average yields in Argentina, China and South Africa were only about a half of this, and in Brazil slightly above one-third; but all show clear rising trends over time. On the other hand, average yields in a number of less industrialized countries are only in the range of 1-2 tonne/ha, and do not yet show a clear trend of improving.

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Soybean

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Soybean

GENERAL DESCRIPTION

Cultivated soybean (*Glycine max* (L.) Merr.) is a major oilseed and protein rich annual legume crop grown on about 99 million ha and producing 223 million tonne of grain worldwide (*FAO, 2011*). The crop originated in China and is closely related to *Glycine soja*, its wild progenitor. Soybean represents nearly 50 percent of the total area cropped with seeds providing approximately 56 percent of the total edible oilseeds and 30 percent of vegetable oil production worldwide. Over the last 50 years, world production has increased eight times as a result of the substantial increase in average yields and the expansion in cultivated area (Figure 1).

Soybean is grown from the equator to latitudes 55° N or S and as high as 2 000 m. However, main soybean production is concentrated between 25° and 45° N regions, and generally grown below 1 000 m altitude (Singh *et al.*, 2009) (Figure 2). The five top producers of soybean, the United States, Brazil, Argentina, China and India, in that order, account for more than 93 percent of global production. Soybean cultivation is also increasingly popular in Paraguay, Canada, Bolivia, Ukraine, Uruguay, Indonesia, Russian Federation and Nigeria.

Today most commercially grown soybeans are the yellow-seeded field cultivars used for animal feed, oil production (for food and industrial uses), and as a protein-rich food. Other cultivars are available for special use: forage and hay (with an abundance of stems and leaves) and as a vegetable (large-seeded, various coloured varieties).

Soybean fits well into crop rotations and intercropping systems. Most prominent cropping sequences are soybean-maize and soybean-wheat in the United States, Brazil and Argentina. Soybean-chickpea, soybean-mustard, soybean-wheat sequences and soybean intercropping with pigeonpea or cotton are common in India and China. In Indonesia double or even triple cropping is practised with rice(-rice)-soybean, where soybean is grown on the residual moisture in rice fields in the dry season. In Vietnam soybean is grown as a late summer crop for fodder after the rice harvest. Work by International Crop Research Institute for the Semi-arid Tropics (ICRISAT) in India had shown that yield increases with soybean-chickpea and soybean/pigeonpea sequential and intercrop systems was possibly because more nitrogen is made available when one legume crop follows another. If soybeans have not been grown in a particular location for

FIGURE 1 World soybean harvested area and average yield over the period 1961-2009 (FAO, 2011).

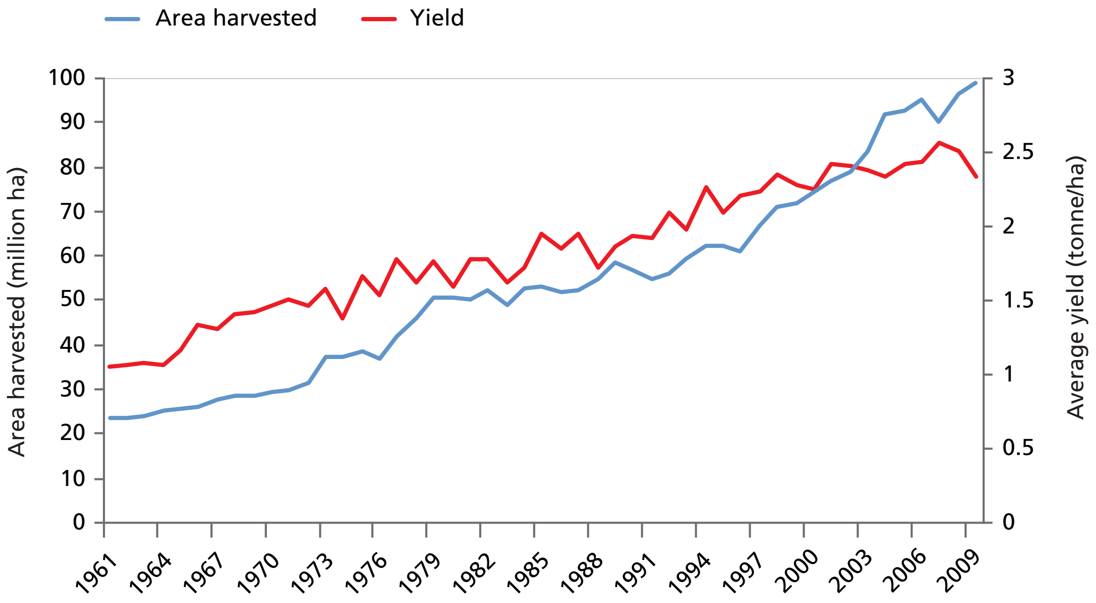
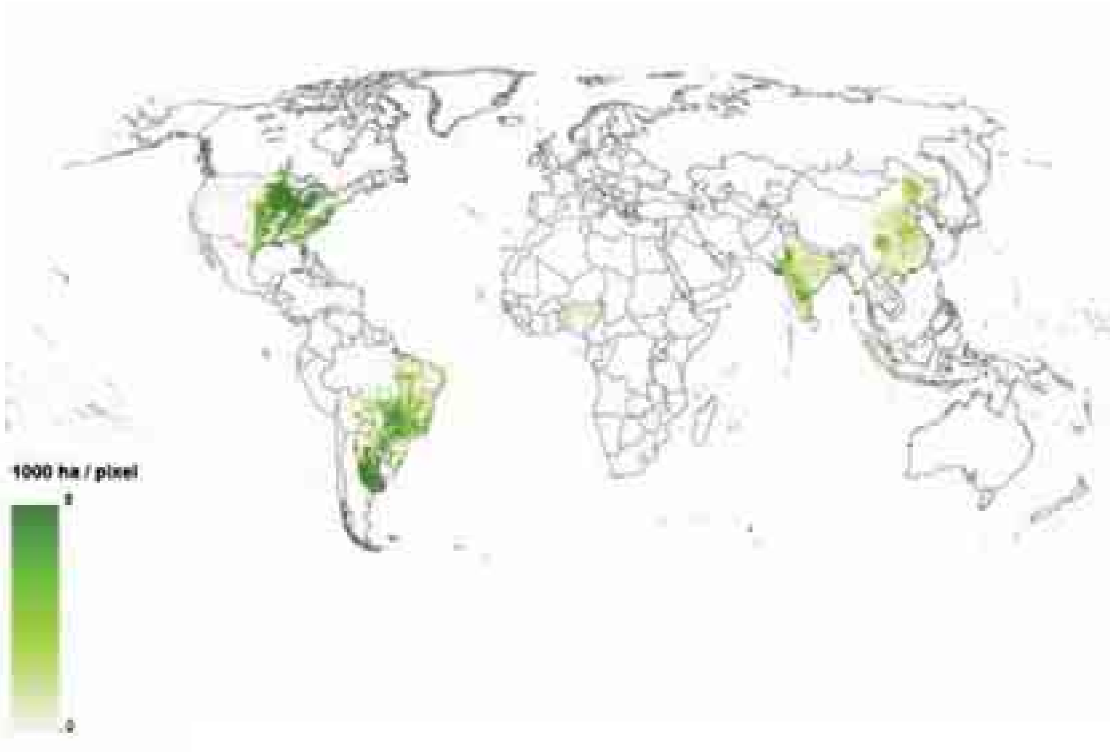


FIGURE 2 Soybean harvested area (GAEZ, 2011).



Reference year 2000

three or more years, it is best to inoculate the seed with an effective strain of nitrogen-fixing bacteria (*Rhizobium*).

GROWTH AND DEVELOPMENT

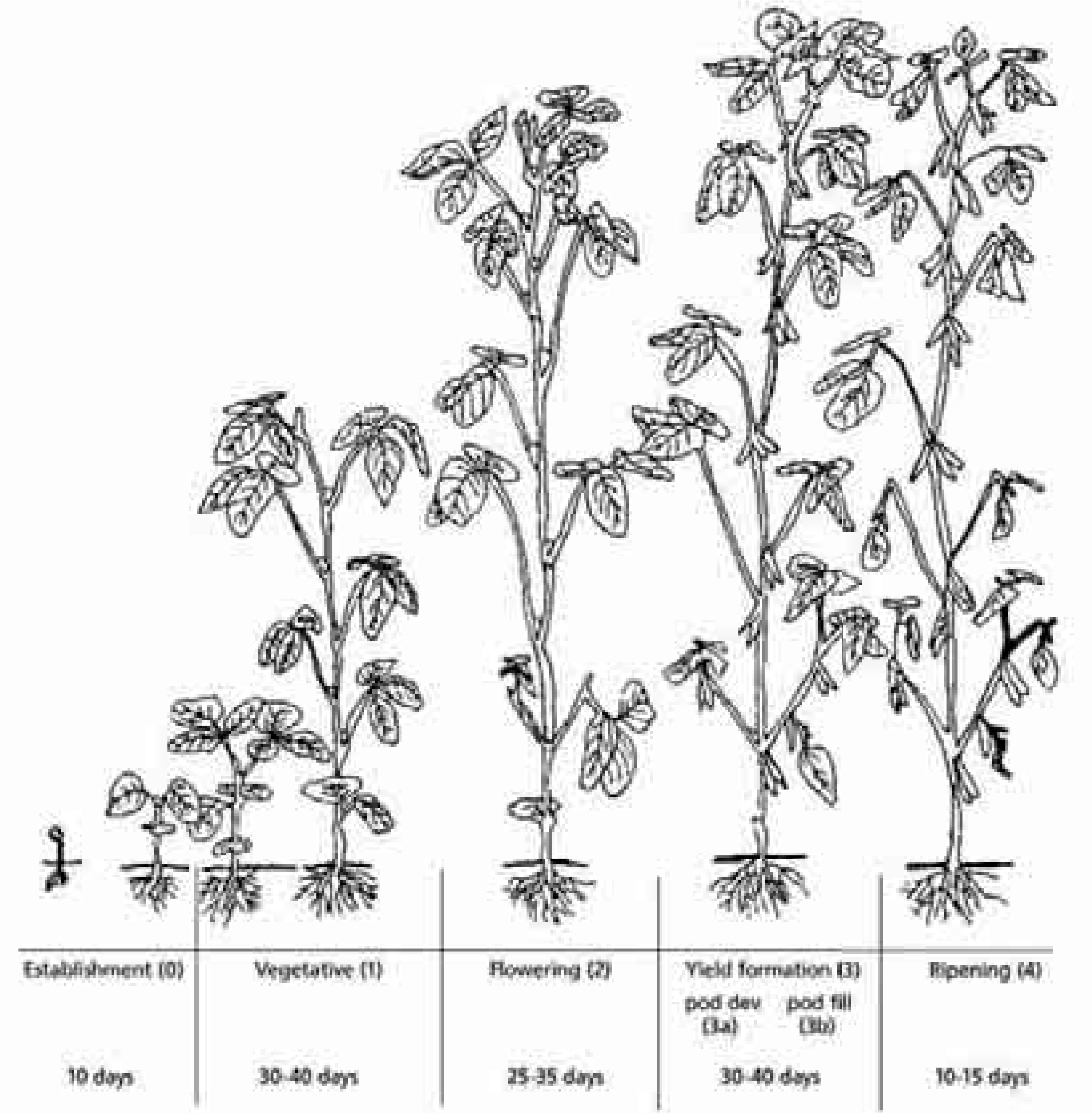
Soybean cultivars vary from being highly determinate to indeterminate. Indeterminate plants are those that continue to produce leaves, new flowers and pods for several weeks after the start of flowering. They typically grow taller, to 1 m, and are more common at higher latitudes with short growing seasons. Growth is stopped by cold temperature near the season's end. Determinate plants complete their growth in height and then produce the flowers at about the same time. They are usually one-half to two-thirds (0.45 to 0.6 m) as tall as indeterminate cultivars. There is however no correlation between plant height and seed yield (Figure 3).

Soybean is grown mainly under rainfed conditions in late spring or summer, when there is rain. In India and China, soybean is mostly sown in May/June to early July but may be grown in spring and sown between February and March in the southern regions. In the United States, Brazil, and Argentina sowing season starts in May and ends by mid-July as the summer crop or is planted after winter wheat. Late plantings generally have smaller canopies and produce less than early plantings. In areas of high rainfall, raised seedbeds in the form of broad-bed and furrow or ridge and furrow land forms are well suited to draining out excess water from Vertisols and to providing good aeration of the root zone. Planting density ranges from 150 000 to 500 000 plant/ha, depending on seed cost and environmental factors. In India, optimum plant population of 330 000 plant/ha is recommended, and it can be achieved with a seed rate of 80-100 kg/ha based on seed size. In the United States, common row spacing is 0.50 m, while in Brazil, Argentina, China and India, rows are often narrower (0.33 m). Sowing depth of 2.5 to 4.0 cm is optimum for good germination. Optimum average air temperature for rapid germination is approximately 30 °C.

Soybean is very adaptable to different cropping systems, as there is wide variation in the length of the life cycle, between 70 and 140 days depending on the cultivar and season. Because of variation in season length with latitude and the need to fit into a particular time span in crop rotations, life cycle length was important enough to prompt the designation of soybean cultivars by maturity groups in North America. The designation uses Roman numerals up to X, with the duration to maturity increasing as the numeral increases. The breeding of lines with even shorter life cycles later caused the extension of the low end of the maturity groups, from I to 0, 00, and 000. Soybean flowering is determined by photoperiod and thermal regime. Cultivars in late maturity groups, grown in lower latitudes, initiate flowers at shorter day length (e.g. 10 hours), whereas cultivars in early maturity groups, grown in higher latitudes, initiate flowers at longer day length (e.g. 13 hours). It is important to grow locally-adapted cultivars at a given latitude. For example, if a cultivar suitable for a higher latitude is grown at a lower latitude, it would flower and mature too early and yield less.

Short duration cultivars, ranging from 95 to 115 days, are popular in India, the USA, China (Heilongjiang province and Huai river valley), while even shorter life cycles are used in Korea. Medium duration cultivars of 120 to 140 days are grown in China (Northeast and Loess plateau). Brazil and Argentina prefer the longer season cultivars, which produce up to 20

FIGURE 3 Typical developmental stages of soybean.



percent higher yield than the early maturing. Most cultivars suitable for the rainy season are medium maturing, between 95 and 115 days. For cultivars of this maturity range, indicative duration of the different growth phases is as follows:

- sowing to emergence: 6 days;
- sowing to maximum canopy: 50-55 days (depends on plant density);
- sowing to onset of canopy senescence: 80 days, and time from onset to completion of canopy senescence: 25 days;
- sowing to physiological maturity: 105 days; and
- sowing to flowering: 36-45 days, and flowering duration: 14-20 days.

Determinant cultivars reach maximum canopy cover and height at early reproductive stages (between R1 and R3 of soybean growth stages), while the canopy of the indeterminate type can continue to grow after this. Maximum canopy cover varies between 65 and 95 percent depending mostly on row spacing and plant density. Soybean flowers are white or purple, very small and borne in short clusters. Only about 25 to 60 percent of the flowers actually produce pods, which become prominent one to two weeks after the flowers appear. Pod setting lasts two to several weeks, longer for the indeterminate cultivars. When conditions are not limiting, a pod produces three to four seeds and they fill in about one month.

As for all crops, soybean preferentially grow roots relative to shoot at germination to shortly after emergence. Maximum depth of rooting for soybean is about 1.3 to 1.8 m deep and can reach up to 2.40 m, depending on water status, soil type and temperature, and life cycle length of the cultivar (Kanemasu, 1981). Most roots are located in the upper 0.3 m of soil, but prolonged dry periods cause roots to proliferate more in the deeper soil layers. As is the case for other crops, water stress increases the root to shoot ratio, and tends to increase total root length. Soybean genotypes vary in their growth and development of root systems.

WATER USE & PRODUCTIVITY

Depending on climate, soils, crop cultivar, and management practices, evapotranspiration (ET) of soybean varies between 300 mm and 800 mm. In India, soybean ET was reported to be around 450 mm. Seasonal water use of 330 mm to 760 mm has been reported in the United States, and similar values in Australia. *FAO Irrigation and Drainage Paper* No. 56 presented values between 450 and 825 mm. Peak daily water use of soybean is about 8-9 mm/day, which normally occurs as maximum canopy cover is reached (near full bloom to beginning of pod filling).

Biomass water productivity ($WP_{B/ET}$) of soybean, i.e. slope of the linear relationship between biomass and cumulated ET, has been found to vary from 1.2 to 1.6 kg/m^3 in studies carried out in different parts of the world. Higher $WP_{B/ET}$ values were observed in the United States/Canada studies while lower values were found in India. The difference may be due to limitation of nitrogen and other mineral nutrients in the latter. For oilseed crops such as sunflower and soybean, $WP_{B/ET}$ decreases after anthesis because the protein and oil in the seed require more energy and photosynthetic assimilates to make than cell walls or starch. Soybean showed significant increase in seed yield with elevated atmospheric CO_2, by up to 35 percent.

RESPONSE TO STRESSES

Water, temperature, nutrient stresses affect the growth and development of soybean. Vegetative (leaf and stem) growth is very sensitive to water deficits. Water stress that occurs at the beginning of podsetting to full seed-filling has a greater negative impact on yield than when it occurs at other stages. The seed-filling period is very critical to yield. If environmental conditions are adverse (drought, hail, or disease), seed-fill will be restricted and yields will be cut severely (Doorenboos and Kassam, 1986).

Soybean is very sensitive to frost at seed emergence and pod filling, but losses due to frost in grain yields for indeterminate cultivars are less compared to other cultivars because of the extended flowering period.

A number of studies indicate that soybean yields are not substantially affected until the root zone soil has been depleted below 60 percent of total available water (TAW), provided canopy development has not been hampered by prolonged mild water deficits during the vegetative phase. Water stress during grain filling reduces seed size considerably, and water stress after flowering and during pod filling is most critical (Doss and Thurlow, 1974). In addition to the usual inhibitory effects on leaf expansion, transpiration and photosynthesis, water deficits also inhibits nitrogen fixation in soybean.

Excess moisture severely affects germination and early growth of soybean. However soybean tolerates flooding or waterlogging up to 7 days, but yield can be reduced by more than 40 percent if prolonged flooding occurs at floral initiation or beginning of the seed filling stage. In addition to being detrimental to root activities, flooding reduces nodulation. Soybean exposed to flooding for more than 8 days produce adventitious roots on the stem with aerenchyma tissue which facilitates oxygen diffusion to the submerged apical root portion (Mayaki *et al.*, 1976).

Soybean can be grown in a wide range of soils, except those that are very sandy, with optimum growth in alluvial soils high in organic matter. Usually, the fertilizer phosphorus and potassium requirements are 35 to 70 kg/ha P_2O_5, and 36 to 84 kg/ha K_2O. Soybean is often assumed to be capable of fixing atmospheric nitrogen to meet its requirement for high yield; although benefit from a starter dose of 10 to 20 kg/ha N is recognized. However, this assumption may not hold under conditions of high yield potential but with a soil low in organic and mineral nitrogen. A soybean crop at maturity contains on average 70 kg of N, 30 kg of P_2O_5, and 60 kg of K_2O per tonne of grain produced. So a yield of 3 tonne/ha would require at least 210 kg/ha of N by symbiotic fixation and uptake from the soil. A number of studies have shown that even under favourable conditions, symbiotic fixation usually supplies not much more than half of the N, with the rest coming from the soil. Nitrogen fixation is reduced under water stress; irrigation and rainfall distribution greatly affect N accumulation and N supplies from those fixed.

Soybean cultivation is successful in climates with warm summers, and optimum growing conditions at mean temperatures of 20 °C to 30 °C. Days to flowering of soybean were shortest at 30 °C, and an increase in days to flowering at 25 °C, 35 °C and 20 °C has been observed. At 20 °C self pollination without opening of the flowers has been reported for various cultivars, so has abortion of flower and newly set fruit at 35 °C. High canopy temperature (approaching 40 °C) reduces CO_2 assimilation rate, and low stem temperature slows translocation, which stops in soybean at 2 °C to 3 °C.

Soybean is generally sensitive to salinity, but cultivars differ substantially in their salt tolerance. Some moderately tolerant cultivars exclude chloride from their leaves. High phosphate supply in the growth medium increases sodium uptake and reduces salt tolerance of some cultivars.

IRRIGATION PRACTICE

Soybean is commonly grown under rainfed conditions; for example, only 8 percent of the total area in the United States is irrigated. Efficiency of applied water is highest when irrigation is applied during the reproductive stage (around R3 stage) relative to applications before flowering. Irrigation during pod filling also prevents or stops accelerated canopy senescence caused by water stress, ensuring good green canopy cover to continue photosynthesis and maximize translocation of assimilates and minerals from leaves to seeds. As with other crops, the irrigation requirement of soybean varies, depending on rainfall, climate, water storage capacity of the soil and rooting depth. The number of applications varies from a minimum of 2 to a maximum of 8 irrigations in the season to ensure that the crop is not exposed to substantial stress once pod setting has begun. Irrigation scheduling, based on 60 percent depletion of TAW, consumes less water without severely affecting crop yields if soil water content is adequate at sowing. In many cases a single irrigation at late bloom is most beneficial compared to any other growth stage.

Surface irrigation by flooding, ridge and furrow, basin, and border application methods are commonly practised. Sprinkler irrigation by center-pivot, side-roll, traveling-gun, tow-line, and solid-set, is also practised in some countries. When soil water is deficient, irrigation increases plant height, leaf area, leaf number and length of primary root, as well as the dry weight of stems, leaves, reproductive organs and roots (Rhine *et al.*, 2009).

YIELD

Soybean yield averages around 2.0 to 2.5 tonne seed/ha (at 13-14 percent seed moisture content) for major producing countries but in developing countries, a large yield gap exists between farmers' yields and achievable soybean yield. Average soybean yields in the United States approach 3 tonne/ha, and in Brazil, 2.7 tonne/ha (Bhatia *et al.*, 2008; Singh *et al.*, 2009). In Europe, Italy has the highest average yield, at 3.5 tonne/ha. The yield is 1.6 tonne/ha in China while it is only 1 tonne/ha in India. The yield potential of cultivars of variable duration (65-130 days) in India ranges between 1.2 to over 4 tonne/ha with low to high input crop management (Singh *et al*. 2009). In the United States, top yields of over 5 tonne are not unusual in some areas. This difference in yield is probably related to differences in management practices and to the different nutrient status of the soil, including nitrogen, with a tendency of the crop to be exposed to nutritional stress in low-yielding farming systems. Soybean is primarily utilized as the source of protein and oil. The seeds contain 40-42 percent protein and 17.5 percent to 20 percent oil, with polyunsaturated fatty acids such As oleic and linoleic acids dominating. Soybeans grown in different locations can vary substantially in protein, amino acids and lipid concentrations, as indicated by a study comparing the chemical compositions of beans grown in China with those grown in the United States and Brazil (Grieshop and Fahey, 2001). It appears that environmental conditions under which soybeans are grown can significantly impact chemical composition and nutritional quality.

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Barley

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Barley

GENERAL DESCRIPTION

Barley (*Hordeum vulgare L.*) ranks fourth among cereals in terms of total world production. In 2009, around 54 million ha of barley were harvested, producing 152 million tonne of grain at an average yield of 2.8 tonne/ha (FAO, 2011). Over the last 50 years, the average yield per hectare has increased noticeably. However, because of changes in the area cropped, total production rose only to the 1980s, followed by a decline in the 1990s, and possibly stabilizing since then (Figure 1). Barley is the main feedstock for beer and also an important feedstock for whisky. The fluctuation in area harvested may partly be the result of changing market demand.

Barley was one of the first domesticated cereals, originating in the Fertile Crescent area of the Near East about 10 000 years ago. It is adapted to and produced over a wide range of environmental conditions. It is a cool-season crop cultivated in the spring and summer at higher latitudes and in the tropics at high elevations, and in the winter and spring at lower to semitropical latitudes. The main production countries are the Russian Federation, Ukraine, France, Germany, Spain and Australia (Figure 2).

Two botanical types can be distinguished, two- and six-row barleys, depending on the number of fertile and developed spikelets at each node of the rachis. Spikelets alternate on nodes along the rachis. In wild relatives, the two lateral spikelets are infertile and only the central spikelet is fertile, giving the appearance of having two-rows of spikelets, one at each side. Cultivars that retain this wild characteristic are two-row barleys. In six-row barleys, mutations resulted in the lateral spikelets being fertile, with three (one central and two lateral) spikelets at each node of the rachis.

The two main uses of barley grains are as animal feed and as malting for beer and whisky. In general, six-row barley tends to have higher protein concentration than two-rowed barley and, therefore, it is better suited for animal feed. Two-row malting barley has been traditionally grown in Europe, Australia, South America, and some other regions of the world, while six-row malting barley is more common in North America. Currently, two- and six-row malting barley can be found in all growing areas of the world.

Barley is similar to wheat and consequently several aspects of the crops` management are analogous. Although direct comparisons between the

FIGURE 1 World barley harvested area and average yield over the period 1961-2009 (FAO, 2011).

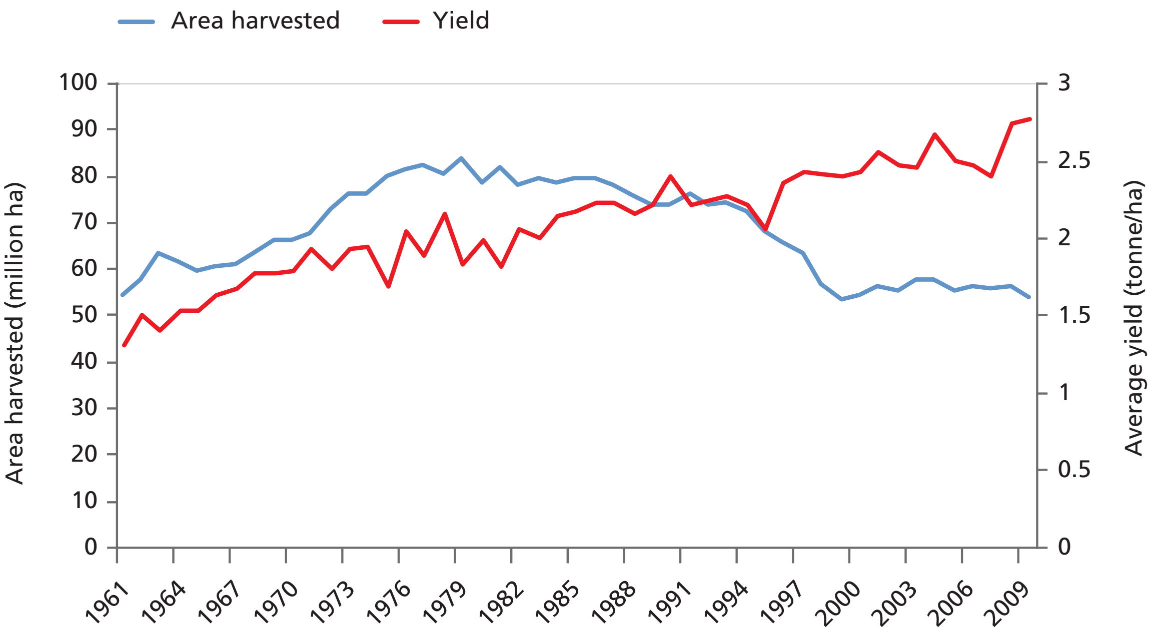
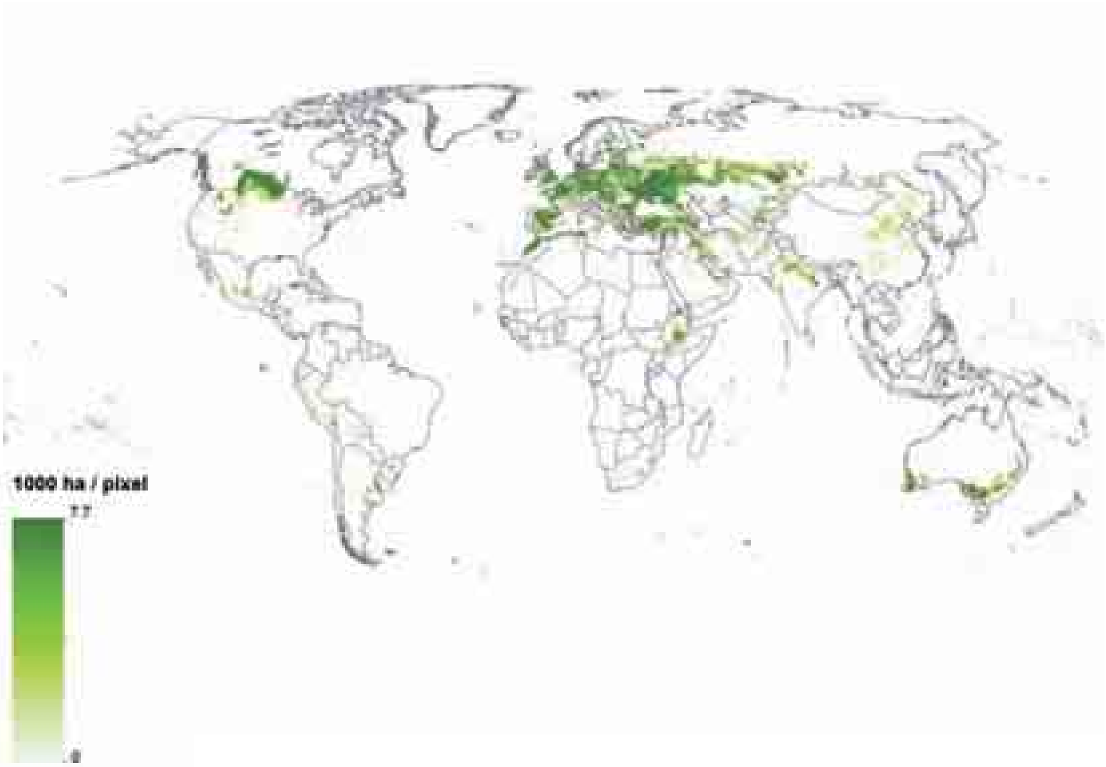


FIGURE 2 Barley harvested area (GAEZ, 2011).



Reference year 2000

two cereals are scarce, one of the main differences is that barley is generally believed to be better adapted than wheat to stressful situations and therefore it is normally sown in harsher environments than wheat (see Cossani *et al.*, 2009). In many areas, where one crop is produced per year, barley is grown in rotation with a variety of other winter annuals such as other cereals, oilseed crops, and pulses; but in dry environments barley monoculture is common (i.e. in the Mediterranean basin in areas where annual rainfall is less than 350 mm). The season length of barley tends to be shorter than that of wheat, making it more suitable for double cropping. For instance, barley may be followed immediately by either maize or soybean.

GROWTH AND DEVELOPMENT

Barley genotypes are generally grouped into two categories according to their sowing time: winter and spring cultivars. Winter barley is sown in autumn and requires a cold period (vernalization) during early growth for flowering under long days, and matures in late spring to early summer. This ensures flowering when the risk of late frost is low, leading to a long yield formation period that maximizes potential yield. In areas where winter is harsh enough to kill a significant number of seedlings, instead of winter barley, spring barley, not requiring vernalization, is sown in the spring when soil temperatures are adequate for germination and seedling emergence and it is also photoperiod sensitive. Because of the much shortened duration in the field, spring barley has lower yield potential than winter types. In environments with quite mild winters, winter type may be sown in the middle of winter and still flowers (mid-spring) and matures (early summer) under favourable conditions to give yields similar to those obtained when winter types are sown in autumn. This practice of sowing winter types late is traditional for much of the barley growing region of the Mediterranean Basin, particularly in North Africa, and the cultivars can be termed Mediterranean genotypes. They are usually facultatively sensitive to vernalization (facultative barleys). It is generally accepted that within the normal growing season a delay in sowing date has a negative effect on grain yield. The season length of a spring type ranges from 90 to 130 days while a winter type needs about 180 to 250 days to mature, and Mediterranean types are intermediate. Samples of duration of various growth phases are given in Table 1.

TABLE 1 Sample duration (calendar days) of different stages of Mediterranean, spring and winter barley from the literature. Data are averages of different cultivars.

Barley type	Sowing-emergence	Sowing-heading*	Sowing-maturity	Reference
Mediterranean	10-12	107-118	137-150	Abeledo *et al.*, 2003; Abeledo, 2009 unpublished
Spring	10-14	45-52	91-96	Muurinen *et al.*, 2007; Peltonen-Sainio, P., pers. Comm.
Winter, Southern Europe	14-16	144-169	172-212	Albrizio *et al.*, 2010; Cossani *et al.*, 2009
Winter, Northern Europe	-	225	280	HGCA, 2006

*****pollination in barley, unlike in wheat, occurs at heading*

Barley development may be thought of as occuring in three phases, vegetative, reproductive and grain filling. During vegetative phase all leaves are initiated and then emerge continuously until the final leaf emerges. Tillers are initiated after leaf 3-4 emerges from nodes on the main shoot and continues until stem elongation. During the reproductive phase, spikelet differentiation starts in the apex and continues with the development of floret primordia within previously differentiated spiklelets and finishes with the determination of fertile florets. During the second half of the reproductive phase the stems, and later the spikes, grow rapidly while some tillers die and some of the initiated spikelets do not progress in their development towards a fertile spikelet at heading. During this period dry matter of the juvenile spike is accumulated and this growth of the spike is related to the survival of floret and spikelet primordia. This is the reason why there is a close relationship between grain number per unit area and the dry weight of the heads at anthesis (Prystupa *et al.*, 2004), provided there is no post anthesis stress. Barley florets are self-pollinating and anthesis starts as the head emerges from the flag leaf sheath.

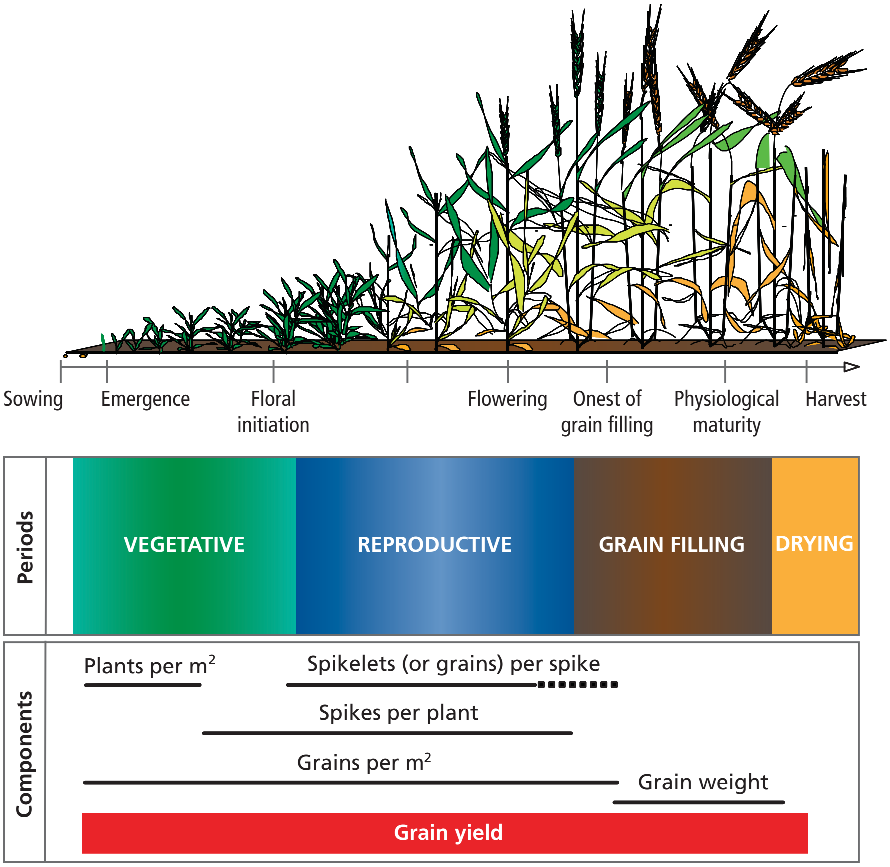
In the grain-filling phase, grains accumulate dry matter up to their final grain weight. Again, if assimilates are limiting, some of the potential grains may be aborted early or fail to develop fully.

The major environmental factors affecting barley phenology are temperature and photoperiod. As for all crops, temperature affects the rate of progression through the various phases, and is accounted for when *AquaCrop* is run in the growing degree day (GDD) mode. The base temperature and upper temperature for barley should be similar to that of wheat, 0 °C and around 25 °C, respectively. Another key temperature effect is on vernalization, which requires cold temperature. Vernalization, together with photoperiod, largely determines the time of heading and flowering of winter cultivars. Figure 3 shows typical development of a barley plant, illustrating the particular developmental phases.

Plant density is a management practice that modifies the crop canopy size and development, and hence ability of the crop to capture photosynthetically active radiation. As for other temperate cereals with tillering habits, plant densities may range widely, with low density being compensated for by more tiller formation. For this reason, planting densities are normally higher for spring than for winter or Mediterranean type. Actual sowing rates aim to establish stands of 50 to 300 seedlings/m^2, with most common densities being between 150 and 250 plants/m^2 for temperate zone with adequate rainfall. For rainfed semi-arid and arid areas, the sowing rates would be at the low end of the range. Row spacing is typically between 0.15 and 0.25 m. When barley is grown as a forage crop, the optimum plant density is higher than that for grain production.

The pattern of root growth can be described as exponential between sowing and the onset of stem elongation (when more assimilates are used for stem and spike growth), and then continues some past anthesis. Maximum rooting depth can vary from 0.30 m in shallow soils to more than 2 m on deep sands and loams. Root growth patterns are strongly modified by fertilizer locations in the soil and soil moisture conditions. Barley, like wheat, can grow on a wide range of soils from deep sands and shallow soils to loams to heavy clays.

FIGURE 3 Typical developmental stages of barley: sowing, seedling emergence, floral initiation or 'collar' stage, awn initiation, flowering, beginning of grain-filling period, physiological maturity and harvest. Boxes indicate different phases and yield components formation (adapted Garcia del Moral *et al.* 2002).



WATER USE AND PRODUCTIVITY

Water is often the resource that most significantly limits barley yield, depending on severity of the deficiency. Seasonal evapotranspiration (ET) of barley ranges from 100 to 500 mm. The relationship between grain yield and ET is usually linear with the intercept on the abscissa taken as an estimate of soil evaporation. Hence the slope of the linear relationship can be interpreted as the transpiration yield efficiency of the crop ($WP_{Y/Tr}$), which is reported to be around 1.2-1.4 kg/m^3.

As is the case for all crops, the response of barley to water stress depends on timing, duration, and severity of the stress. Therefore, stress effects on yield may range from slight enhancement, to virtually no effect, to different ranges of yield reduction, and even to crop failure. In terms of yield components, it has been well established for both wheat and barley that yield is determined largely by the number of grains per unit land area, and, to a substantially lesser degree, by the weight per grain. Of course, the number of grains per unit land area is the product of plant density, fruitful shoots per plant, and grains per fruitful shoot (head). The number of grains per head is particularly sensitive to stress occurring during the period from the onset of stem elongation to the end of anthesis, when stress may limit the number of fertile florets produced from the florets initiated, and the proportion of the fertile florets pollinated and set. During the grain filling period, yield is also reduced by water stress strong enough to inhibit assimilation, leading to reduced weight per grain. In terminal drought situations common to the Mediterranean climate, yield loss is most likely the combined result of fewer grains resulting from early abortion of young developing embryos, and reduced weight per grain. In addition to reducing stomatal opening and photosynthesis, terminal drought also accelerates leaf and hence canopy senescence, causing premature cessation of assimilate production. Consequently, harvest index is reduced because vegetative biomass is formed mostly in the early part of the season when water is not as limiting whereas grain biomass derives largely from that assimilated during the late part of the season under drought.

Yield is also significantly affected by stresses during the early part of the grain filling period when potential grain size is being determined and grain number may be reduced by abortion of the developing embryos. Before the onset of stem elongation, the detrimental effects of stress are due to either poor stand establishment and/or slow tiller and canopy development. Either a poor stand or slow canopy development reduces radiation captured for photosynthesis, and hence, biomass accumulation rate. Slow development of tillers also reduces the number of heads per unit of land area. That is why for instance an early control of weeds is essential to avoid yield penalties.

Various aspects of temperature effects have already been discussed under Growth and Development. An additional effect is that on grain filling. In most temperate conditions grain filling occurs when the weather is getting hotter. High temperatures (above 30-32 °C) accelerate seed development towards maturity, shortening the grain filling period and hence reduces weight per grain at harvest. The effect is noticeable even if periods of high temperature are short (even only 3 days). Another possible negative effect of high temperature late in the season is acceleration of canopy senescence, although this may partly be the indirect effect of water stress induced by high transpiration under high temperature. In addition to lower yields, stresses over grain filling may reduce grain quality for malting, by increasing the proportion of grains smaller than 2.5 mm, increasing protein percentage and reducing the malt extract.

Salinity is a prominent stress for barley production in some irrigated areas. However, barley is considered to be the most salt tolerant of cereals. Regarding mineral nutrients, soil fertilization requirements can only be determined in relation to achievable yield and soil type and native fertility. As a rough guide, for each tonne of yield per hectare, barley needs to take up about 30 kg of N, 5 kg of P and 20 kg of K. The amount of actual uptake depends on the availability of the native and fertilizer nutrients as well as the crop uptake efficiency. Broadly speaking, uptake efficiency is seldom higher than 0.6. The crop N status not only influences yield but also grain protein percentage. Low protein percentage is more suitable for malting, whereas high percentage is more suitable for animal feed.

IRRIGATION PRACTICE

Barley is usually grown under rainfed situations. In some cases, however, full or partial irrigation may be applied, especially when barley is grown for malting or where double cropping is practised, with an early-maturing barley followed by late-sown maize (or soybean).

The seasonal water requirements for barley depend on cultivar, target yield and crop management. Malt barley requires better water management than food barley to meet the standards set by the industry. During initial growth stages, crop water use ranges from 1 to 3 mm/day, rising to 5 - 8 mm/day after canopy approaches complete cover (usually at the appearance of flag leaves), and remains high until the beginning of canopy senescence. Although winter rainfall is sufficient in many climates to supply the full barley water requirements in the early vegetative phase, effective rootzone soil moisture should not be depleted beyond 50 percent of total available water from emergence until flag leaf, after which depletions should probably not exceed 60 percent of the total available soil water until the soft dough stage. Normally, with adequate winter rainfall, border or flood irrigation of malt barley will require 2 to 3 irrigations on heavier soils corresponding with the critical growth stages. Light, sandy soils would require more frequent irrigations.

Excessive soil moisture during the jointing and boot stage, coupled with high nitrogen fertility, may promote vegetative growth that could result in lodging as the crop develops. Excessive irrigation after the crop is well developed also promotes lodging.

YIELD

Barley yields can vary from less than 1 to about 3 tonne/ha in water-limited rainfed conditions to 4-10 tonne/ha in rainfed temperate (such as western and northern Europe) climates. Potential yields up to 12 tonne/ha have been observed. As discussed earlier, barley yield is more sensitive to changes in growing conditions during the period when grain number is set, from stem elongation to just before the onset of grain filling. The cumulative growth during this phase is important enough to justify the assumption of some risk of frost at flowering; the sooner the flowering occurs the higher the crop growth throughout the phase from stem elongation to the onset of grain filling.

Harvest index for barley is similar or only slightly lower than for wheat, and ranges from 0.45 to 0.5 for modern cultivars under favourable conditions. As is the case for other cereals, the rise in yield over time owes much to the rise in HI as the result of plant breeding. Interestingly, the increase in HI over time for barley has been somewhat slower than that for wheat and rice (Evans, 1993), possibly because of the grain quality constraints imposed by brewers. There is no simple, clear and unanimously accepted quality standard based on a set of variables for malt barley. Quality requirements represent a consensus of specifications commercial brewers developed to ensure efficient production consistent with desired product properties or traditional methodologies (Savin and Molina-Cano, 2002), which vary with geographical regions. However, protein content is regarded as one of the main quality attributes. In general there is a negative relationship between protein content and malting quality; the target is to keep maximum grain protein content of malt barley around 10-12 percent.

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Sorghum

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Sorghum

GENERAL DESCRIPTION

Sorghum (*Sorghum bicolor* [L.] Moench) is a crop indigenous to Africa, where it appears to have been domesticated in Ethiopia about 5 000 years ago. It is now widely cultivated in dry areas of Africa, Asia, the Americas, Europe and Australia between latitudes of up to 50 °N in North America and Russia and 40 °S in Argentine. Sweet sorghum is a variant closely related to grain sorghum; it differs mainly in that its stalks are taller and juicier with higher sugar content than the grain sorghum type. Sorghum is the fifth most important cereal in the world after wheat, rice, maize and barley. In Africa it comes second after maize in terms of production. Sorghum is well adapted to tropical climates with several traits making it a drought-tolerant crop that survives under adverse climatic conditions, and thus is often relegated to poor soils and low-input management. It is extensively grown under rainfed conditions for grain and forage production. High production may be achieved when sufficient water and nutrients are applied especially at critical stages of crop growth.

World sorghum production during 2009 was about 59 million tonne of grain from 40 million ha with an average productivity of 1.4 tonne/ha (FAO, 2011), with the United States, India, Mexico, Nigeria, Sudan, Ethiopia, Australia, and Brazil as major producing countries, in that order (FAO, 2011) (Figure 1).

Sorghum is mainly cultivated in dry areas, often on shallow to medium deep, lighter to medium textured soils, and also on medium to deep soils of high water retention capacity as a post-rainy season crop (Figure 2).

In India, rainy season (*kharif*) sorghum is sown between the second week of June and the first week of July, with rains of the southwest monsoon. However, sorghums are prone to fungal attacks leading to grain *mould* if late season rains occur during grain maturity. Post-rainy season (*rabi*) sorghum is sown generally from the last week of September to second week of October, and is generally exposed to low winter temperatures at sowing resulting in low germination and poor stand establishment. Late sown *rabi* season crops are exposed to terminal drought when grown on black soils (Vertisols) with stored soil moisture and are prone to disease such as charcoal rot. Sorghum planting season in the United States starts from the second week of May to first week of August in Kansas and South Dakota, and from the last week of March until the first week of August on the Great Plains. In the subtropical and temperate regions of Argentina,

FIGURE 1 Typical developmental stages of sorghum (FAO 2011).

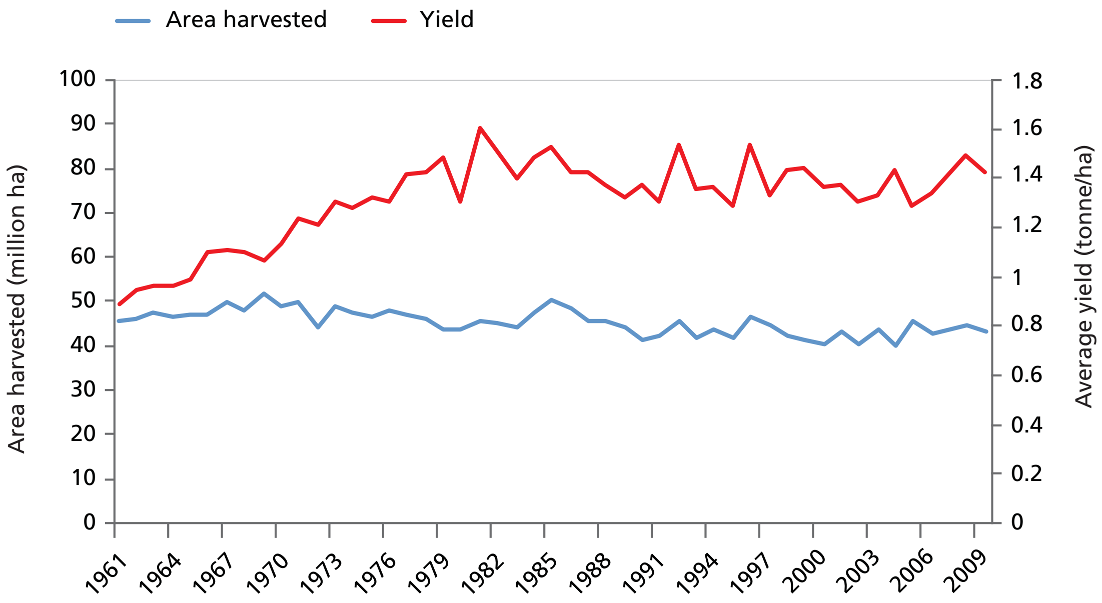
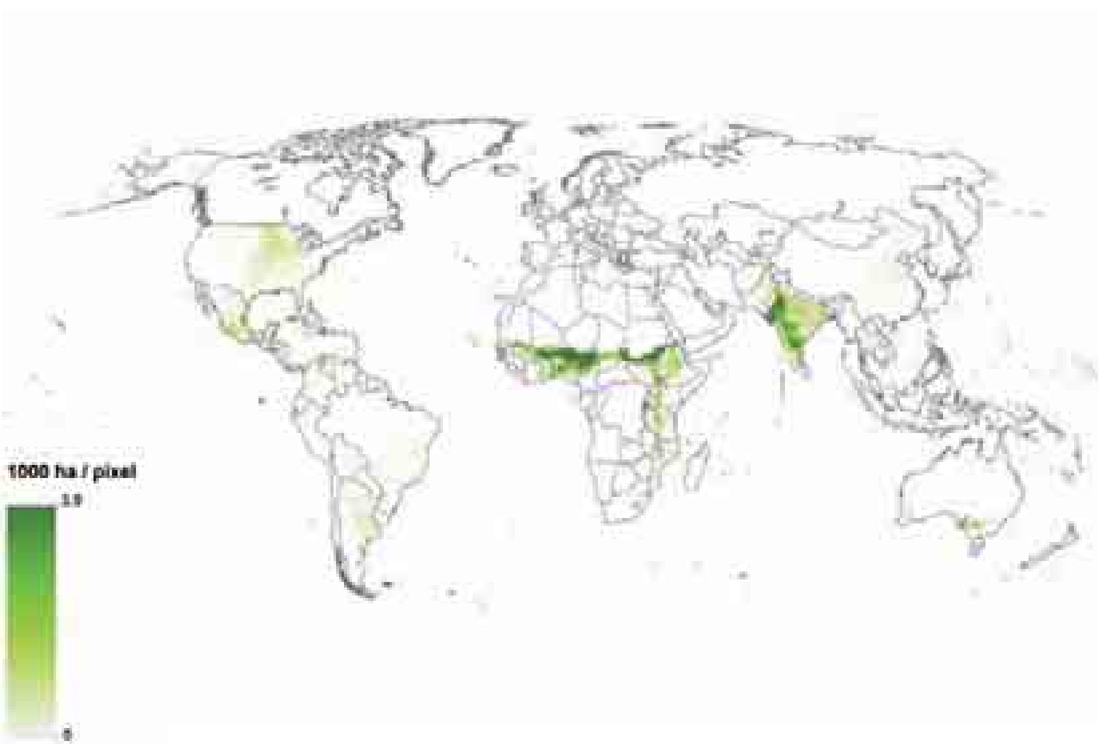


FIGURE 2 Sorghum harvested area (GAEZ, 2011).



Reference year 2000

sowing usually starts in late September and continues to October; although late sowing may take place between the end of November to the beginning of January. In Sudan and Burkina Faso, sorghum planting starts in late May and continues up to early July, but late plantings take place from late July until early August in areas of erratic rainfall in West Africa. Sorghum is normally planted from mid-October to mid-December in Southern Africa. Season length of early maturing sorghum cultivars, which include most hybrids, is 110 days or even less, whereas long season sorghum may last as long as 5 to 7 months.

In rainfed situations, plant populations may range from 50 000 to 150 000 plant/ha, with low densities in the low rainfall areas. Under irrigation or non-limiting moisture, 120 000 to 200 000 plant/ha are generally recommended. Overly high plant populations increase plant competition, increase the chances of charcoal rot, and may increase water use. The advantage of more heads per unit land area is counterbalanced by reduced head size, leading to very little increase in grain yield. On low fertility soils with low input management in some African countries, 50 000 plant/ha have been found to be optimal. As for sweet sorghum, 110 000 to 120 000 plant/ha have been found to be optimal for the rainy season in India.

Sorghum grown mixed with assorted pulse crops for domestic consumption is a traditional practice of poor dryland farmers in India and Africa. Sorghum intercropped with pigeonpea at 2:1 row ratio is a prevalent cropping system on Vertisols in India. Paired rows of sorghum intercropped with paired rows of groundnut at a 4:2 row ratio in India, and sorghum intercropping with cowpea at 2:2 row ratios in Africa, are also popular with farmers on Alfisols with short growing seasons. Post-rainy season sorghum, after rainy season fallow, is most common on Vertisols in India and Ethiopia. In China and the United States sorghum is frequently grown with irrigation after the first season soybean, or after winter wheat as a double crop.

GROWTH AND DEVELOPMENT

As a C_4 crop, sorghum does not tolerate cool temperature regimes. For seed germination, the minimum temperature is about 8 °C, and optimum temperature, 21–35 °C (*Peacock, 1982*). Under field conditions, a minimum soil temperature in the range of 15–18 °C is required for 80 percent emergence in 10-12 days. Normally in the field emergence takes 5–10 days. Panicle initiation takes place after approximately one-third of the growth cycle, after the last leaf has initiated and about one-third of total leaf area has developed. Rapid leaf development and stem elongation follow panicle initiation. Rapid growth of the panicle starts after all but the last two or three leaves emerge. By the time the flag leaf is visible, all but the final 3 to 4 leaves are fully expanded and light interception is approaching its maximum; a few lower leaves may begin to senesce if nitrogen is not plentiful or the crop is planted very densely.

The rate of leaf appearance in sorghum is closely related to thermal time. When temperature is not limiting, it takes about 2 days for each new leaf to emerge. For a cultivar with 18 leaves, in India a typical phenology and growth stages of 0 to 9 (as defined by Vanderlip and Reeves, 1972) are as follows: emergence (0); 3-leaf stage (6 days after emergence, 6 DAE/6); 5-leaf stage (16 DAE/10); panicle initiation (32 DAE/16, approximately 9 leaf stage); flag leaf appearance (50 DAE/18, tip of final leaf visible in the whorl); boot stage (head enlarges in flag leaf sheath, 60 DAE/10); 50 percent flowering (68 DAE/8, half of the plants complete pollination, from the tip downwards); soft dough stage (80 DAE/12 squeezing kernel between fingers results in little or no milk); hard dough stage (96 DAE/16 when seed cannot be compressed between fingers); and physiological maturity (106 DAE/10 black layer (spot) appearance on the hilum at the base of the seed).

Sorghum leaves are upright when young but blades tend to bend downwards with maturity. Sorghum leaves develop on either side of the stem, exactly opposite to one another. As for all crops, rate of dry matter production is strongly affected by radiation intercepted, which depends on leaf area, especially between emergence and panicle initiation. Number of leaves per plant varies widely, from 7 to 24 depending on cultivar and climatic conditions. Sorghum is a short-day plant and panicle initiation is hastened by short days and longer nights. Since panicle initiates only after all leaves have initiated, if panicle initiation and blooming is earlier, the plant would have fewer leaves. Panicle initiation can be strongly affected by temperature regimes in addition to photoperiod. There are rather complicated interactions between photoperiod and temperature regimes, as well as a dependence on the cultivar's maturity group (Morgan *et al.*, 1987). Generally within the temperature range favourable for growth, leaf number tends to decrease as temperature decreases in growth Stage I, especially when the decrease is in night temperature (Quinby *et al.*, 1973).

As for all crops, leaf area index (LAI) depends on plant density, leaf number per plant, and the stage of growth. Maximum light interception, hence full canopy cover, is reached at LAI of 4 to 5. The aim of grain sorghum is to achieve full canopy cover but avoid excessive LAI since excessive vegetative growth tends to reduce the harvest index. Fodder sorghums exceed LAI of 7 with populations of more than 150 000 plants/ha and high input management in the tropics. In short duration sorghum with reduced leaf number, maximum leaf area (and canopy cover) is achieved at 50 days or earlier after emergence under favourable temperatures. However, planting density must be substantially higher than that for long season cultivars to achieve full canopy cover because of fewer leaves per plant. Sorghum seeds are considerably smaller than those of maize, hence the initial leaf area (initial canopy size per seedling, cc_o) of sorghum seedling is smaller compared to that of maize. Sorghum develops less leaf area than maize under similar input, environment and plant density because of its smaller leaf sizes.

Sorghum head is a panicle, with spikelets in pairs. The inflorescence (panicle) is either compact or open, developed on the main stem (peduncle) with primary or secondary branches on which the florets are borne. The peduncle length varies from 75 to 500 mm in different cultivars. The floral structure is suited for self-pollination; however, approximately 6 percent cross-pollination occurs naturally with wind. Hybrid sorghum seed is produced utilizing cytoplasmic male sterility line as the female parent. Sorghum flowers begin to open and pollinate soon after the panicle has completely emerged from the boot. Pollen shedding begins at the top of the panicle and progresses downward for 6 to 9 days. Pollination happens soon after sunrise in the colder part of the day. At maturity, about 600 to 3 000 seeds have developed on the panicle, all enclosed in glumes varying in colour from black, red, brown to tan. The seed number per panicle, a key component setting yield, is determined mostly during the periods of panicle initiation and flowering.

Under seasonal average daily temperatures greater than 20 °C, early grain cultivars take 90 to 110 days and medium-duration cultivars, 110 to 140 days to mature. When mean daily temperature is below 20 °C, there is an extension of about 10 to 20 days in the growing season for each 0.5 °C decrease in temperature, depending on cultivar. At an average temperature of

15 °C, grain sorghum takes 250 to 300 days to mature. It follows that in cool climates, sorghum is grown mostly as a forage crop.

As for all cereals, the root system has two components, the seminal root system and a secondary root system that develops from nodes below and just above the soil surface. Nodal roots start appearing at the third and fourth leaf stage and branches both laterally and downwards. Roots initiated at nodes close to and above the soil (so called prop roots) develop and penetrate into the soil only when the surface soil is moist. The fully developed root system is approximately 1 m wide laterally and down to about 2 m into the soil, and can reach 3 m in very open subsoils. The maximum depth is generally approached at the time of flowering, but the roots continue to extend during the reproductive phase, at least under dryland conditions. When the soil profile is moist, most of the water is taken up from the top one-fifth of the root zone. As the soil water depletes and the upper part of the profile dries out, the uptake zone moves progressively downward. This uptake pattern repeats after each irrigation or heavy rain. Normally, when sorghum is full grown, nearly all of the water extracted is from the top 1 to 2 m of soil.

WATER USE AND PRODUCTIVITY

Rainfall of 500–800 mm well distributed over the cropping season is normally adequate for cultivars maturing in 3–4 months. Sorghum tolerates water logging and can also be grown in areas of high rainfall. The consumptive use (ET) of 110 to 130-day sorghum crops range between 450 and 750 mm, depending on evaporative demand. Seasonal water use is higher for late maturing genotypes because of longer growing periods. For rainy season sorghum in India, consumptive water productivity for biomass ($WP_{B/ET}$) ranges from 2.3 to 6.0 kg/m^3, and consumptive water productivity for grain yield ($WP_{Y/ET}$) ranges from 1.0 to 1.5 kg/m^3, in different environments. For post-rainy season sorghum in India, $WP_{Y/ET}$ ranges from 0.23 to 2.2 kg/m^3, with a mean of 1.2 kg/m^3 from several studies across many soil types and cultivars. An analysis of many years of data in Texas, the United States, yielded a mean $WP_{Y/ET}$ of 1.5 kg/m^3 (Krieg and Lascano, 1990). One study at the same location varying planting density and geometry found $WP_{B/ET}$ of dryland sorghum to be in the range of 3.0 to 3.6 kg/m^3, but $WP_{Y/ET}$ to be more variable, in the range of 0.8 to 1.3 (Steiner, 1986). Harvest index was different for different densities, accounting for the wider range of $WP_{Y/ET}$. In Nebraska, the United States, another study found $WP_{Y/ET}$ to be 1.2, 1.8, and 1.9 kg/m^3 for three different cultivars (Garrity *et al.*, 1982).

RESPONSES TO STRESSES

Sorghum is considered to be drought resistant, especially in comparison to maize. A part of the perceived resistance may be because sorghum cultivars grown in water-limited areas are the short-season type, thus their water requirement is less than that of maize, a crop generally with a longer life cycle. That said, there are real differences in drought-resistance traits. Sorghum with its tillering habit is much less determinant than maize, and therefore is more 'plastic' in reproductive development. If short water stress during the panicle initiation stage reduces the potential grain number of the main stem panicle, panicles on the tillers that are initiated later, after the stress is over, can produce more grain and make up for much of the loss. If water stress is severe enough at flowering to cause head blast (death of a portion or whole head) tillers may emerge from nodes high on the stem to form branch heads to produce grain and compensate for at least part of the loss, provided that harvest can be delayed (Hsiao *et al.*, 1976). Such compensations are not possible with modern maize cultivars having very limited tillering capacity. The flip side is that if water is ample during the vegetative period, many sorghum cultivars would tiller excessively, with a high portion of the tillers being barren, leading to high biomass produced but with a low harvest index.

Sorghum accumulates solutes and osmotically adjusts in response to developing water stress, apparently more so than maize (Fereres *et al.*, 1978). This would allow sorghum to maintain stomatal opening and carry on photosynthesis longer as the soil water depletes, and possibly also aid in delaying canopy senescence induced by water stress. In addition to stomatal closure, sorghum leaves roll noticeably under water stress, reducing the effective transpiration surface. The rolling is attributed to turgor changes in the rows of motor cells along the midrib and veins on the upper surface of the leaf. Motor cells are also present in maize leaves, but maize leaves roll only minimally under water stress. Leaf growth by expansion is highly sensitive to water stress in both sorghum and maize.

In terminal drought-prone areas such as the Mediterranean region and Australia, lodging of dryland sorghum as the crop matures is often a problem. Breeders have developed cultivars that maintain a green canopy longer at maturity, the so called 'stay-green' trait. Such cultivars apparently have better lodging resistance, presumably because less of the stalk material is remobilized and translocated to the grain at maturity. In terms of *AquaCrop* parameters, the canopy decline coefficient (CDC) would have to be adjusted to a lower value, and probably also the stress coefficient (K_s) for senescence, adjusted by making it less sensitive to water stress, for the stay-green cultivars.

Sorghum is moderately tolerant to salinity. As EC increased from 11 to 18 dS/m, grain yield was reduced from 50 percent to 100 percent. Much of the temperate effects on sorghum have already been discussed under Growth and Development. Leaf extension closely parallels air temperature to approximately 34 °C. Pollination and fruit setting may fail when night temperatures fall below 12-15 °C at flowering, and pollens produced below 10 °C and above 40 °C are most likely non-viable. Sorghum grain contains around 1.5 percent nitrogen and 0.25 percent phosphorus. For a high yield of 8 tonne, the grain alone removes 120 kg of N and 20 kg of P. To achieve this yield, fertilization must account also for the N and P in the stover residue and the efficiency of applied nutrients and native soil supply. For water-limited situations, fertilization rates would be adjusted downward. In areas prone to terminal drought, care must be taken to avoid too much N supply early in the season because the resultant fast early growth would exhaust water stored in the soil and accentuate the terminal drought damage.

IRRIGATION PRACTICE

In dry areas with low and/or erratic rainfall the crop responds well to supplemental irrigation. However, considerable differences exist among cultivars in their response to irrigation. The timing of irrigation should aim to avoid water deficits during the critical growth stages of the crop, the period that starts at panicle initiation and ends at early grain filling. Water stress during panicle initiation would reduce panicle size and potential grain number; severe stress at flowering would inhibit pollination; and stress at early grain filling would cause abortion of youngest developing grains and reduce weight per grain. Grain size is also reduced if stress occurs late during grain filling and causes early canopy senescence, with the consequence of premature ending of CO_2 assimilation. In terms of total available water (TAW) in the root zone, about two-thirds can be depleted before irrigation without significant effect on transpiration. Up to 75 percent may be depleted during the ripening phase. When water supply is limited, irrigation around booting/flowering, after moderate stress during the vegetative phase, and increasing stress during the ripening period is a deficit irrigation strategy that minimizes yield loss. For fodder sorghum, a late light irrigation maintains stalk quality at harvest. The number of irrigations normally varies between one and four, depending on climatic conditions, and soil texture. Methods of irrigation include furrow irrigation, often in alternate rows, and other surface methods (border, basin or corrugation).

YIELD

Average yield of sorghum varies widely from the high productivity country averages of 4.7 tonne/ ha in the the United States and Argentina, and 4.3 tonne/ha in China to productivity levels of 0.6 tonne/ha in Sudan, and 1.0-1.5 tonne/ha in India, Burkina Faso or Ethiopia. Modern high-yielding cultivars are bred with heads held high above the foliage for machine harvest. On small farms in developing countries, harvesting is mostly done by hand cutting the panicles placing them in sacks and taking them to the threshing floor for further drying to a moisture content of 12–13 percent. Sorghum grain can only be threshed when seed moisture is 20-25 percent or less, even though the seed is physiologically mature at higher moisture levels (around 30-35 percent). Some hybrids have a loose, open type of panicle, which hastens field drying. In India and for fodder production, sweet sorghum is harvested generally at milk-ripe stage and when sucrose content is in the range of 17 to 18 percent. Sweet sorghum yields between 35 to 45 tonne per hectare of fresh biomass and grain yields are in the range of 1-1.5 tonne/ha (Rao *et al.*, 2008). Productivity of post-rainy season sown (October-November) sweet sorghums are less than rainy-season sorghums in India (by 30-35 percent) because of short day length and low night temperature.

Average yield under irrigation is 5 to 7 tonne/ha while yield potential exceeds 12 tonne/ha, substantially less than a comparable maize crop. Average sorghum grain yields on farmers' fields in Africa are as low as 0.5–0.9 tonne/ha because sorghum is often grown in marginal areas under traditional low input practices based on landraces. Forage yields from open-pollinated and hybrid cultivars can reach 25 tonne/ha of dry matter.

Harvest index of sorghum is more variable than that of maize, mainly because of variable tillering in sorghum. Generally, reported HI of sorghum are more frequently low, between 0.3 to 0.4 (e.g. Muchow, 1989; Steiner, 1986). Higher HI (>0.5), however, have been observed and are apparently the result of vegetative (tiller) growth being inhibited by water deficit, which differ among cultivars (Hsiao *et al.*, 1976). High HI can also be deduced from the data of Garrity *et al.* 1982, Prihar and Stewart, 1991.

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Cotton

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Cotton

GENERAL DESCRIPTION

Cotton is a woody, perennial, indeterminate plant with the C_3 photosynthesis pathway grown in warm and some temperate climates for fibre, but also for its seeds high in oil and protein content. Of the four cultivated species of cotton, the dominant one in production is *Gossypium hirsutum*, also known as Upland cotton, which is managed as an annual. Long staple (Pima) cotton (*Gossypium barbadense*) is also produced, but it accounts for <10 percent of cultivation. Since 1980, overall cotton production has increased 60 percent, while the area harvested worldwide remained stable (Figure 1). In 2007, world production was 24.2 million tonne of seed and lint. Cotton is grown around the world from the tropics to latitudes as great as 42° (Uzbekistan), with major producers being China (31 percent), India (20 percent), Pakistan and the United States (each 10 percent), Uzbekistan (6 percent), Brazil (5 percent), and Turkey (3 percent) (FAO, 2011). See Figure 2 for map of harvested areas.

Successful cultivation of cotton requires a long frost-free period, plenty of sunshine and warm temperature, and moderate rainfall or irrigation, usually from 600 to 1 200 mm. Being salt and drought tolerant, cotton does well in arid and semi-arid regions. Although rainfed production is well possible, optimal and consistent yields are usually obtained with irrigation.

Cotton is frequently grown as the principal cash crop, as a monoculture that is only modified when inclement weather, such as a late hail, forces establishment of an alternative crop. The crop for this unplanned rotation is often rapid maturing and has compatible herbicide tolerances, such as short season soybeans and sunflowers. As with most monocultures, the management of diseases, insects, and weeds (as noted for dryland cropping systems, Baumhardt and Salinas-Garcia, 2006) usually becomes problematic for cotton. Inoculums of Verticillium wilt and black root rot as well as nematodes increase in the soil as the cotton host is repeatedly grown. Likewise, populations of weeds resistant or adapted to common production herbicides can develop. The problem is ameliorated by crop rotation, with non-host crops for the pathogen or with crops that are resistant to the herbicides needed to control the weed species. Crops for this purpose include maize, sorghum, alfalfa and wheat. In China, more

FIGURE 1 World cotton harvested area and average yield over the period 1961-2009 (FAO, 2011).

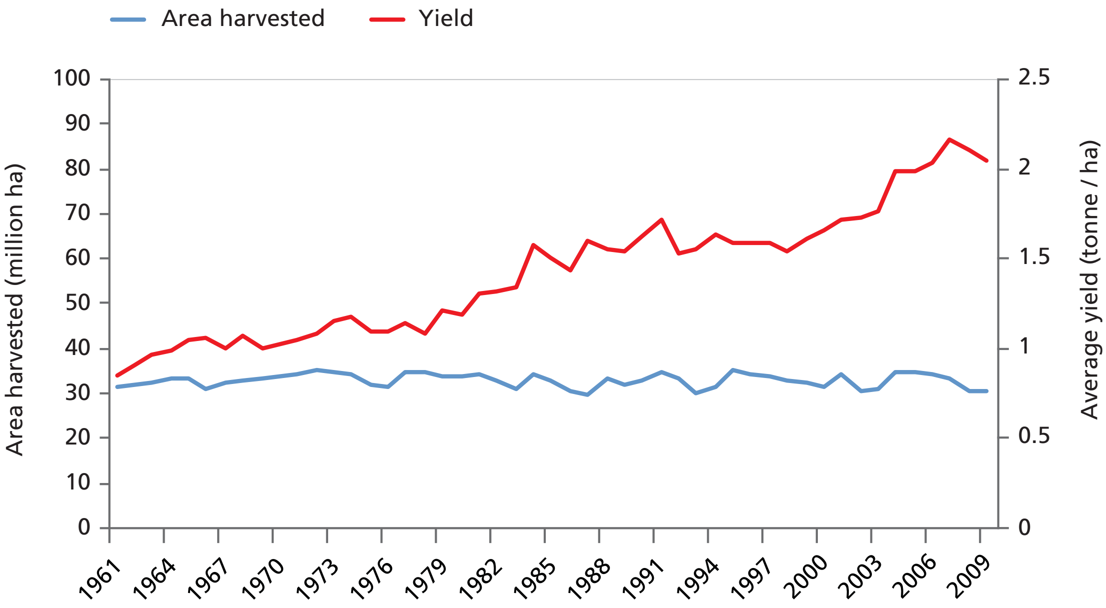
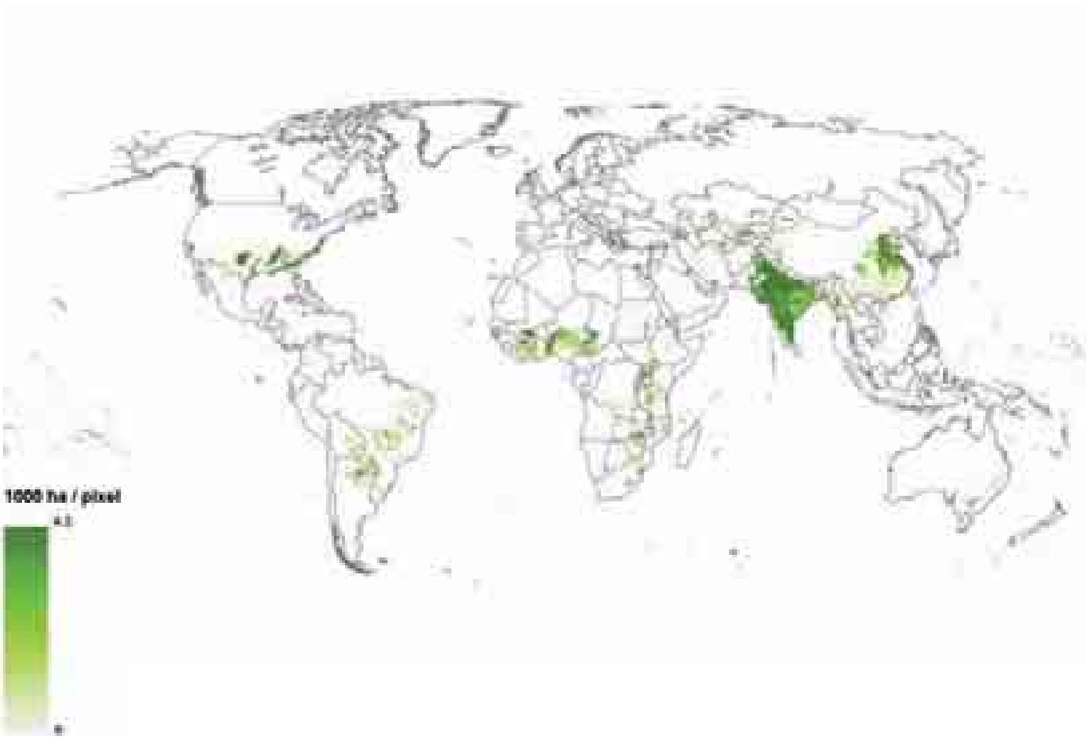


FIGURE 2 Cotton harvested area (GAEZ, 2011).



Reference year 2000

than 1.4 million ha of cotton are relay intercropped with winter wheat, cotton being sown in April during the reproductive phase of wheat in narrow strips left empty between swaths of wheat. Delayed plant development and fruit formation in this system has been tied to lower temperatures experienced by seedlings shaded by the wheat (Zhang *et al.,* 2008).

GROWTH AND DEVELOPMENT

Planting typically begins when soil temperature reaches 16 °C at 0.10 m depth in more temperate zones or 18 °C at 0.20 m depth in warmer regions. Though seeds germinate down to 12-14 °C, the optimum air temperature ranges from 31 to 33 °C, but the germination limiting temperature maximum is 40-42 °C. Emergence is optimal at 32-34 °C. Fungal diseases are prevalent when germination is delayed. Row spacing is often near 1.00 m, but spacing as narrow as 0.50 m has been used successfully. Spacing of 0.76 m is common in some areas. In several studies, narrower row spacing gave slightly higher yield because canopy cover and radiation interception were more complete early in the season. Traditionally, row width has been dictated by tillage and harvesting equipment in most cases. Plant densities vary from 6 to 20 plants/m^2. Cotton is often planted on beds because they promote drainage and soil warming. In some semi-arid locations cotton is produced in a skip-row pattern (two rows planted side by side and then one or two rows intentionally skipped or not planted).

Under optimal conditions, the number of days to emerge, develop flower buds, begin flowering, open bolls, and reach harvest may vary considerably (Table 1). For warmer climates there is greater consistency. Total growing period ranges from 150 to 180 days when soil temperature is >16 °C. Because cotton is indeterminate, crop growth stages overlap, rendering a distinction of growing stages difficult. Early vegetative growth depends on temperature, the daily maximum of which should be at least 20 °C, though 30 °C is better. First square, or flower bud formation, may occur at between 35 to 50 days after planting, depending on cultivar and temperature. Vegetative growth continues during flowering, which for common cultivars begins at 55 to 70 days after planting, and flowering continues during boll growth. Bolls begin to mature and open 100 to 120 days after planting or about 50 to 60 days after first flower. For genotypes ranging from very early to very late, time to 60 percent open bolls may range from 141 to 186 days for early planting and from 130 to 170 days for late planting (Bange and Milroy, 2004). As temperature increases, times to growth stages are shortened, but there is little change for mean temperatures >24 °C and little cultivar difference (Roussopoulos *et al.,* 1998) although development of early cultivars has complicated this picture. Days with similar mean temperatures but different amplitudes result in different growth rates[1].

Cotton plants form a strong tap-root, down to nearly 3 m on good soil. Suitable soil varies widely, but favoured soils are loamy to clayey, deep, well drained and with good water-holding capacity. On soils with hard pans, subsoiling is common to facilitate drainage and root deepening.

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[1] Meaning that plant growth models based on heat units should consider time intervals <1 day (Roussopoulos *et al.,* 1998; Ng and Loomis, 1984).

TABLE 1 Days for development stage by cropping region.

Emergence	1st square	1st flower	1st open boll	Harvest	Cropping region
5	38	59	116	140	Tifton, Georgia, USA (31.5°N)
7	45	65	110	152	South Texas, USA (Ko *et al.* 2009)
10	--	70	115	170	Khorezm, Uzbekistan (41°N), (Sommer *et al.*, 2008)
5–15	35–50	55–70	100–120	150–180	Southern Texas High Plains, USA (Gowda *et al.*, 2007)
9-12				155-181	Texas, USA (39°N) (Howell *et al.*, 2002)
			138-151		Henan, China (32-36°N) (Zhang *et al.*, 2008)
--	--	60	115	--	Egypt, Pakistan, California USA
--	--	60	115	--	Yemen

WATER USE AND PRODUCTIVITY

Water requirements vary widely depending on growing season length, climate, cultivar, irrigation method, and production goals, but may range from 700 to 1 200 mm. In regions with limited rainfall, yields increase linearly with irrigation application over the range of 600 to 900 mm, depending on the cultivar and provided the growing season is long enough to allow for complete boll and fibre development.

Cotton water use and water productivity (WP) can be affected by irrigation method and amount. In several experimental studies at different locations (Texas, California and Uzbekistan), $WP_{lint/et}$ as well as lint yield have been shown to be improved substantially (e.g., by 50 percent for $WP_{lint/ET}$) by using drip instead of furrow irrigation. Values of $WP_{lint/ET}$ ranged from 0.15 kg/m^3 to 0.33 kg/m^3. The improvement in $WP_{lint/ET}$ is most likely attributable to the enhanced yield as well as to reduced soil evaporation and transpiration. How these improvements come about are discussed in the following sections.

Water use (ET) varies from 410 to 780 mm per season depending on irrigation method (less for drip and low energy precision application (LEPA) drag socks compared with furrow irrigation) and how much deficit irrigation is applied; but the range is similar for several different climates: 410 to 720 mm and 560 to 780 mm on the United States southern high plains, 590 to 780 mm in the California Central Valley, and 430 to 740 mm in Uzbekistan (Ayars *et al.*, 1999 ; Colaizzi *et al.*, 2005; Grismer, 2002 ; Howell *et al.*, 2004; Howell *et al.*, 1987; Ibragimov *et al.*, 2007).

RESPONSE TO STRESSES

Cotton stands out among crops as one with extraordinary vegetative/reproductive growth ratio dependence on plant water status. High water status promotes vegetative growth and suppresses reproductive growth. Adequate water is essential for vegetation growth prior to and during flower bud formation. Conversely, overly abundant water supply during flowering, boll growth and fibre development will result in rapid and continued vegetative growth and the dropping of early flowers and young bolls. Alternatively, water stress at reproductive stage, if severe enough, also causes abscission of flowers and bolls. Abundant rainfall or irrigation late in the season can encourage ranky vegetative growth at the expense of boll maturation and fibre development. If water becomes limiting enough to restrict leaf growth markedly, but not yet sufficient to cause boll abscission, cotton then goes into a cutout phase. During this phase the existing bolls mature but almost no new flowers or bolls develop. After the existing bolls mature, the plant would resume producing flowers and bolls, especially if water became plentiful again. Thus, irrigation management of cotton has to strike a delicate balance at different times.

Fertilizer requirements will vary with crop yield and above ground biomass goals, which are typically greater under irrigation, and range from 100 to 180 kg N/ha, 20 to 60 kg P/ha and 50 to 80 kg K/ha. Fertilizers are typically applied at the beginning of the growing season and up to flowering. Excessive nitrogen encourages excessive vegetative growth, which may require applications of growth regulators to control (e.g. mepiquat chloride). Nitrogen application typically follows lint yield goals and is influenced by irrigation capacity and length of growing season. The N application rate ranges from 0.1 to 0.3 kg N/ ha per kg/ha cotton lint, with the lower rate applying to yield goals greater than 500 kg/ha. Phosphorus rates are typically 33 percent of N; and where needed, K is typically 75 percent of N for the first 500 kg/ha of lint yield and 33 percent thereafter. Potassium is important for achieving good fibre quality. Calcium demands are high and application of boron is necessary in some soils.

Much of the temperature effects on cotton have already been discussed in the Growth and Development section. Cotton is sensitive to temperature extremes, particularly soil temperature, with cool temperatures inhibiting fruiting and cool soil temperatures inhibiting emergence and rooting. Excessive water early in the season may cool the soil and inhibit growth as will saturated soil. It is very sensitive to frost. Variations in temperature tolerance of different processes within the cotton plant and with different cultivars, plus complicating effects of diurnal temperature oscillations and extremes, have led some studies to question whether cotton growth modelling should be based on growing degree days (Bange and Milroy, *2004*; Bradow and Davidonis, 2000; Constable, 1976; Sommer *et al.,* 2008). For instance, CO_2 assimilation varies with enzymatic activity and can decrease as leaf or canopy air temperatures exceed 35 °C.

Conversely when night temperatures exceed 21 °C, respiration rates increase markedly and during warm night substantial photosynthate is lost to respiration. Both high daytime and night-time temperature conditions limit the effectiveness of GDD for quantifying plant and boll development. The less extreme daytime temperatures and cooler nights during flowering and boll formation (which corresponds to August in the northern half of the Texas high plains and in Kansas) may explain the more rapid crop maturation in terms of GDD observed during the later growing season as compared with warmer, more southern growing regions (Alam *et al.,* 2008). Nevertheless, most tests with *AquaCrop*, using GDD, showed that the model closely simulated cotton growth and productivity. The effect of day length on flowering is temperature dependent. Flowering is curtailed in daytime temperatures <20 °C and night time temperatures <12 °C or in daytime temperatures >40 °C with night temperatures >27 °C. Soil pH of 7 to 8 is considered optimum; and tolerance to salinity is high, with yield decreases occurring at EC_e values >9 dS/m and yield approaching zero at 27 dS/m.

IRRIGATION PRACTICE

Early irrigation in temperate regions is a compromise between ensuring adequate soil water and minimizing cooling of the soil that inhibits plant growth. For this reason, pre-irrigation may be practised to fill the profile enough to provide for deep rooting between emergence and flowering, followed by a delay of irrigation before and after planting until the soil warms enough for germination, root deepening and early growth.

Because the cotton ratio of vegetative to reproductive growth is sensitive to plant water status, irrigation should meet crop demand (when growth is not limited by cool temperature) during the vegetative phase to speed up canopy development, but should be controlled at a slightly deficit level as the canopy approaches closure. As the time of harvest approaches, even more deficit may be needed to promote cutout, especially when the life cycle of the cultivar is substantially longer than the season of favourable temperature. Plant water status affects the interaction between vegetative and reproductive growth in this indeterminate species such that the growing season is prolonged or shortened depending on rain and irrigation management.

Cotton is grown using practically all irrigation methods. Furrow irrigation is extensively used around the world, but in some regions this method is being replaced by centre pivot (75 percent of irrigated area in the Texas Panhandle) and drip irrigation. Systems that avoid wetting the entire soil surface can result in warmer seed beds early in the season and better early root development and plant growth (Colaizzi *et al.,* 2006*;* Alam *et al.,* 2008). Such systems include subsurface drip irrigation and low energy precision application (LEPA) drag socks on moving irrigation systems when water is applied to between every other row. Scheduling for full irrigation can follow general guidelines, but deficit irrigation will require adjustments for local conditions (Howell *et al.,* 2004*;* Hunsaker, 1999; Hunsaker *et al.,* 2005).

YIELD

Cotton yield consists of lint plus seeds, with lint being typically 37-39 percent. The oil content of cotton seed is approximately 18 percent by weight, but perhaps only 16 percent is recoverable. Cotton seed oil is widely used for cooking after refining to remove gossypol. Cotton seed meal, the end product after oil has been pressed out, contains approximately 40 percent protein, which makes it a valuable animal feed or organic fertilizer.

Typically, harvest takes place even though immature bolls are still on the plant. Harvesting by mechanized cotton pickers is typically done once, sometimes twice. Where harvesting is done manually, two to four harvests or more may occur over a six-week period. Lint yield ranges from 0.65 to 1.3 tonne/ha for surface and sprinkler irrigation, and from 0.9 to 1.6 tonne/ha for drip irrigation in the United States southern high plains, depending on irrigation level, versus an average of 1.3 tonne/ha for Upland and 1.1 tonne/ha for Pima in the Central Valley of California. This contrasts with lint yields ranging from 1 to 1.7 tonne/ha in sub-humid Alabama where irrigation is supplemental (Balkcom *et al.*, 2006). Excessive irrigation (> 700 mm or total of irrigation + precipitation > 900 mm) causes yield declines. Narrow row (< 0.76 m row width) cotton may increase yields by 10 to 30 percent in many environments. Yield levels in other cotton production regions of the world range from 0.5 to 1.9 tonne/ha. The impact of irrigation and water regimes on yield can be caused at least in part by changes in harvest index which is increased (up to 0.46, for yield of lint plus seed, (Garcia-Vila *et al.*, 2009) by water deficit sufficient to inhibit vegetative growth but not enough to suppress substantially photosynthesis per canopy area. Alternatively, yield is reduced by high plant water status stimulating rank growth and biomass production (down to HI=0.35 with biomass >12 tonne/ha). If water deficit restricts vegetative growth and canopy development from very early on, canopy would be too sparse and would capture less of the incident solar radiation for growth and production. In that case, biomass production could be reduced sufficiently to result in less yield in spite of a high HI. *AquaCrop* has been constructed to account for these rather nuanced effects of water status on HI and yield.

The cases of highest $WP_{lint/ET}$ under drip irrigation, mentioned earlier, are likely the combined effects of reduced soil evaporation and a more controlled deficit. Surface irrigation, generally with a minimum of 30 to 40 mm applied periodically, provides enough water for good vegetative growth at least for a few days, whereas drip irrigation can be managed to keep the plant within a more controlled range of mild water deficit.

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Sunflower

Sunflower

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GENERAL DESCRIPTION

Sunflower (*Helianthus annuus L.*) is an annual plant that originated in Central and North America and is now widely grown throughout the world. Among oil crops, sunflower is the fifth most cultivated annual crop with 23.7 million ha in 2009, after soybean, rapeseed, cotton and groundnuts (*FAO, 2011*). The sunflower area greatly increased after the introduction of hybrids in the early 1970s, and since then average yield increased moderately (Figure 1). World production of sunflower oil (13 million tonne) represents around 9 percent of total world oil production, ranking fourth after palm (30 percent), soybean (26 percent), and rapeseed (15 percent) oil.

Sunflower is grown in arid and semi-arid climates under irrigation or rainfed, and in temperate zones under rainfed conditions. The main producing countries are the Russian Federation, Ukraine, Argentina, China, France, the United States, and Hungary, in that order (see Figure 2 for harvested areas). Growing sunflower in rotation with other crops is very important for the sustainability of the cropping system. In fact, sunflower fits in well as a scavenger crop following shallow-rooted crops, as its deep root system can recover some of the nitrogen applied to the previous crop that has been leached to below its root zone. Residual water left in the subsoil by previous crops can also be exploited by sunflower (Fereres *et al.*, 1993). In addition, its shorter growing season, compared to many other summer crops makes it an attractive option for double cropping. Because of its high water extraction capacity, sunflower can be important in rotations at locations with high probabilities of annual replenishment of soil water at depth. Sunflower is usually grown in 3-4 year rotations (reducing the likelihood of disease) with cereals (e.g. wheat, maize, sorghum), soybean, and beans.

GROWTH AND DEVELOPMENT

Even though sunflower was originally a summer crop, it can be sown over a wide time period (once soils have warmed to 7-9 °C) because of its fast growth at relatively low temperatures; efficient photosynthetic radiation capture by sun tracking; and the early maturity of most cultivars. In temperate regions with mild winters, highest yields and oil percentages are obtained by sowing quite early, before spring arrives (Gimeno *et al.*, 1989). Normal sowing dates in colder environments range from early to late

FIGURE 1 World sunflower harvested area and average yield over the period 1961-2009 (FAO, 2011).

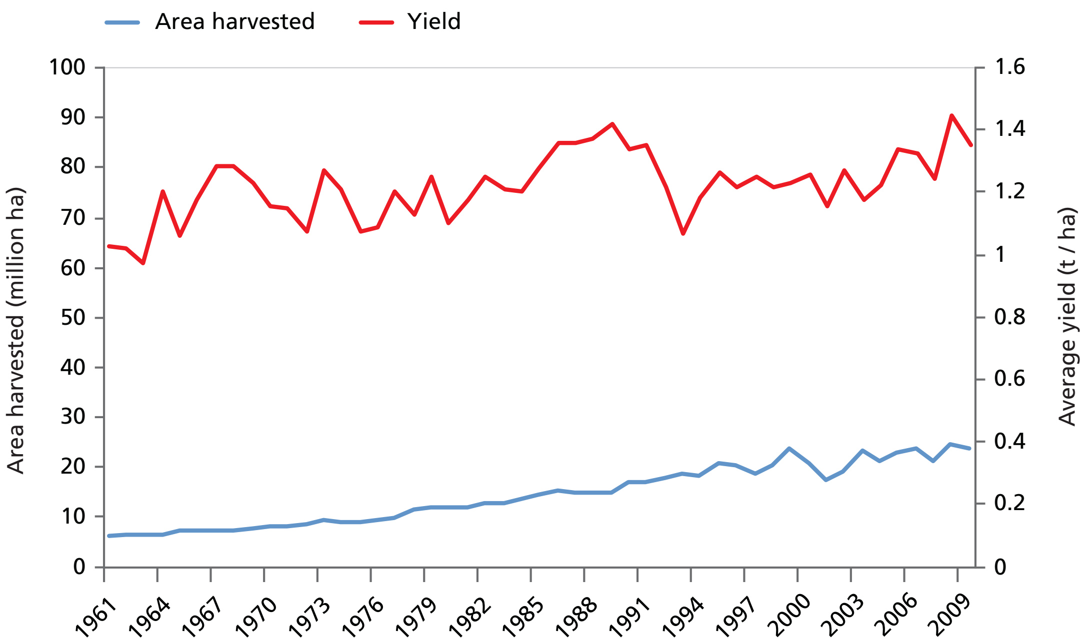
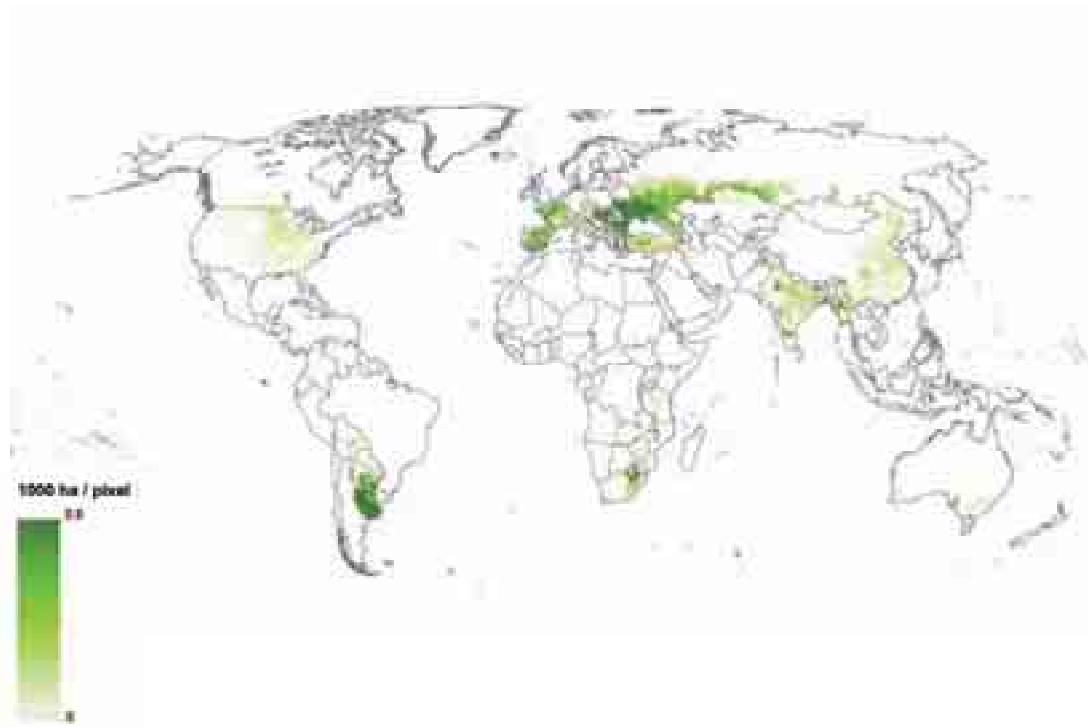


FIGURE 2 Sunflower harvested area (GAEZ, 2011).



Reference year 2000

spring. In double cropping, sowing as soon as possible after harvesting the first crop is always desirable to minimize risks (cold, rains) at the end of the season. With early plantings, more of the growing takes place under low evaporative demand, so water productivity is higher, and high summer temperatures during grain filling are avoided. However, the risk of losing the plant stand increases as planting date is advanced because of cold or frost damage to seedlings, which are quite sensitive up to the sixth-leaf stage (Villalobos and Ritchie, 1992). The cardinal temperatures for crop development are: basal temperature = 4 °C; optimum temperature = 28 °C, and maximum temperature = 40 °C. The tentative setting of T_{upper} for the calculation of growing degree day (GDD) in *AquaCrop* for sunflower is 30 °C, i.e. GDD does not increase further when temperature rises above 30 °C.

Direct sowing is normally practised with a recommended seeding depth of around 5 cm. Plant density depends on rainfall, cultivars, water availability and fertility management. Sunflower is a crop having high plasticity giving similar yields over a wide-range of plant populations. Row spacing for water-limited plantings is customarily wider than under ample water supply (75 -100 cm vs. 50-75 cm). Plant densities between 45 000 and 60 000 plant/ha are common under rainfed conditions, while up to 80 000-100 000 plant/ha can be planted with irrigation. In disease-prone areas, planting densities are in the low range (50 000 to 70 000 plant/ha) even with ample water and nitrogen availability to reduce the incidence of disease and lodging risks. Given the plant's high capacity to intercept radiation, yields are relatively insensitive to variations in plant density provided near full cover is achieved at maximum canopy cover, and similar grain yields are obtained over wide variations in plant spacing above 50 000 plant/ha.

The duration from sowing to emergence varies between 7 and 30 days. Sunflower requires around 4 to 5 days to emerge when shallowly planted in warm soil, while it will take a number of days more in cooler soils or when planted deeper. Minimum temperature for germination can be as low as 3 °C, although it may go up to 5 to 10 °C depending on the various field conditions. The maximum germination percentage is maintained from 6 to 23 °C, declining rapidly above 25 °C (Connor and Sadras, 1992). Seedlings in the cotyledon stage can survive temperatures down to -5 °C. Failure of emergence may result in suboptimal plant populations.

Sunflower grows rapidly, producing large and rough leaves. Leaf appearance rate is affected by temperature and photoperiod (Rawson *et al.*, 1984). Temperature affects the growth pattern and final area of individual leaves, along the cardinal temperatures described above. Thermal time per leaf is between 20 and 25 °C day, calculated with a base temperature of 4 °C (Villalobos and Ritchie, 1992). Maximum canopy cover under standard densities is high, between 90 and 98 percent, and is reached quite quickly. This is because the light extinction coefficient of sunflower canopies is quite high and a leaf area index (LAI) of 2 is sufficient to intercept more than 90 percent of the incoming radiation, while a maize canopy with an LAI of 2 only intercepts around 70 percent of the radiation. Possibly, as the results of canopy growth coefficient (CGC) of sunflower, a C_3 species, is considerably higher than that of most other C_3 crops, about the same as for maize, a C_4 species. Under near optimal temperatures, sunflower maximum canopy cover is reached between 40 and 50 days after planting. For early plantings in cool climates, 60 to 70 days must pass before maximum canopy cover is reached.

Floral initiation occurs early in the growth cycle, 25 to 25 days after sowing, and its timing is predominantly controlled by thermal time and photoperiod. The response of sunflower genotypes to photoperiod is variable, exhibiting a long-day response for floral initiation in most sunflower genotypes. Water and N supply are secondary factors in determining the timing of floral initiation. Cultivar differences for maturity date are usually associated with changes in the length of the vegetative period before the head becomes visible, and longer periods usually are associated with higher leaf numbers per plant. Therefore, the length of the vegetative period depends on the cultivar, temperature and photoperiod (Rawson *et al.*, 1984). As the head enlarges and the two or three leaves subtending the head approach their final size, anthesis begins and lasts 8 to 12 days. The number of grains per head are determined in a period lasting 30 to 40 days centred around anthesis. Post-anthesis effect on grain number is mostly the result of abortion of the youngest developing grains, apparently as determined by the amount of available assimilate to fill them. Canopy senescence starts with the oldest leaves soon after anthesis, but the upper part of the canopy stays green until a couple of weeks before physiological maturity.

Sunflower has a deep and aggressive root system and, as already mentioned, is capable of fully depleting the water present in subsoil layers (Bremner *et al.*, 1986; Sadras *et al.*, 1989). Rooting depth is one of the highest among annual crops, with some studies reporting a rooting depth beyond 3 m in easily penetrable soils. Rooting depth depends on life cycle length of the cultivar; long-season cultivars may reach 3 m while the root system of short-season cultivars in the same soil would not extend beyond 2.3 m (Gimenez and Fereres, 1986). The rate of root deepening of the sunflower is also very high, averaging 3.5 cm/day in the above-mentioned study. In the very open soils of the experimental farm at University of California, Davis, apparent deepening rates of sunflower of about 4.5 cm/day have been observed in a field where maize and sorghum root systems deepened at about 3 cm/day (Berengena, 1976, unpublished).

WATER USE AND PRODUCTIVITY

The combination of season length and different climate generates a wide range of consumptive water use (ET) by sunflower. ET for short-season cultivars may be less than 450 mm, while for long-season cultivars it may exceed 800 mm in some situations (Gimenez and Fereres, 1986). Typical values between 500 and 650 mm are normally found. For a C_3 species sunflower has a high photosynthetic rate, and its efficiency in the use of transpired water for biomass production ($WP_{B/ET}$) is between 2.5 and 3.5 kg/m^3 (25 to 35 kg/ha per mm). $WP_{B/ET}$ decreases after anthesis because of the high energy requirements for the biosynthesis of sunflower seeds high in oil content (Villalobos *et al.*, 1996; Steduto *et al.*, 2007).

RESPONSES TO STRESSES

Sunflower is often reported as a drought-tolerant crop given its high capacity to extract water from the subsoil. Water deficits have differential effects on leaf expansion and stomatal conductance, and hence on transpiration of sunflower genotypes (Connor and Jones, 1985; Connor *et al.*, 1985). No impact has been observed on leaf expansion until the fraction of total available water (TAW) in the root zone declined below 0.85, but it has to decline below 0.4 to induce stomatal closure. The threshold for leaf expansion rate depends on the evaporative demand (Sadras *et al.*, 1993). Prior to anthesis, transpiration is largely dependent on canopy size as affected by soil water deficit, and stomatal control plays a minor role. After anthesis, the leaves are fully grown and consequently the control of transpiration is more dependent upon stomatal closure and the extent of canopy senescence. Periods of water deficit at any growth stage can cause canopy senescence with subsequent reduction in seed yield. There is genetic variability in the response of sunflower genotypes to water deficits. Long-season genotypes have greater canopy cover and produce more biomass under drought conditions, because of their ability to extract more water from the subsoil (Gimenez and Fereres, 1986). Also, it has been observed that sunflower cultivars adapted to an arid climate are less sensitive to water stress than the cultivars developed for humid climates.

Under water stress, the time between planting and flowering remains relatively constant, and inflorescence initiation is also relatively insensitive to water stress. Subsequent development of the inflorescence is, however, affected by water deficits and water stress reduces the number of flowers. The entire flowering period is thus the most sensitive to water deficits as the number of seeds may be negatively affected. Seed filling following flowering is the next most sensitive period to water deficits that reduce both seed weight, seed number (because of abortion) and oil content. Therefore, the reproductive stages (flowering and ripening stages) are more sensitive to water stress than the vegetative stages. Maintenance of green leaf area and photosynthesis after anthesis is key, as seed weight and oil content are mostly influenced by intercepted radiation and carbon assimilation during seed filling. During this phase, both stomatal closure and leaf senescence play a role in the control of plant water status. On the other hand, there is the associated cost of reduced CO_2 assimilation. The contribution that carbon fixed before anthesis makes to grain-filling of sunflower may be important under water stress after anthesis. Nevertheless, the harvest index of sunflower is often negatively affected by water deficits during the reproductive phase.

Genotypes having a gradual response to water stress may be most suited to environments with severe water deficits. In environments with short, frequent and moderate soil water deficits alternating with well-watered periods, maintaining organ expansion and biomass production would result in better agronomic performance. Several studies of sunflower have demonstrated that there is a close relationship between canopy size at flowering and crop seed yield. The plasticity of the crop, in terms of adapting leaf area development to water availability, is well known.

Sunflower is moderately tolerant to salinity, being unaffected by soil salinity up to 4.8 dS/m. It is currently cultivated in dry areas where salinity can be a threat. Thus, it could be adapted to salt-affected soils, provided irrigation management is adequate and salt leaching is practised. In all cases, leaching is important to limit salt accumulation in the root zone, avoiding the reduction of seed and oil yield under salt stress. It would be feasible to use moderately saline water to irrigate sunflower. Nevertheless it is necessary to maintain high soil water content in the root zone all the time, and to minimize salinity built up by leaching.

The nutrient content extracted by a sunflower crop producing around 1 tonne of seed yield per hectare includes around: 50 kg/ha of N, 15 kg/ha of P_2O_5, and 35 kg/ha of K_2O. Fertilizer application depends on the expected yields and the residual nutrients, varying from 20 to 140 kg/ha of N, 15 to 70 kg/ha of P_2O_5, and 15 to 150 kg/ha of K_2O.

IRRIGATION PRACTICE

Sunflower is grown without irrigation in many areas around the world. In subhumid and semiarid regions with limited precipitation, however, irrigation is practised. The ideal schedule under full irrigation must ensure the quick development of a canopy, avoid water deficits at anthesis, and maintain a green canopy throughout the seed-filling period all the way to maturity, thus fully exploiting the genetic potential of the cultivar. This would be achieved by refilling the root zone before damaging water deficits develop at any stage. However, the irrigation schedule should take into account the capacity of this crop to extract subsoil water by conserving irrigation water near the end of the season. Furrow and sprinkler are the most common water application methods for sunflower.

Deficit irrigation is frequently practised. In areas having winter rainfall, the best strategy is to develop the canopy based on stored soil water at planting and concentrate irrigation applications during flowering and seed filling. During these two periods, the ideal schedule should avoid stomatal closure and the hastening of canopy senescence, while the root zone should be fully depleted of soil water at maturity. In situations where water resources are very limited, the best choice for deficit irrigation is to concentrate the irrigation water around flowering and early seed filling. It has been shown that when vegetative growth is manipulated by delayed irrigation, which conserves water for the flowering and seed-filling period, the harvest index can be increased relative to full irrigation regimes.

YIELD

Sunflower yields vary between less than 0.5 tonne/ha in rainfed production on shallow soils or in low rainfall areas to over 5 tonne/ha under ample water and nitrogen supply. Typically, rainfed production between 1.5 to 2.0 tonne/ha is achieved in semiarid areas, reaching 3-3.5 tonne/ha in subhumid areas of good soils. When short season cultivars are grown as a double crop under irrigation, yields of around 3 tonne/ha are obtained. Maximum yields of a single crop under irrigation are around 5-5.5 tonne/ha. Sunflower seeds contain a very high percentage of oil (around 50 percent) and between 15 and 17 percent of protein. Consequently, the harvest index of sunflower (computed on a dry matter basis) is relatively low, from less than 0.3 in long-season cultivars up to 0.4 in short-season hybrids. Sunflower oil is accepted as high quality oil and is in high demand, not only for human consumption, but also for the chemical and cosmetic industries. The oil contains two main unsaturated fatty acids (oleic acid and linoleic acid) and saturated fatty acids (palmitic and stearic). High quality of sunflower oil is associated with higher oleic acid content. Oil concentration is increased when adequate irrigation is provided, especially in the grain-filling stage. However, irrigation does not increase significantly the amount of oleic and linoleic acids. Direct effects of water deficits on oil content of the seed are less than those on seed yield.

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Sugarcane

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Sugarcane

GENERAL DESCRIPTION

Sugarcane is a C_4 carbon-fixing perennial, and commercial cultivars are complex hybrids (spp.) derived from various *Saccharum* species native to Southeast Asia. It is grown in 100 countries (17 countries produced more than 10 million tonne of fresh cane stalks in 2008) in tropical and subtropical regions of the world. The total production of fresh stalks in 2009 was 1 661 million tonne from 24 million ha (Figure 1), resulting in a global average yield of 69.8 tonne of cane/ha per year (FAO, 2011). Brazil produced the most sugarcane (671 million tonne) followed by India (285 million tonne), China (116 million tonne), Thailand (66 million tonne) and Pakistan (50 million tonne). The world harvested areas are shown in Figure 2. Yields vary from region-to-region depending on climatic potential, management level, cropping cycle and whether cane production is irrigated or rainfed. The highest national average yield of countries producing more than 10 million tonne of cane is Egypt with 121 tonne/ha (FAO, 2011). There is a long-term trend of increasing global average cane yield of about 4 tonne/ha per year.

Sugarcane is mostly grown as a monoculture and propagated vegetatively. A crop established by planting cuttings of live cane stalks, is called a plant crop (or plant-cane crop). After the first harvest of the mature stalks, another crop, a ratoon crop, is regenerated from the plant stubbles. Depending on soil and crop health, three to seven ratoon crops can be obtained from one plant crop. Row spacing varies from 1.0 to 2.0 m depending on climate, irrigation practices and mechanization requirements. Rows can be configured as single, evenly spaced rows or as tram lines (double rows spaced around 60 cm apart with tram line centres spaced at intervals of 1.8 or 2.0 m. Burned or green cane is harvested by hand or by machines. Fallow crops are sometimes planted before cane is replanted for a new cycle. The time from crop start to harvest varies from 9 months in areas with limited growing period because of freezing temperatures (e.g. United States) to 12 months (warm climates) and 24 months (cool climate with little or no frost). In irrigated production the normal crop cycle is 12 months.

A sugarcane stalk, after being topped (green immature top of the stalk and green leaves removed) and stripped of dead leaves, typically consists of about 70 percent water, 15 percent fibre, 13 percent sucrose and 2 percent of hexose sugars and other impurities. Sucrose is the main product extracted from sugarcane juice and is used to manufacture sugar. Sugarcane is also used

FIGURE 1 World sugarcane harvested area and average fresh stalk yield over the period 1961-2009 (FAO, 2011).

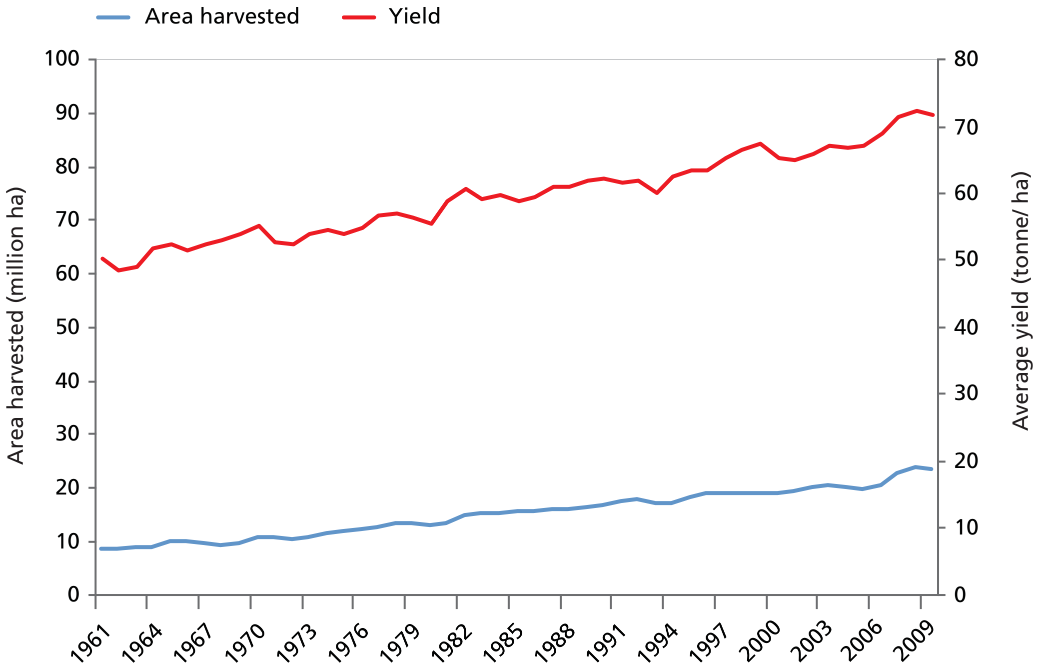
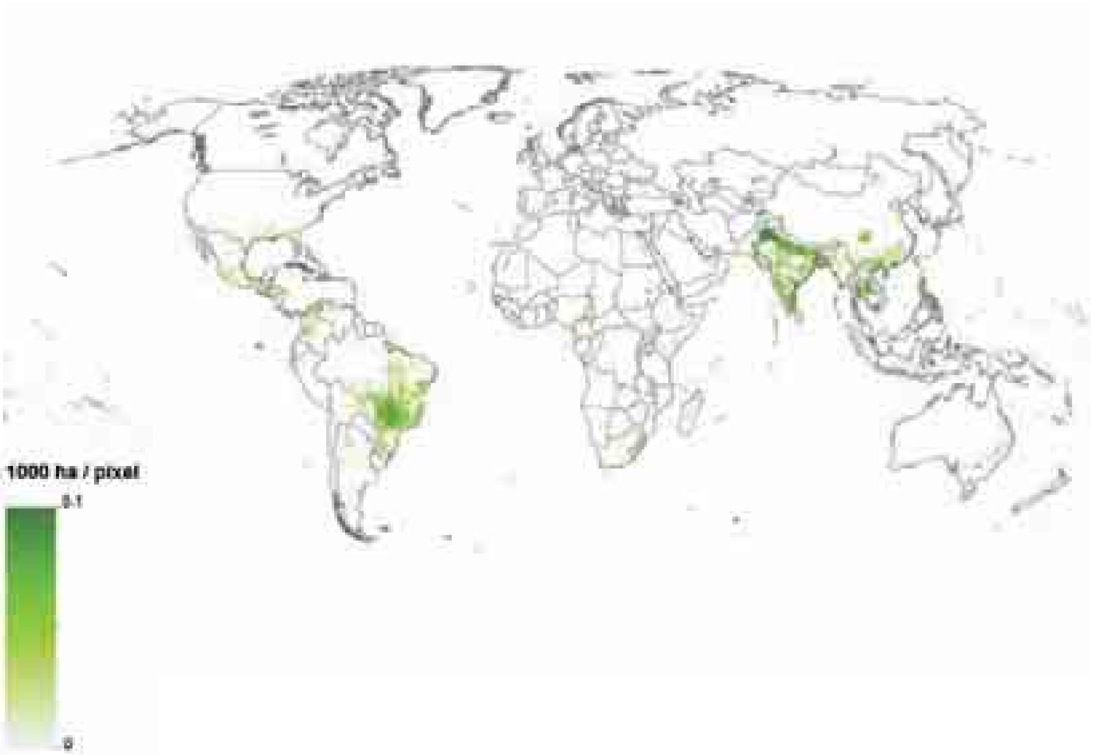


FIGURE 2 Sugarcane harvested area (GAEZ, 2011).



Reference year 2000

to produce energy (electricity from burning stalk fibre and ethanol from fermenting sugars) on a large scale in several countries and this is gaining momentum because it is a renewable source. In Brazil about 40 percent of the cane is used to produce alcohol as auto fuel.

GROWTH AND DEVELOPMENT

The stalk cuttings to establish a plant crop are termed setts and are several internodes long. One primary shoot and many sett roots are produced from each viable node of the sett. These are later followed by roots that grow rapidly (up to 22 mm/day) from shoot nodes and enables deep (up to 4.7 m) exploration of soil profiles (Carr and Knox, 2011). The rate of bud sprouting and primary shoot emergence depends on planting depth, temperature and soil water status (van Dillewijn, 1952). The number of shoots that emerge and the subsequent rate of tillering, depends on the amount of viable buds that were planted (typically 10 to 30 buds/m^2) and row configuration. Sugarcane tillers profusely from the time shortly after primary shoot emergence to canopy closure. At canopy closure, peak tiller population (up to 40/m^2) is reached and the youngest tillers start to senesce, leaving between 4 to 18 tillers/m^2 to develop into stalks that elongate, thicken and accumulate sucrose (Singels *et al.*, 2005; Bell and Garside, 2005). Unless flowering is initiated, stalks will continue to grow and add nodes and internodes as long as water and nutrients are available and temperature is not limiting. Leaves will appear on each new node, expand and senesce at given GGD intervals (Inman-Bamber 1994b).

TABLE 1 Range in duration of different development stages (in calendar days).

Development stage	Plant crop		Ratoon crop	
	Tropical [1]	Subtropical [1]	Tropical	Subtropical
Planting/ratooning to emergence	21-40	28-70	5-10	7 - 21
Planting/ratooning to start of yield formation (coincides roughly with achieving maximum canopy)	110-130	135-175	85-105	105-145
Planting/ratooning to start of maturation [2]	335-395	335-700	335-395	335-700
Planting/ratooning to harvest [3]	365-425	365-730	365-425	365-730
Building harvest index	225-275	200-544	250-300	230-585

[1] Assumed annual range in daily mean temperature: Tropical – 20-28 °C; Subtropical 17 -26 °C
[2] Assumed 30 days before harvest
[3] Harvest at 12 to 14 months in tropical areas, 12 to 24 months in subtropical areas

The stalk is composed of an immature, rapidly growing section at the top with a low sucrose content (top 8 internodes) and a mature, slower growing section with high sucrose content at the bottom. As the stalks become longer (up to 3 m) and older (8 months and older) the mature section forms a large portion of the stalk making it suitable for harvest. The maturation process can be enhanced by withholding irrigation to induce a mild water deficit (Smith and Inman-Bamber, 2005) or by applying chemical ripeners.

Flowering is initiated when minimum temperature exceeds 18 °C and water status is favourable during a 3-week window period of declining photoperiod at about 12.5 hours (Bull and Glasziou, 1976). When a stalk has initiated a flower, it will cease initiating new leaves and internodes and the stalk will mature and, if left long enough, produce side shoots resulting in inferior cane quality. Cultivars differ hugely in their propensity to flower.

The duration of the different development stages are shown in Table 1. With its tropical origin, sugarcane is intolerant to cold temperature. Studies of various growth and related processes of sugarcane have pegged the base temperature in a range of 8 to 18 °C, and the optimum temperature in the range of 30 to 35 °C (Ebrahim *et al.*, 1998; van Dillewijn, 1952; Inman-Bamber, 1994). At the time of this publication, the T_{base} and T_{upper} are set at 9 °C and 32 °C in the preliminary calibration of *AquaCrop* for sugarcane, and may be adjusted slightly as more data become available for calibration and testing.

WATER USE AND IRRIGATION PRACTICES

Although sugarcane develops a canopy relatively slowly (especially for a C_4 species), evapotranspiration of a fully canopied crop is a little higher than that from short grass (Inman-Bamber and McGlinchey, 2003). Depending on climate, peak evapotranspiration rates ranges from 6 to 15 mm/day (Thompson, 1976), and annual ET is between 800 and 2 000 mm of water. At least 850 mm of water per year is required for sustainable rainfed production. For commercial production, full irrigation is practised when annual rainfall is less than 800 mm and supplemental irrigation is applied when annual rainfall is less than 1 000 mm. Irrigation is applied using furrow, sprinkler (portable and centre pivot) and drip systems and scheduled according to soil water status as determined by (1) direct measurements of soil water potential (threshold -40 to -80 kPa) or soil water content (threshold 50 percent of available capacity) or by (2) profit and loss method using weather data (Carr and Knox, 2011). The latter involves estimates of reference evapotranspiration determined from United States Department of Agriculture (USDA) Class A-pan evaporation, evaporation mini-pans or weather data and crop canopy cover (crop factor). Profit and loss methods include simple calculations or complex methods using simulation models.

Adequate irrigation is important during crop establishment and during the stalk growth phase. Irrigations could be reduced during the tiller and maturation phases without significant yield losses (Carr and Knox, 2011). In fact, controlled water deficit during the dry out period near harvest increases sugar content per unit dry stalk biomass and can enhance sugar yield.

RESPONSE TO STRESS

Low temperature

Sugarcane is sensitive to low temperatures. A substantial amount of work has been done to assess the minimum temperature required in the field for various developmental and growth processes. Depending on the process and the particular study, the minimum temperature required was found in the range of 9 °C to 19 °C (Inman-Bamber 1994; Lingle, 1999). Nonetheless, as mentioned, the base temperature for *AquaCrop* is tentatively set at 9 °C at the time of this publication. Frost damage occurs on actively growing parts when they are exposed to freezing temperatures, resulting in the death of the growing points and a subsequent drop in cane quality due to side shooting. In severe cases the entire stalk may die.

Water

Sugarcane can tolerate some drought. Elongation of leaves and stalk are much more sensitive than photosynthesis to water stress. Stalk height and its increase has been used as an indicator of irrigation needs in management. Although growth and cane yield are reduced generally when available soil-water content (TAW) drops below 50 percent, during the maturation phase, periods of mild water deficit (TAW between 80 and 50 percent) actually enhanced sucrose accumulation and sucrose yields (Inman-Bamber *et al.*, 2002; Smith and Inman-Bamber, 2005), by restricting leaf and stalk fibre growth and storing the assimilates as sucrose in the stalk. Largely grown in tropical and subtropical climates with substantial rainfall, sugarcane appears to be exceptionally resistant to waterlogging, withstanding periods of up to 14 days of shallow standing water or saturated soil in a Florida study (Glaz and Morris, 2010).

Fertility

Sugarcane requires appreciable quantities of fertilizer because of its high biomass production. As for other crops, nutrient uptake rates are most rapid during the early phase (tillering and stalk elongation) when biomass accumulation rates are high (Golden and Ricaud, 1963). Sugarcane can grow in a wide range of soils but prefers deep, well-drained soils with an optimum pH of between 6 and 7.5. A sugarcane crop producing 100 tonne of fresh stalks can remove 120-200 kg nitrogen/ha, 20-40 kg phosphorus/ha and 150-300 kg potassium/ha. High levels of nitrogen are undesirable during the maturation phase as nitrogen promotes vegetative growth at the expense of sucrose accumulation.

Salinity

Sugarcane is moderately sensitive to salinity and sensitive to sodicity (Nelson and Ham, 2000). High salinity can induce water stress and symptoms include wilting, scorching of leaves and restricted growth. Soil salinity, measured as saturated paste electrical conductivity, of less than 20 dS/m have little or no effect on crop growth, cane yields decrease between 30-40 dS/m, with 40 dS/m representing the economic production threshold (Rozeff, 1995).

YIELD AND HARVEST INDEX

Commercial yields vary hugely. Under favourable climatic conditions (7 300 MJ/m^2 of radiation over the life cycle, 4 000 GDD using a base temperature of 10 °C) and adequate water supply (1 800 mm net) experimental yield of 200 tonne/ha fresh cane (24 tonne sucrose/ha) per year can be achieved (derived from Inman-Bamber, 1995). Actual commercial yields under irrigation vary from 80 to 150 tonne/ha fresh cane (10 to 17 tonne sucrose/ha) (Waclawovsky *et al*., 2010). Worldwide a yield of 120 tonne/ha (14 tonne sucrose/ha) is considered a good yield under full irrigation. Rainfed cane yields vary from 30 to 90 tonne/ha of fresh cane per year depending on soil and climatic conditions, with a yield of 60 tonne/ha considered as good. Water productivity in terms of above ground biomass and evapotranspiration ($WP_{B/ET}$) ranges from 3.5 to 5.5 kg/m^3, and, in terms of sucrose and evapotranspiration ($WP_{sucrose/ET}$), from 1.3 to 2.2 kg/m^3 (derived from Thompson, 1976; Olivier and Singels, 2003; Carr and Knox, 2011).

The sucrose content of fresh stalk varies in extremes from 5 to 16 percent and from 20 percent to 58 percent on a dry mass basis, depending on genotype, crop age and growth conditions (temperature and water status) during the last four weeks preceding harvest. Typical stalk sucrose content at harvest is around 12.5 percent on a fresh mass basis and around 50 percent on a dry mass basis. Expressed as sucrose mass per unit of aboveground biomass the harvest index varies around 35 percent (derived from Thompson *et al*., 1976; Inman-Bamber *et al*., 2002; Carr and Knox, 2011)

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Potato

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Potato

GENERAL DESCRIPTION

Potato (*Solanum tuberosum*) is a starchy tuberous crop that originated in the Andes, and the two subspecies of the cultivated potato, *S. tuberosum tuberosum* and *S. tuberosum andigena*, account for nearly all of the world's production. Potato ranks as the fourth largest food crop in the world, following rice, wheat, and maize, with a production of 329 million tonne on 18.6 million ha (FAO, 2011) (Figure 1). The largest potato production continents are Asia and Europe with 44 percent and 37 percent of the world's production, respectively. China, India, the Russian Federation, Ukraine and the United States are the largest producers. Rapid expansion of potato production over the past 20 years has occurred in developing countries, particularly in Africa and Asia where production has more than doubled. Potato remains an essential crop in developed countries where per capita production is still the highest in the world (Figure 2).

Potato is particularly suited to a cool climate. It is widely cultivated in the temperate, subtropical, and cool tropical regions where it is grown as a monoculture, in crop rotation, or in multiple cropping. Rotation with other crops is often necessary to ameliorate problems of disease and other pests. In temperate regions, cold temperature and a short frost-free period limit potato production to once a year as a monoculture, or in a three or more year crop rotation with maize, soybean, sorghum, or sugar beet in areas with high rainfall or irrigation; and with wheat, maize, millet, barley, and oats in arid and semi-arid environments. This region includes the water deficit areas of northern China where potato is a rainfed and short season crop (90-110 days); supplementary irrigation is needed but not frequently applied. In northern Europe and North America, potato production is generally carried out with intensive agricultural practices, including high rates of fertilization, pesticide use, and irrigation where necessary. Two- to four-year rotations include oilseeds, cereals and legumes. In the subtropics potato is found in a range of cropping systems. It is in multiple cropping systems with two or even three crops per year in rotation with wheat or maize in the central plains of China, in intercropping systems particularly with maize at lower elevations there, as a single spring crop in higher altitudes of southwest China, or as an irrigated and short season winter crop in rotation with rice or wheat in the Indogangetic plains, lower elevations of southwest China and North Vietnam. In the cool tropics, potato is commonly a once-a-year (in a couple of countries twice-a-year) rainfed crop, a long growing season (180 days) monoculture or is included in rotations with maize, legumes,

FIGURE 1 World potato harvested area and average yield over the period 1961-2009 (FAO, 2011).

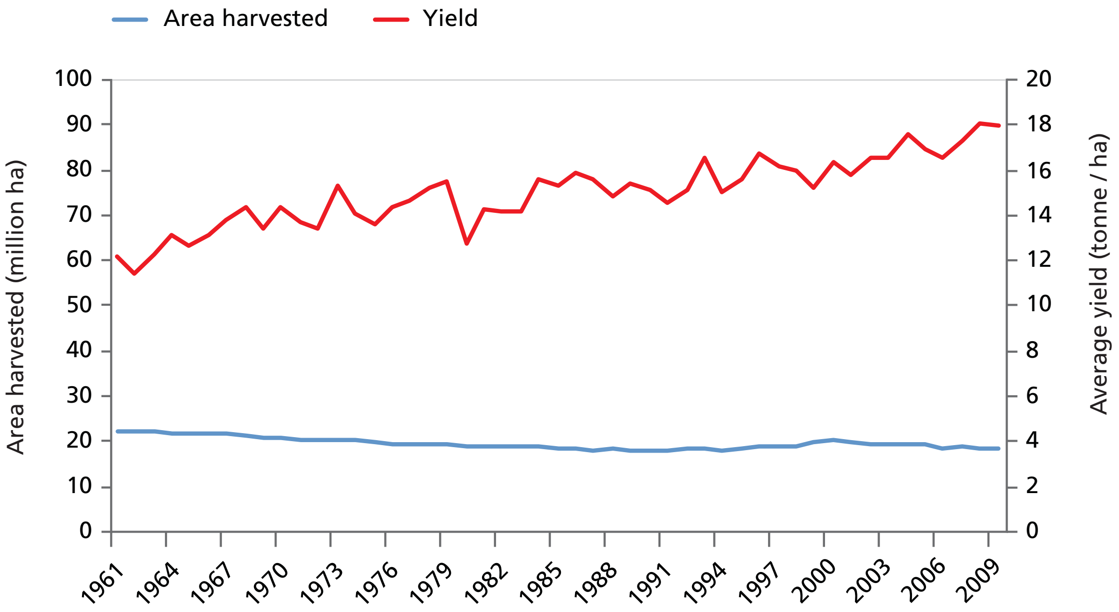
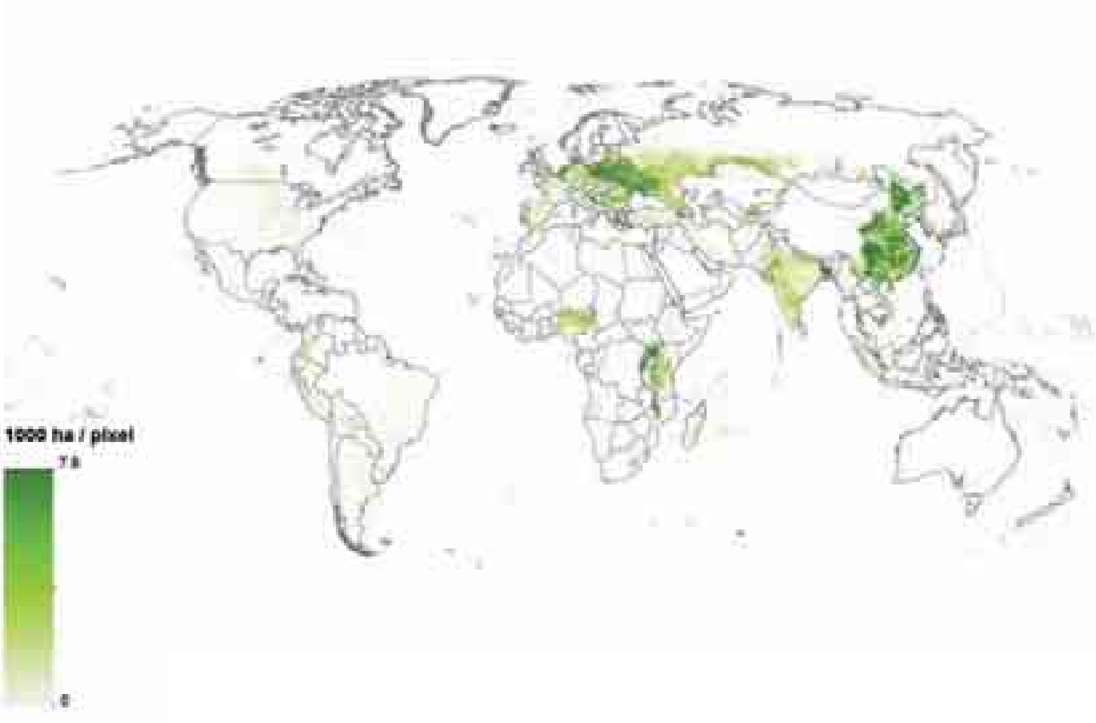


FIGURE 2 Potato harvested area (GAEZ, 2011).



Reference year 2000

quinoa, or vegetables as in the Andean and East Africa highlands. Two crops per year are not uncommon at lower elevations.

GROWTH AND DEVELOPMENT

Potato is grown on ridges or on flat soil. For rainfed production in dry conditions, such as in southwest China and at higher elevations of semi-arid cool tropics, flat planting tends to give higher yields as a result of soil-water conservation. Under irrigation the crop is mainly grown on ridges. Although potato can be planted as botanical seeds, in nearly all cases it is planted as tubers. The tuber seed should have two to three eyes, from which the new buds and shoots sprout. The sowing depth is generally 5 to 10 cm, while deeper planting is preferred in dry areas. Plant density ranges from 30 000 to 60 000 plant/ha and varies depending on seed size, cultivar, and use. Higher plant density is used under irrigation and lower density in rainfed conditions. Cultivation during the growing period must avoid damage to roots and tubers, and often ridges are earthed up to avoid greening of tubers.

The plant emerges about 7 days after planting under good conditions. Emergence may be delayed by lower soil temperature, limited soil moisture, unsprouted or young tubers, and deep planting. Initial canopy cover (CC_o) depends on seed tuber density and the numbers of developing shoots per seed tuber, and whether beds are widely or narrowly spaced. Cultivars may also differ in this regard. The time from planting to maximum canopy cover (CC_x) can be shortened by denser planting, and by practices conducive to earlier plant emergence, warm temperatures, and good water supply. At maximum canopy, the percentage of canopy cover ranges from 45 percent to nearly 100 percent in the cool tropics. At the early vegetative stage, between emergence and tuber initiation, stolon formation begins, followed by tuberization and tuber enlargement. The duration of the growth cycle and total tuber production depends on cultivar, temperature and day length. Tuberization comes before flowering and flowering is not necessary to produce tubers.

As is true for other crops, the rooting depth of potato depends strongly on soil conditions, the absence of impeding layers and soil temperature. Root water extraction has been shown to go deeper than 1.8 m under favourable conditions (Wolfe *et al.*, 1983), although often potato is said to be shallow rooted. Normally, when the upper soil profile is not dry, 70 percent of the total water uptake occurs from the upper 0.30 m and nearly 100 percent from the upper 0.40 to 0.60 m soil depth. The uptake pattern is, however, also dependent on the location of water and nutrients, with water extraction mainly from deeper layers when the upper part of the soil profile is dry.

The subspecies *tuberosum* tuberizes under the 14 to 17 hours photoperiod prevalent in the higher latitude regions but is grown worldwide as it adapts to shorter photoperiods. Some cultivars of *S. tuberosum tuberosum*, when grown under short days may initiate tubers earlier, have a reduced canopy with little or no flowering, and mature earlier but with less tuber yield potential (Condori *et al.*, 2010). *S. tuberosum andigena* and the other seven cultivated Solanum species (other than *Solanum tuberosum*) tuberize under 10 to 12 hours photoperiod prevalent in the tropical region and are grown in the Andes. Hybrids of *tuberosum* and *andigena* are being increasingly grown in developing countries where and when day length is short. *S. tuberosum andigena* and its hybrids, when grown under long days, may have a late tuber initiation, vigorous canopy, profuse flowering, and mature later, but also have a reduced tuber yield potential. Nonetheless, the breeding of long-day adapted *andigena* resulted in large increases in yield (Bradshaw, 2009).

WATER USE & PRODUCTIVITY

Potato requires from 0.35 to 0.8 m^3 of water to produce 1 kg of tuber dry matter. Under field conditions, this translates into a water requirement during the growing period of 350 to 650 mm, which is dependent on climate and cultivar (Sood and Singh, 2003). The water productivity for yield of fresh tuber ($WP_{fresh\ Y/ET}$), which contains about 75 percent moisture, is 4 to 11 kg/m^3. Expressed as dry tuber mass, the yield water productivity ($WP_{Y/ET}$) ranges from 1.3 to 2.8 kg/m^3. Under conditions of limited water supply the available supply should preferably be directed towards maximizing yield per hectare rather than spreading the limited water over a larger area. Savings in water can be made mainly through improved timing and depth of irrigation application.

RESPONSES TO STRESSES

Potato is sensitive to water deficits. Water shortages may result in a reduced tuber yield, number and size, and loss of tuber quality. To optimize yield, generally the total available soil water (TAW) should not be depleted by more than 30 to 50 percent. Water deficit in the early stages, during stolon formation, tuber initiation, and after tuber initiation have the greatest adverse effect on final yield. Although leaf growth is very sensitive to water deficit, if the deficit is moderate and short, leaf growth after the defict is released by rain or irrigation can compensate, and the effect on yield would be minor. The senescence stage is less sensitive, provided the deficit is not severe enough to shorten the duration of green canopy markedly. In general, water deficits in the middle to late part of the growing period tend to reduce yield less than in the early part, but this can vary with cultivar. Some cultivars respond better to irrigation in the earlier tuber formation stage while others show a better response in the latter part of that stage.

Soil and air temperatures affect growth and tuber yield. The temperature for frost or cold stress for potato is considered 1 °C and less, whereas that of heat stress is 35 °C or higher. However, potato cultivars vary in their tolerance to frost, cold and heat stress, and the extent of damage depends on stress intensity and duration. A base temperature of 2 °C has been used in some potato crop models for growing degree days (GDD) computation (Stol *et al.*, 1991). A base temperature of 0 °C can be used for the subspecies *S. tuberosum andigena*. Optimum soil temperature for tuber growth is 15 to 18 °C whereas air temperature requirements for growing potatoes are a diurnal temperature of 25 to 32 °C and night temperature of 12 to 18 °C. As temperature increases from the low end of the optimum, vegetative growth of potato is enhanced, whereas tuber initiation and growth begin to be suppressed as temperature rises further.

Fertilizer requirements of the potato crop are relatively high. The amount of NPK removed by potato plants is estimated at 4 to 6 kg N, 0.6 to 1.1 kg P and 7 to 11 kg K per tonne of fresh tubers produced. Depending on nutrient status of the soil, to obtain high yield recommended fertilization rates range from 100 to 250 kg/ha N, 50 to 100 kg/ha P_2O_5, and 60 to 260 kg/ha K_2O, for soils ranging from highly fertile to highly deficient in the specific nutrient.

The crop is moderately sensitive to soil salinity with a threshold of the electrical conductivity of the saturated soil paste extract (EC_e) of 2-3 dS/m, reaching 100 percent yield loss at 10 dS/m.

IRRIGATION PRACTICE

Most common irrigation methods for potato are furrow and sprinkler. Yield response to frequent irrigation is considerable and very high yields are obtained with the mechanized sprinkler systems where evapotranspiration losses are replenished each or every two days. Frequent and timely irrigation reduces the proportion of malformed tubers at harvest. Where rainfall is low and water supply is restricted, irrigation scheduling should be aimed at avoiding water deficits during the stage of stolon formation, tuber initiation and after tuber initiation. Supply of water can be restricted during the early growth, i.e. before flowering, but canopy growth would be slowed so the restriction must be within bounds. To use up more of the water stored in the soil, irrigation should be cut back toward or at the senescence stage. This practice may also hasten maturity and increase dry matter content of tubers. Correct timing of irrigation may save 1 to 4 irrigation applications, including the last irrigation prior to harvest, depending on the situation.

YIELD

In the temperate region of northern Europe and North America, a good yield, under irrigation where required, is more than 40-50 tonne of fresh tubers per ha. In very humid regions, yield tends to be less as diseases are more difficult to control. Yields of rainfed and even irrigated potato in the subtropics and cool tropics are much lower, ranging from 5 to 25 tonne per ha. Planting low quality seed tubers, less dense planting, lower rates of fertilizer and irrigation, and pest and disease problems led to the low yields. Seed tuber quality is very important for high production, as reflected in the large amount of seed tuber in world trade, amounting to about 1.4 million tonne per year. Dry matter content of fresh tubers normally varies between 20-25 percent of fresh weight.

Economic yield depends strongly on tuber quality, and can be affected by irrigation management. Water deficit in the early part of the tuberization stage increases the occurrence of spindled tubers, which is more noticeable in cultivars of cylindrical tuber compared to those of round tuber. Water deficit during this stage followed by irrigation may result in tuber cracking or tubers with black heart. Water deficit following tuber initiation can reduce the yield of marketable tubers from 90 percent to 70 percent or even 50 percent.

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Tomato

GENERAL DESCRIPTION

The tomato *Solanum lycopersicum*, L. (*formerly Lycopersicon esculentum*, Mill.) is a daylength neutral, herbaceous perennial plant usually grown as an annual in temperate regions. There are three types of cultivated tomato, indeterminate, semi-determinate and determinate. Indeterminate plants are tall, frequently more than 2 m high, with vegetative growth continuing much longer after the start of flowering than in the other two types. Fruit ripens gradually, starting from the basal fruit clusters. Semi-determinate plants are less tall than the former reaching a maximum height of 0.9-1.5 m, their characteristic is that the main fruit clusters ripen together, but the plant will also continue to produce additional fruit. Indeterminate and semi-determinate tomatoes need to be staked or trellised, and are grown for the fresh market and harvested by hand. Determinate-types, the so-called bush tomato, mostly rest on the ground and have a relatively concentrated flowering and fruit setting lasting only about three weeks. In this period vegetative growth continues. Most fruit of determinate cultivars matures in a relatively short period and for this reason are suitable for mechanical harvesting. Processing tomato cultivars are bred for firmness and strong skin and are of the determinate type, except for San Marzano type peeled tomatoes which are indeterminate or semi-determinate cultivars. The parameters of the current version of *AquaCrop* are set for processing tomato only, since it considers a single harvest per crop.

Current world production of tomato is about 152 million tonne of fresh fruit from about 4.4 million ha (Figure 1). Tomato is the second most valuable vegetable crop next to potato (FAO, 2011). The cropped area increased 1.4 millions ha (+40 percent) in the period 1997-2007, but total fruit production, including fresh market tomato, increased by only 20 million tonne (15 percent). More than 38 million tonne per year are grown for the processing industry, making tomato the world's leading vegetable for processing. Fruit production for processing increased even more in proportion, by 11 million tonne (+49 percent), while only 0.5 million ha (+10 percent) were cropped with processing tomato (*WPTC, 2011*). Global tomato consumption increased by an average of 4.5 percent per year between 1990 and 2004. Tomato producers are mainly located between subtropical and temperate zones, the main cropping countries being China, the United States, India, Turkey, Egypt, Italy, Iran, Spain, Brazil and Mexico. (See Figure 2 for harvested areas).

FIGURE 1 World tomato harvested area and average yield over the period 1961-2009 (FAO, 2011).

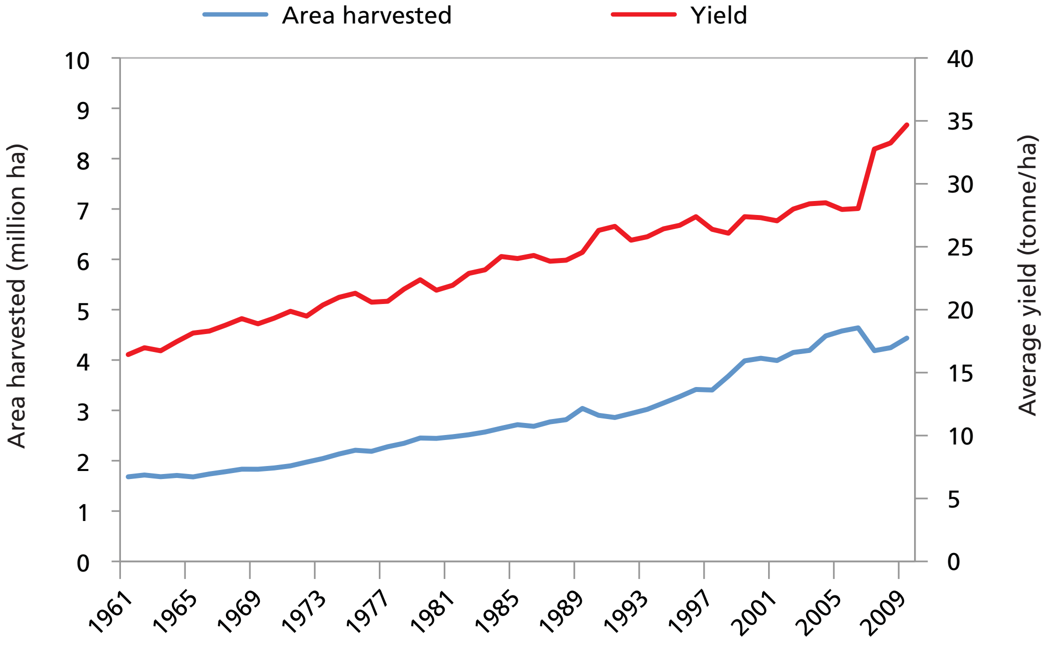
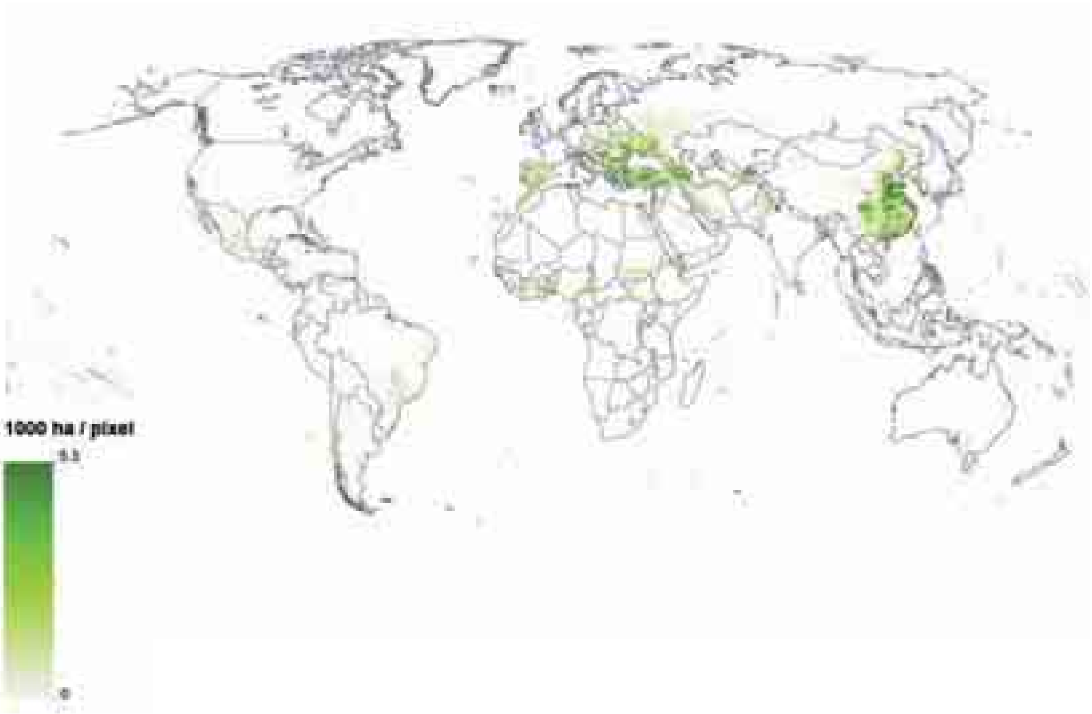


FIGURE 2 Tomato harvested area (SAGE, 2000).



Reference year 2000

Tomato requires soils with proper water-holding capacity and aeration. Well drained, deep, sandy loam soils are preferred, but heavier soils can also be highly productive under proper management. Tomato is intolerant to soil compaction and waterlogging, thus the upper 15-20 cm soil layer needs to be permeable. In clay soils, deep ploughing is sometimes necessary to allows for water drainage and better root penetration. At some locations tomato needs a 3-year rotation, with crops other than solanaceous (e.g. potato, pepper, eggplant, tobacco), to minimize nematodes, virus and bacterial diseases. Generally tomato is grown in rotation, often with only a 2-year cycle.

GROWTH AND DEVELOPMENT

More commonly, tomatoes are transplanted to achieve more uniform plant emergence, density and development. Because of its small seeds it is difficult to attain uniformity and high percentage of emergence when sown in the field. Direct sowing is usually limited to standard cultivars, with hybrids this method is uneconomic because of the high seed cost. Seed beds must be carefully prepared to eliminate soil clogs for direct sowing. The use of precision sowing machines, compared to traditional planters or manual sowing, allows for the use of pelleted seed and avoids the thinning at the fourth leaf or later stage. Tomatoes are best sown when the 7-day average soil temperature of the top 100 mm layer is ≥ 10 °C. Sowing period ranges from end of February to May in the Northern Hemisphere, or from August to mid-December in the Southern Hemisphere. Of course, the season is much less defined in the tropics and subtropics.

The optimal sowing depth is 2-4 cm. The density of sown processing tomatoes is generally higher than those that are transplanted because, up to a point, higher plant densities lead to higher yields and this is counter-balanced by the increasing cost of seedlings for transplanting at higher densities. About 100 000 seeds per hectare (1-1.5 kg/ha) are necessary when traditionally sowing processing tomato. In contrast, 0.3-0.5 kg/ha of seeds are used in case of precision sowing with pelleted seeds. Seedlings for transplanting are sown in a nursery in plug trays (25-35 mm diameter per seedling) at a density of between 750 and 1 000 seedlings/m^2, and transplanted at 25 000-33 000 plant/ha. Seedlings are commonly transplanted at the 4-5 true-leaf stage, 4 to 7 weeks after sowing. Seedlings should be short, 150-200 mm, including the root clod, and less if transplanting is by machine, and should have a thick stem base (diameter ≥ 4 mm). These requirements are met only if the radiation level is high in the nursery. The transplanting period ranges from the end of March to the end of June-early July in the Northern Hemisphere, or from September to mid-December in the Southern Hemisphere.

Plant spacing varies widely depending on conditions, seed or seedling cost, plant type and cultivars and local practices. Density ranges from 2 to 6 plants/m^2 and row spacing ranges from 0.75 m to 1.6 m, with processing tomato often planted more densely than market tomato. in the latter case, wider space is left for picker's access, so that the ripe fruit can be harvested frequently. On wide beds, processing tomato may be planted in double rows to obtain a slightly higher yield. Generally, tomato starts to flower early, 25-40 days after transplanting or 35-50 days after emergence, depending largely on temperature. The life cycle varies from 95-115 days for processing tomato or up to more than 145 days for undetermined fresh market tomato.

Tomato flowers develop from buds situated in the axis of the angle between the leaf and stem. Consequently, flowers form in sequence as the number of leaves increases on the stem, and flower and fruit initiation overlap vegetative growth for the whole period. This period lasts longer in the indeterminate than the determinate type because of the difference in how long new leaves keep on developing. The first nodes on the stem that can potentially form flowers occur between the fifth and the seventh node, according to cultivar and temperatures in the initial weeks of crop (Dieleman and Heuvelink, 1992); however, there is not much different between the three determinacy types.

Tomato has a strong tendency to drop early flower buds, flowers and young fruit under certain conditions, including low solar radiation level and temperature and high humidity. Nitrogen and water status of the plant are equally influential. High nitrogen and/or high water status stimulates vegetative growth, this apparently competes with the developing flowers and fruit for assimilates, causing abscission of flowers and abortion of young fruit. In addition, restricted water supply can suppress new leaf development, resulting in a shortened yield formation period. Hence, field observation of phenological stages of tomato can be quite variable at times, even for the same cultivar and plant type, making it difficult to generalize. On the other hand, the remarkable adaptability of the tomato plant means cultivation worldwide is possible along with the application of diverse cropping techniques in greenhouses and in the field.

Tomato plants grown from seed develop a strong taproot that reaches a depth > 1.5 m in soils without impeding layers restricting root growth (Battilani *et al.*, 2002). In good and deep soils in California, rooting down to nearly 3 m has been documented. However, most water and nutrient uptake occurs in the 0.2-0.75 m soil layer, where 50-80 percent of the roots concentrate. Lateral roots are normally initiated within 5 cm of the tip of the taproot, increasing in length upward along the taproot to a position about 20 cm from the taproot tip. The taproot of transplant is broken or curved, thus, several large laterals develop in the first 3-4 weeks as main roots and penetrated downward. When soil receives water intermittently as rain or irrigation, the higher root length density is in the top 40 cm soil layer, where the majority of the active roots are concentrated. Drip irrigation alters root development pattern; however, roots grow preferentially in wet soil, irrespective of the areas wetted by surface or subsurface drip (Oliveira *et al.,* 1996).

WATER USE AND PRODUCTIVITY

Processing tomato consumes 400-800 mm of water from emergence/transplanting to harvest, depending on climate, plant type, soil, irrigation and crop management. Tomato plants can tolerate drought to some degree, therefore soil moisture levels can reach 50 percent of total available water (TAW) without significant yield losses after the development of the canopy is completed. It is important to maintain adequate soil moisture levels early in the life cycle, at transplanting, and from the first flower until complete fruit setting (e.g. of the fifth truss on the main axes). Irrigation can stop a few weeks prior to harvest, depending on soil water storage and rainfall expectancy. Over the peak growing period, maximum water use averages 4-7 mm/day in a sub humid climate, but can reach 8-9 mm/day in more arid areas. Tomato water productivity for biomass ($WP_{B/ET}$) ranges from 1.3 to 3.5 kg/m^3, with 3 kg/m^3 being considered as common for favourable conditions and practices (Battilani, 2006). The low end of the range is likely observed in climates of high evaporative demand, as well as where canopy cover is low and there is frequent wetting of exposed soil surface by rain or irrigation. The latter increases the E part of the ET. $WP_{B/ET}$ was found in some studies to be largely independent of nitrogen fertilization and of salinity, but within limits. If nitrogen or salinity is limiting, $WP_{B/ET}$ would be reduced (Heuvelink and Dorais, 2005). *AquaCrop* then requires a local calibration with biomass produced by a treatment of optimal nitrogen (or a non-saline treatment), in order to simulate such cases realistically.

RESPONSE TO STRESSES

Similar to cotton (see Cotton chapter), the vegetative/reproductive ratio of tomato also depends on plant-water status, but to a lesser degree. As already mentioned, high water status stimulates vegetative growth and commonly leads to the dropping of flowers and newly set fruit early in the season. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture. Photosynthesis per unit leaf area is moderately resistant to water stress. Thus, the crop is fairly resistant to moderate drought once good canopy cover is achieved. Over irrigation causes excessive leaf growth, and plants high in vegetative vigour tend to produce low quality fruit because of reduced content of soluble solids. Moreover, excess water near harvest can cause nitrate accumulation in the fruit. For some cultivars, wide fluctuations in soil moisture levels during fruit maturation can cause fruit cracking, blotchy ripening, blossom-end rot and varied size and shape.

The crop is sensitive to frost. Low temperatures, if persisting for more than a few days, reduces leaf and truss initiation rates, and the plant produces thicker leaves, so they intercept less light; fruit set is reduced as a result of poor pollination. Dropping of flowers and young fruit under cold temperatures has already been noted. Exposure to high temperatures causes a reduction in the number of pollen grains and impairs their viability and germinability, markedly affecting fruit set. High day and night temperatures cause hastening in flowering and marked reduction in number of trusses, flowers per truss and an increase of blossom drop and fruit abortion. High humidity, combined with temperatures above about 27 °C, also affects pollen germination, resulting in reduced yield. Tomato, as with many other crops, can compensate for day and night temperatures, mitigating the stresses already suffered. Nevertheless, differences between day and night temperatures of less than about 12 °C adversely affect yield of many cultivars (Gent and Ma, 1998). Processing tomato cultivars bred for semi-arid warm climates, however, do not respond negatively to maximum temperatures in the range of 35-40 °C.

As is true for other crops, mineral nutrient requirement is high for high production. Fertilizer applications may be up to 220-250 kg N, 40-80 kg P_2O_5, 300 kg K_2O, and 20-50 kg MgO per ha for crops yielding about 100 tonne/ha. Fresh market tomatoes yielding over 150 tonne/ha requires up to 300-600 kg N, 150-300 kg P_2O_5, 600-1000 kg K_2O per ha. Nitrogen is often given in split applications, at planting and one at the early stage of fruit setting. Nitrogen, either in excess or when applied late during the growing season, affects fruit ripening by delaying fruit maturation. Too much nitrogen early in the season induces fruit drop and minimizes fruit set (Adam, 1986; Benton,1999).

The crop is moderately sensitive to salinity. The average root zone salinity threshold (EC_e) is about 2.5 dS/m. Yield decreases as EC_e increases, to about 50 percent at EC_e of 8 dS/m, and nil at EC_e of 13 dS/m in some studies. For practical purposes, the irrigation water salinity threshold for long-term use is about 3.5 dS/m on sandy soils, 2.0 dS/m on loamy soils and 1.2 dS/m on clay soils (Ayers and Westcot, 1985). During fruit ripening, light saline stresses can improve the fruit quality without any detrimental effect on yield. In fact, fruit quality is better with moderate salinity but at the cost of reduced yield, as shown by a number of studies in Israel.

IRRIGATION PRACTICE

Surface irrigation by furrow is still commonly practised. Pressurised irrigation methods (sprinkler, mini-sprinkler and drip irrigation) are now common in many main cropping countries. Large-scale tomato growers have long learned to limit irrigation as the crop approaches maturity. Because of its vegetative vs. reproductive changes in response to water status, irrigation management should focus on water saving while maintaining yield and enhancing fruit quality. In recent years, experiments with deficit irrigation have been directed at these objectives, with either the deficit maintained at a selected level over a long time (often referred to as DI), or with the irrigation being deficit only at selected stages of the crop's life cycle, referred to as regulated deficit irrigation (RDI) (Battilani *et al.*, 2008). In more arid areas preplant irrigation is practised when past rainfall is insufficient to replenish the soil profile. Preplant irrigations are also used to leach more saline soils. Frequently, if soil is well charged initially, one to two irrigations over a 2-4 week period are used for stand establishment after transplant or seeding. During canopy development and much of the flowering period, irrigation needs to be sufficient to ensure fast canopy growth and yet not so much as to cause excessive leaf growth and the associated dropping of flowers and young fruit. Soon after fruit colour change, irrigation should be reduced, but the start of irrigation cutback depends on the water remaining in the root zone of the soil, and the ET rate for that period. These are readily simulated by *AquaCrop*. The cutback over the ripening stage saves water but needs to be optimal to improve fruit quality while allowing last fruits to reach commercial size and maintaining the canopy coverage to protect fruit from sunburn.

YIELD

Yield of processing tomatoes has increased by more than 50 percent over the past 30 years in California and Mediterranean countries. A good commercial fresh fruit yield ranges from 60 to 120 tonne/ha for processing tomatoes and up to more than 150 tonne/ha for fresh market cultivars. Yield can be much higher in greenhouse production for fresh markets. In drier areas, rainfed crop production ranges from 40 to 70 percent of irrigated. Soluble solids content of the juice of most widely used cultivars can vary between 4.2 and 5.5 percent. Factories requires a minimal quality for processing tomatoes: juice acidity must range between 0.34 and 0.40 g/100 ml, reducing sugars between 2.5 and 3.0 g/100 ml and Bostwick consistency between 8 and 12 cm/30 s. Dry matter content of fresh fruit ranges from 4.0 to 7.0 percent (Leoni, 2002). Harvest Index (HI, the ratio of yield measured as dry matter to total above ground biomass) normally ranges from 0.5 to 0.65. HI decreases when plants are over watered or receive excessive nitrogen fertilization because of excessive vegetative growth, but yield may not be affected or even slightly increased, as long as the increased biomass production compensates for the lower HI. On the other hand, yield can be negatively affected when vegetative growth is so excessive that fruit setting is much delayed and HI is reduced sufficiently. *AquaCrop* provides the means to simulate this behaviour and the possibility of optimizing yield by using the appropriate irrigation strategy.

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Sugarbeet

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Sugar Beet

GENERAL DESCRIPTION

Sugar beet (*Beta vulgaris*) is a biennial plant that produces a large storage root as a part of tap root containing 14 to 20 percent sucrose on a fresh mass basis. When cultivated for sugar production, it is harvested in the first season, while for flowering and seed production the cultivation is prolonged to the second year. The first season for autumn planted crop is autumn to early summer of the next year, and for spring planted crop, from spring to autumn of the same year.

Current world production is about 227 million tonne of beets produced on 4.2 million ha (FAO, 2011). The cropped area has been decreasing over the past two decades; total root production, however, remained stable over the same period because of increasing yields (Figure 1). Sugar beet is cropped in the belt from 60° LAT N to 30° LAT S, with the main producing countries being France, United States, Germany, Russian Federation, Turkey, Poland, Ukraine, United Kingdom and China, in that order (FAO, 2011) (Figure 2).

Sugar beet is usually cropped in rotation with cereals (Europe, Russian Federation, Ukraine), maize (Southern Europe, America), beans and soybean (United States, China), in 3-5 year rotations (e.g. wheat – sugar beet – barley – peas). Optimal beet yields are obtained following wheat or barley, while excessive nitrogen availability after maize or soybean reduces sugar yield. At least a 3-year rotation is required to minimize root disease, Cercospora leaf spot, and herbicide carryover.

GROWTH AND DEVELOPMENT

Beet seeds are bulky and light in mass, one seed weighs only about 10 mg. Seeds are planted 1 to 2 cm deep in a single row, seldom in a double row, with rows spaced 0.40 to 0.76 m apart. Monogerm seeds allow precision sowing with 120 000 seeds/ha to obtain 60 000 to 110 000 plant/ha at harvest. In some situations, thinning by hand or by machine is needed to obtain optimal plant density and uniform spacing. Planting should be done when soil temperature is higher than 4 °C and the risks of frost is nil, and also depends on crop management and harvest scheduling. The sowing period ranges from autumn (India, Mediterranean-type climates), to early spring (Western and Eastern Europe, Eastern Europe, United States), to late spring (Russian Federation, United Kingdom, United States). Sowing in

FIGURE 1 World sugar beet harvested area and average yield over the period 1961-2009 (FAO, 2011).

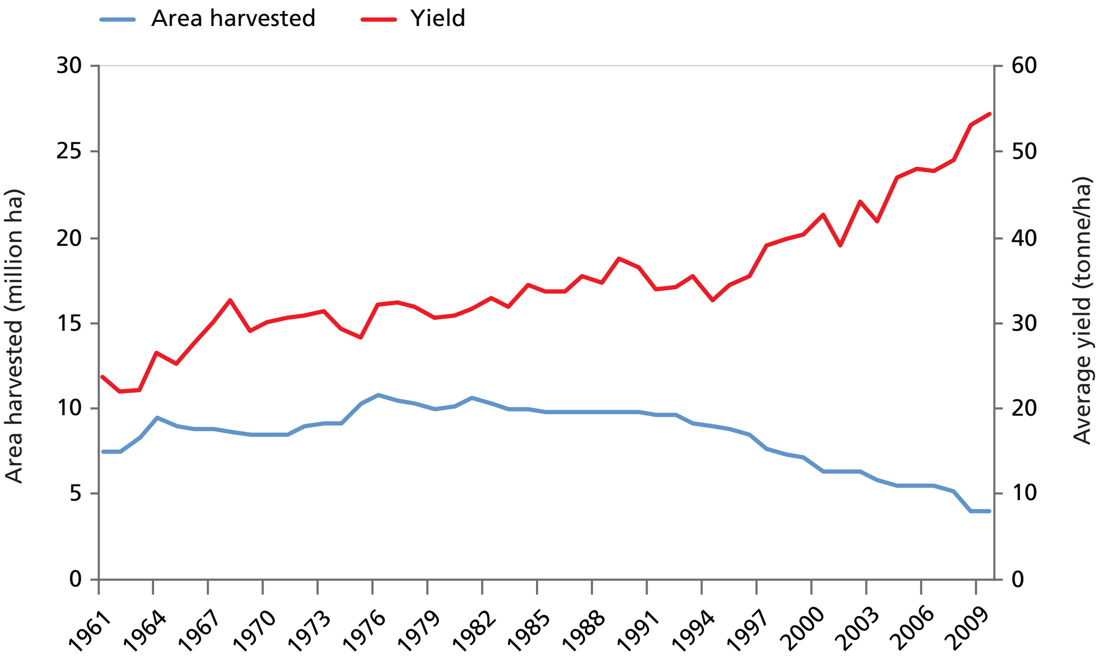


FIGURE 2 Sugar beet harvested area (GAEZ, 2011).

Reference year 2000

North Africa and near East ranges from September to December, depending on the beginning of rainfall. Sowing in India can be in summer, winter and *kharif* period. Extending the sowing time of sugar beet in winter and autumn has been an important breeding goal in the last decades, in order to reduce water requirement by avoiding parts of the summer, while lengthening the crop cycle and thus increasing productivity (Rinaldi and Vonella, 2005).

Minimum soil temperature for germination can be as low as 4 °C. Once established, the seedling enters a period of leaf initiation with virtually no enlargement of the upper portion of tap root for storage. By six weeks the plant has 8-10 leaves but the storage portion of the root is just enlarging (see Table 1 and Figure 3). From this stage onwards, growth of leaves and storage portion of root occur simultaneously with the root making up an increasing proportion of total plant dry weight.

Sugar beets develop an effective root zone of 1.20 m or deeper. In deep soils the crop can develop a deep tap root system. As is the case for other crops, when the soil profile is relatively wet, normally most of the water is extracted from the upper half of the soil of the root zone, although water extraction down to 3 m has been reported for deficit-irrigated sugar beet in very deep, open soils. Since this crop is cultivated for sugar production, the season length influences the root sucrose concentration. The length of time when the crop is in the field is limited by the biennial cycle duration and by the water, light and temperature constraints; in general, a prolonged crop cycle during the summer can modify the source-sink relationship between leaves and root and, consequently, reduce the storage root sucrose content that can flow to the leaves.

The evolution of canopy cover (CC) is mainly temperature dependent, and often maximum CC (CC_x) is reached after about 8 to 10 weeks. The duration in days is merely indicative because temperatures and water availability can influence the length of each phase. How long the leaves (hence the canopy) remain green depends on temperature and water stress. Spring planted crops in western and Eastern Europe and United States are harvested between September and November, while autumn planted crops are harvested at the end of spring or early summer (May to July in the Northern Hemisphere). Lengths of main crop stages are reported in Table 1 with reference to different cropping regions and sowing dates.

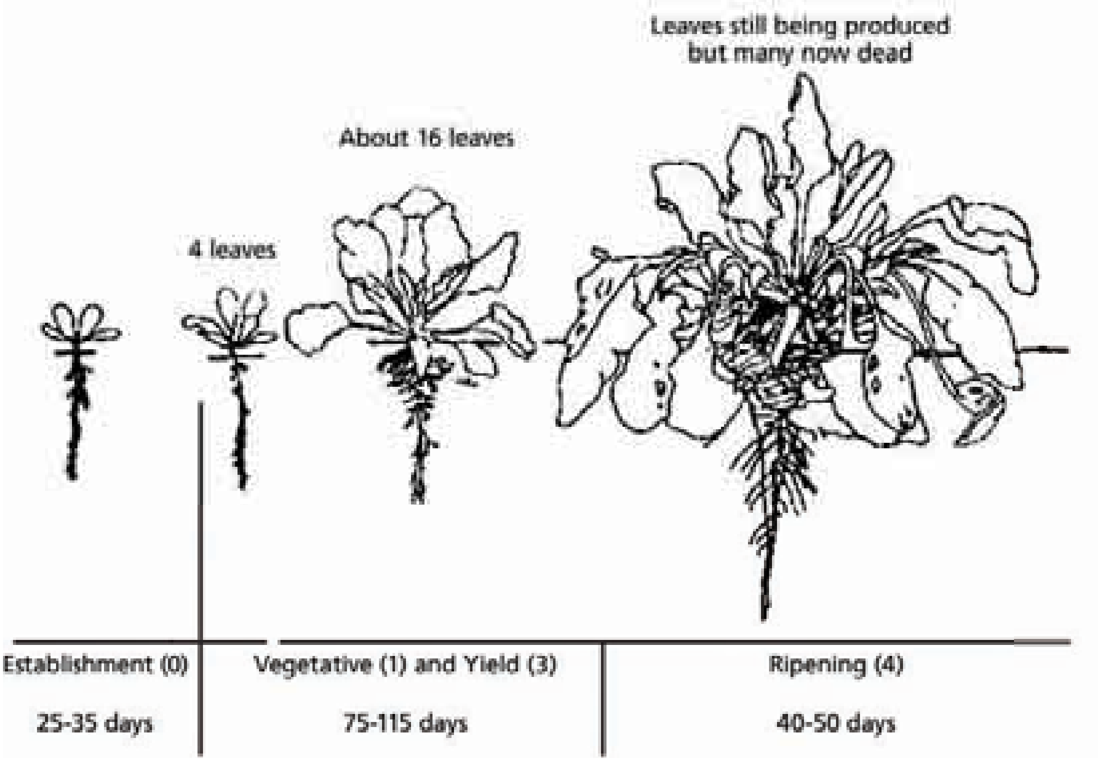
When grown at several constant temperatures (range of 7 to 31 °C, spaced 4 to 7 °C apart), fastest leaf growth was obtained at 24 °C, and fastest tap/storage-root growth was observed a considerably lower temperature, at less than 17 °C (Terry, 1968; Milford and Riley, 1980). Leaf growth is a linear function of temperature above 3 °C, and in the field leaf growth is close to a linear function of growing degree days calculated with a base temperature of 1 °C (Milford *et al.,* 1985).

Modern sugar beet cultivars are almost insensitive to day-length, and bolting (appearance of flowering stalk) and flowering do not take place under normal cropping conditions in the first season. Bolting reduces sucrose yield and is induced by a combination of low winter temperatures (0-10 °C) and long days. Breeders have selected cultivars with very strong flower induction requirements that can now be used for early sowing. The plant only flowers in the second year when seed production is the goal.

TABLE 1 Phenology of sugar beet in several environments (durations are in days).

	Sowing period	Sowing-emergence	Sowing-maximum canopy cover	Sowing-start canopy senescence	Sowing-maturity
Mediterranean countries	November	10-14	100-130	130-160	200-250
	February	16-20	80-100	100-130	150-180
Northern Europe	March	18-22	80-100	100-120	160-190
	April	18-22	70-90	90-120	150-180
India	October	8-12	40-60	60-80	120-140
USA	September	8-20	90-110	110-130	240-270
	March	16-20	80-100	100-120	170-190
	June	7-17	70-80	80-90	130-150

FIGURE 3 Typical developmental stages of sugar beet.



WATER USE & PRODUCTIVITY

Sugar beets consume 500-800 mm of water during the growing season. The seasonal water requirements depend on climate and weather conditions, planting date and density, irrigation, and crop management (Allen *et al.,* 1998). Sugar beets are most sensitive to moisture shortages in the early growing stages but their peak water consumption comes late in the season when maximum canopy cover is reached. Soil moisture levels should be maintained above one-half to one-third of total available water (TAW) to avoid stomatal closure. Over the peak 30-day growing period, maximum water use ranges from 6 to 9 mm/day, depending on climate. Commonly there is a positive relationship between water use, root production, and sugar content. Water stress reduces yield, while overirrigation near harvest reduces root sucrose concentration and increases processing costs, thus reducing profit (Ehlig and LeMert, 1979).

As for water productivity, spring sown beet commonly studied in Northern Europe and America, have reported consumptive water productivity for dry matter production ($WP_{B/ET}$) between 2.1 and 6.8 kg/m^3 (Dunham, 1993). This wide range of values reflect the diversity of climates in terms of evaporative demand and the fact that many $WP_{B/ET}$ values were not normalized for this parameter. It is pertinent to indicate here that the dry matter of concern is mainly composed of storage root dry matter, with shoot dry matter making up only a small portion (e.g. 20 percent). This is in contrast to all non-root crops, for which dry matter of concern is focused on the above–ground portion, neglecting the root portion because it is extremely difficult to extract quantitatively from the soil (Rinaldi *et al.,* 2006).

RESPONSE TO STRESSES

Sugar beet is sensitive to water deficits at the time of crop emergence and for a period of about one month after emergence. Frequent, light irrigations are preferred during this period, and irrigation may also be needed to reduce crust formation on the soil and to reduce salinity of the top soil. Early over-watering may retard leaf development and can encourage flowering during the first year (bolting). Water deficits in the middle of the growing period (vegetative and yield formation periods) tend to affect sugar yields more strongly than when occurring during later periods. Unrestricted water supply near harvest time tends to reduce root sugar concentration although it increases root fresh weight, with the final effect on sucrose yield being small. Moderate water deficits, together with mild nitrogen deficiency towards the end of the growing period, reduce root growth but increase sucrose concentration. In general, top growth toward the end of the growing period tends to be negatively correlated with sugar production, apparently the result of competition for assimilates between vegetative growth and root storage. Normally, the irrigation season ends between 2 to 4 weeks before harvest, depending on the water-holding capacity of the soil, to increase sucrose concentration in the beets. The soil should, however, not be too dry to hamper lifting the beets at harvest. Thus, except during emergence and early growth, it appears that the crop is not very sensitive to moderate water deficits. When plants are under water stress, leaves become dark green in colour and if the stress is severe, the leaves fail to recover from midday wilting in the evening (Hanks *et al.*, 1981).

Adequate soil nitrogen availability is required to ensure a good vegetative growth in spring. Nitrogen is often given in split applications, a small amount at planting and the rest after thinning. As mentioned, excessive nitrogen, especially late in the season, encourages excessive leaf growth and reduces sugar concentration of the beet. Fertilizer applications may be up to 150 kg/ha N, and 50 to 70 kg/ha P_2O_5 and 100 to 160 kg/ha K_2O at planting.

Except for during the early growth stages following stand establishment, the crop is quite tolerant to salinity (Katerji *et al.,* 1997). Yield decrease is 0 percent at an EC_e of 7 dS/m, 50 percent at EC_e of 15 dS/m, and 100 percent at EC_e of 24 dS/m. During early growth EC_e should not exceed 3 dS/m.

IRRIGATION PRACTICE

About one-fourth of the world's 4.2 million ha of sugar beet receives irrigation, but the fraction varies greatly from region-to-region. In the United States, Eastern Mediterranean, Iran and Chile between 80 and 100 percent of the sugar beet area is irrigated; in the western Mediterranean irrigated area amounts to 20-80 percent of total, while in Central and Northern Europe, it is less than 40 percent. In most sugar beet growing areas of the world irrigation is supplemental and typically only 100-200 mm are needed. In other areas (United States, Egypt, Pakistan) irrigation is essential for beet production and 500-1 000 mm are commonly applied. Practically, all irrigation methods are used for sugar beet, mainly sprinkler (pivot, booms), but also surface irrigation, and in rare cases, even drip irrigation.

When water supply is limited but land is not, water should not be used to meet the full water requirement of the crop. Instead irrigation should cutoff earlier and the water saved used to expand the area cropped. This is because the efficiency of water utilization for sucrose yield increases when water is restricted near harvest, for reasons already discussed. Under those conditions, harvest index increases significantly over the value achieved under full irrigation.

YIELD

A good commercial yield of 160 to 200 days sugar beet is 40 to 60 tonne/ha of fresh beet. Under very favourable conditions yields of up to 100 tonne/ha or more have been obtained. Total dry matter production varies from less than 10 tonne/ha to more than 20 tonne/ha. Sucrose content varies, mainly between 14 and 18 percent on a fresh mass basis, corresponding to sucrose yields of 5 up to 15 tonne/ha. $WP_{sucrose/ET}$ varies from 0.9 to 1.7 kg/m^3.

Harvest index (HI) for sugar beet is best defined as the ratio of sucrose produced to biomass of the storage root and shoot. Biomass of fibrous roots is neglected because most studies do not attempt to measure it. Also, shoot biomass is often not measured. On the assumption that storage root biomass is four to eight times the shoot biomass, HI in terms of sucrose produced would commonly fall in the range of 0.4 to 0.55, although values outside of this range are also encountered in the literature. HI tends to decrease when conditions favour luxurious vegetative growth, mainly high nitrogen and high water supply, especially as the harvesting time approaches. Extending the harvesting time to later in the season usually enhances HI, but only up to a point.

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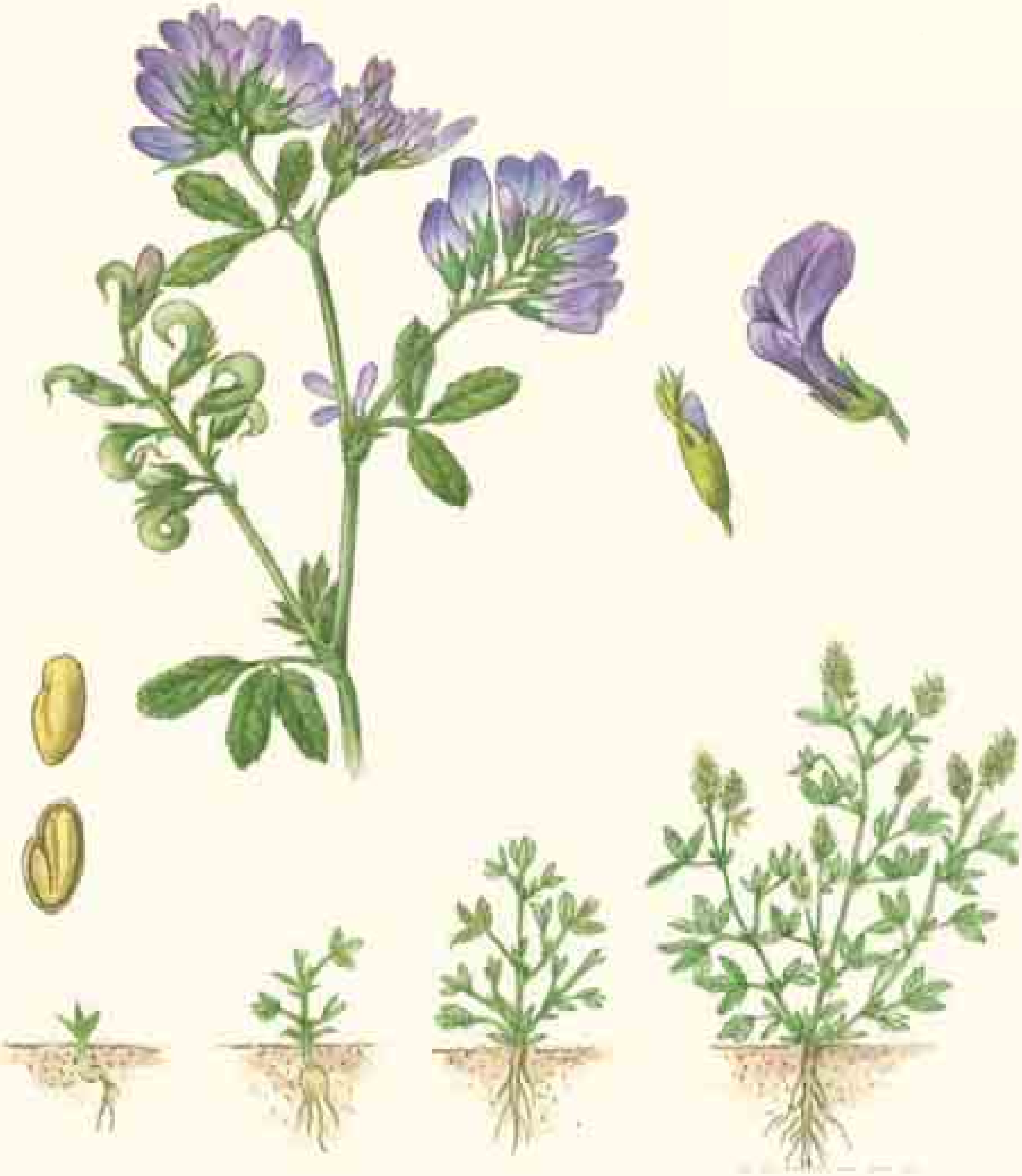

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Alfalfa

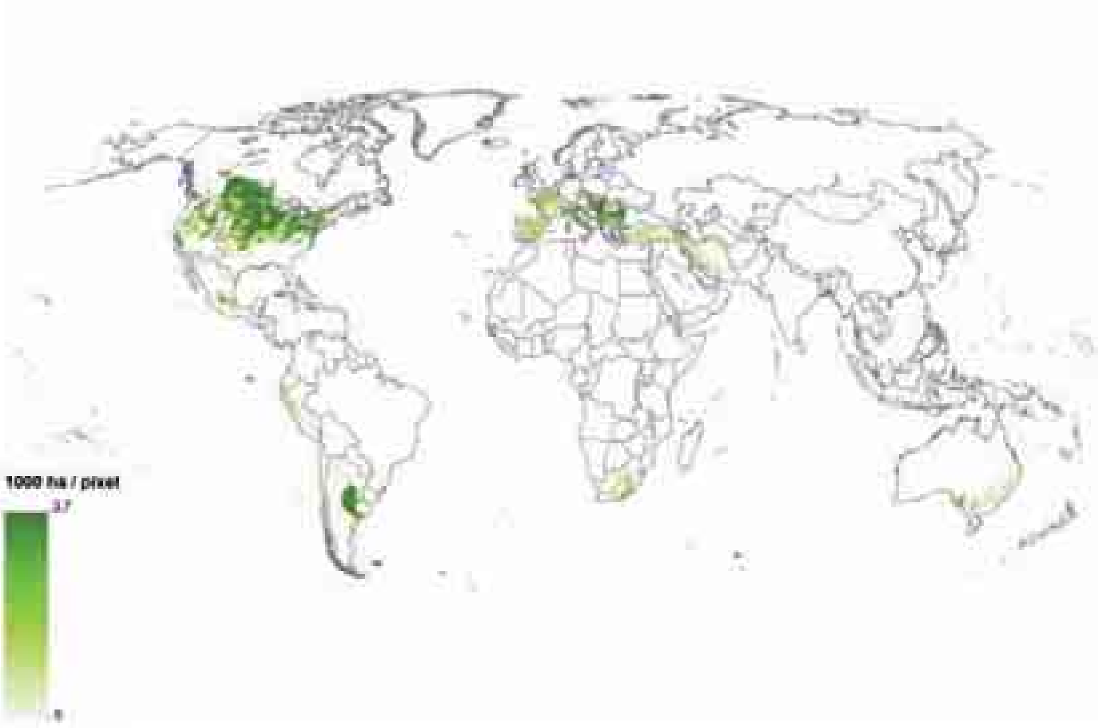
GENERAL DESCRIPTION

Alfalfa (*Medicago sativa* L.) is the oldest and most important forage crop globally (Michaud *et al.*, 1988). It is a perennial legume widely adapted to continental and temperate climates. Alfalfa can be conserved as hay, silage or pellets or grazed in pure stands or in mixtures with grasses. It is an effective source of nitrogen from symbiotic fixation which contributes to its high leaf protein and metabolizable energy content.

Alfalfa originated in the Caucasus region with related species scattered throughout central Asia. It was initially sown across Europe, Mexico and South America by invading armies to feed horses. China has had cultivated alfalfa for over 2 000 years with renewed interest in recent times for its ability to mitigate damage in erosion prone landscapes. In North America, Australia and New Zealand germplasm was introduced from various sources by colonists to support livestock farming. There are now over 30 million ha of alfalfa grown throughout the world as monocultures or in pasture mixes with grasses. (Figure 1 shows the world harvested areas).

The specific agronomic and management requirements of alfalfa are dependent on its intended use and the agro-climatic environment. Alfalfa can be used to dry the soil profile, reduce drainage and nitrogen losses to ground water, and minimize seepage of saline water to the soil surface. It can be established by conventional sowing, after plough, into a fine, firm seed bed or by direct drilling into existing herbage that has been suppressed with a broad spectrum herbicide. Alfalfa seeds are small (~2.0 g/1 000 seeds) so should be sown at depths less than 20 mm when soil moisture conditions are favourable and no deeper that 35 mm in drought prone or semi-arid soils. When spring sown, post emergent alfalfa should be left to grow until plants approach the flowering stage. This enables them to build up root reserves to aid stand establishment. Shoot growth and canopy expansion are slower during the seedling stage because alfalfa preferentially allocates photosynthates below ground. Alfalfa can fix nitrogen (N) once it has formed a symbiotic relationship with rhizobia bacteria, more specifically *Ensifer meliloti. E. meliloti* was formally known as *Rhizobium meliloti* and was also referred to as *Sinorhizobium meliloti* (Willems, 2006).

FIGURE 1 Alfalfa harvested area (SAGE, 2000).



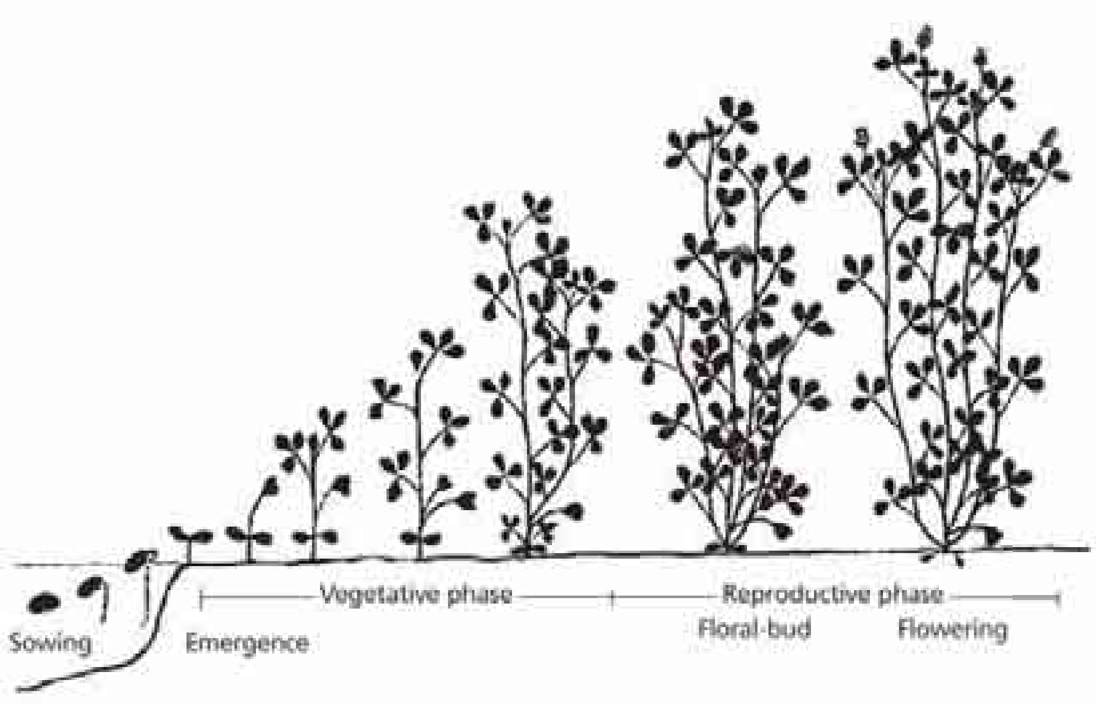
GROWTH AND DEVELOPMENT

Sowing of alfalfa can occur throughout the year depending on environmental conditions such as the availability of soil moisture and the occurrence of frosts. In temperate and continental climates that experience cold winters, stands must be established before the end of summer to enable plants to survive through winter. The earlier the sowing date in spring or summer, the higher the production in the following spring (Justes *et al.,* 2002). The timing and rate of germination are dependent on temperature, moisture conditions, soil salinity and seedling depth. In regions with warm winters, autumn sowing is preferred to ensure adequate weed control and obtain suitable soil moisture and temperature conditions.

Once the crop is established, stand longevity depends largely on plant population, climate and stand management. The initial plant population, determined by sowing and emergence rates, progressively self-thins and consequently the population declines. In most cases this progressive decline does not immediately affect shoot yield. Alfalfa stands have been shown to maintain maximum yields with populations declining from 140 to less than 60 plant/m^2. Yields are maintained over a wide range of populations because the self-thinning is compensated by increases in other yield components namely; (i) the number of shoots per plant (ii) the individual shoot weight, and (iii) the degree of branching. Plant death is mainly caused by competition for light, among alfalfa plants or with other species (e.g. weeds), and accentuated by poor management (e.g. not allowing sufficient regrowth before winter dormancy). Additional stresses such as the occurrence of pests and diseases accelerate plant death. Yield and stand longevity are compromised once plant populations fall below a critical level at which compensation by other yield components is impossible. At this point, re-establishment of the stand is necessary to recover productivity. To maintain high yielding (greater than 10 tonne DM/ha) stands, a plant population of higher than 40 plant/m^2 or about 450 stems/m^2 is required.

The phenological development of alfalfa, from emergence to maturity (Figure 2), is mainly driven by temperature (Fick *et al.,* 1988), quantified by accumulated temperature units (thermal-time in degree-days: °Cd). Development rates are negligible below 5 °C, which defines the base temperature (T_{base}) of alfalfa. Above T_{base}, development rates increase linearly with temperature until an optimum (T_{opt}) of ~30 °C. Above T_{opt}, development rates decline to be zero at greater than 45 °C. Daylength also influences alfalfa development during the vegetative stage. Alfalfa is a long-day plant and reaches reproductive stage (characterized by the appearance of floral buds) faster during summer when daylengths are longest, whereas the vegetative stage is extended when daylength shortens in late summer and autumn. After emergence, in the seedling stage, growth and development is slower than during regrowth. This is because seedlings lack a mature root system, nodulate and preferentially accumulate carbon and nitrogen reserves in perennial organs during this early stage. The seedling crop goes through a 'juvenile' period of vegetative growth when development is insensitive to daylength and flowering is delayed relative to regrowth crops (Teixeira *et al.,* 2011).

FIGURE 2 Typical developmental stages of alfalfa.



The number of times alfalfa can be harvested during a year depends on climatic conditions and management (Teixeira *et al.,* 2007). After each harvest a new cohort of vegetative shoots are generated. The duration from the initiation of new shoots to the reproductive stage may be modified by daylength and temperature. The response to daylength differs with cultivar and is more pronounced at high latitudes. After floral initiation, temperature alone drives development through flowering, seed filling and maturity. Temperatures above 27 °C, water stress or excessive soil moisture conditions can decrease seed yields.

The main factor determining alfalfa growth, i.e. the rate of biomass accumulation, is the amount of carbon assimilated through photosynthesis, which in turn is dependent on the amount of light intercepted by the canopy. Light interception increases with canopy cover as new leaves appear and expand. The rate of leaf appearance is driven by temperature with a new main-stem leaf appearing every 34–37 °Cd under optimal conditions. Daylength can also regulate the rate of leaf appearance with a delay observed during autumn, particularly for dormant cultivars. In summer, alfalfa may expand up to 20 main-stem nodes. It is an indeterminate plant and therefore leaf appearance continues after flowering, although at slower rates. Leaf senescence is a function of leaf age, the canopy light environment, and other environmental stresses. The canopy architecture of alfalfa enables efficient light capture as a result of the distribution of flat leaves in the lower canopy and vertical leaves in the top. This is characterized by its high light extinction coefficient per unit of leaf area of 0.8–0.9, which is high and stable in different commercial alfalfa cultivars. The rate of leaf area expansion is higher in spring and summer than autumn, in response to higher temperatures and longer daylengths.

Alfalfa radiation use efficiency for total biomass (shoots, crowns and roots), a proxy for net canopy photosynthesis, is ~1.8 g/MJ (total solar radiation). Once carbon is assimilated though photosynthesis, biomass can be partitioned to above (leaves and stems) or perennial below-ground organs (crowns and roots). Alfalfa survives during winter by storing carbon and nitrogen compounds as reserves in its perennial organs. These reserves are then used to resume growth during the following spring and after each harvest (Avice *et al.,* 1997). Nitrogen and carbon are mobilized to form new leaves and stems while carbon is also respired to supply energy to sustain root metabolic activities. The partitioning of assimilated carbon to crowns and taproots is seasonal.

During spring, most biomass is retained in shoots and less than 5–15 percent is partitioned below ground. From mid-summer to late-autumn more than 50–60 percent of total assimilated carbon may be partitioned to perennial organs below ground to sustain future spring growth and stand persistence (Teixeira *et al.,* 2008). These seasonal patterns of biomass partitioning differ with alfalfa cultivar, according to their Mediterranean or northern origin. High latitude cultivars have a more evident seasonality with higher biomass partitioning to roots in late-summer/autumn in response to lower temperatures and shorter daylength. The extent of cultivar response to decreasing temperatures and daylengths is defined by its dormancy rating which range from 1 to 11. More dormant cultivars (rating 1-5) have reduced growth rates, shoot production and higher underground partitioning in autumn than non dormant (winter active) cultivars.

WATER USE & PRODUCTIVITY

As a perennial crop, alfalfa can produce dry matter throughout the year if environmental conditions are favourable. During the most active growth period from spring to autumn, daily values of evapotranspiration (ET) are driven by the interaction of environment and defoliation (cutting) management. The removal of leaf area reduces transpiration so ET values less than 1 mm/day occur immediately after defoliation, mainly through soil evaporation, and in cool winter conditions. When the crop reaches full canopy, ET can rise to over 8 mm/day. As the canopy recovers and leaf area index increases the daily ET can be estimated from potential ET multiplied by the fraction of canopy cover (French and Legg, 1979). During this phase the proportion of soil evaporation in relation to ET declines and transpiration increases. The ratio of actual to reference ET peaks at around 1.1-1.15 at full canopy and declines when senescence occurs as a result of self-shading (i.e. at high leaf area indices), the onset of flowering or frost events. Total cumulative ET ranges from less than 200 mm in arid conditions to over 1 000 mm in well watered conditions.

The slope of the relationship between cumulative herbage yield against cumulative water use gives an indication of water productivity ($WP_{Y/ET}$). The average $WP_{Y/ET}$ is typically around 1.0–2.6 kg/m^3 (Grimes *et al.,* 1992) but has been reported as high as 2.9 kg/m^3 (Brown *et al.,* 2005). In one study, $WP_{Y/ET}$ dropped from 2.1 kg/m^3 to 0.4 kg/m^3 immediately after defoliation (Asseng and Hsiao, 2000). In temperate climates, the highest water productivities are recorded in the spring and values decrease through summer and autumn. The high spring time water productivity results from low vapour pressure deficits in the atmosphere and the highest proportions of total biomass production being partitioned to the harvested shoot (leaf and stem) fraction. Water productivity is lower in the summer because of the high evaporative demand and concomitant higher vapour pressure deficits. Water productivity declines in the autumn because of changes in crop partitioning to roots and cold temperatures. This reduces shoot production per unit of water use. The linear relationship between dry matter production and ET appears stable across cultivars of different fall dormancy ratings.

The annual water requirement of an alfalfa crop can be estimated for any location by the sum of daily estimate of ET for the period that the crop is actively growing. The irrigation requirement can then be estimated by subtraction of effective rainfall during the growth period plus the amount of readily available soil water at the start of the growing season from the total crop water demand. If complete recharge of soil water is achieved prior to the start of the growing season a value of 50 percent of the soils available water capacity (field capacity minus lower limit to a depth of 1.5 m) is commonly taken to represent the readily available water. If incomplete recharge occurs, a simple water balance can be used to estimate soil water content at the start of the season and 50 percent of this value used to represent readily available water.

RESPONSE TO WATER STRESS

Alfalfa has a strategy of drought avoidance by accessing water through its deep root system but has poor drought resistance and is rapidly affected by water shortage (Sheaffer *et al.*, 1988). Water shortage occurs when water supply is insufficient to meet water demand. When soil moisture is near field capacity the water use of alfalfa is limited by the requirement set by transpiration demand for the crop canopy which is driven by atmospheric conditions.

When crop water requirements are greater than total soil water available in the root zone, it restricts the major plant processes of canopy expansion, transpiration and photosynthesis or radiation use efficiency, and accelerates leaf senescence. Relative leaf area expansion rates decrease from their maximum at a threshold between 15-20 percent below field capacity, to be negligible as the total available soil water decreases from field capacity down to about 30 percent or more of the total available water capacity of the soil. Radiation use efficiency is less sensitive to water stress than canopy expansion and declines in a 1:1 response to the decrease in available soil water (Brown *et al.*, 2009). If water supply is only half of crop demand, production will only be half of potential.

The amount of water extraction can be calculated for different layers of soil (Brown *et al.* 2009). Starting in the top layer, extraction is the minimum of potential supply from that layer and demand from the atmosphere. Water extraction from underlying layers depends on the remaining demand after extraction by overlying layers. Effectively, alfalfa has a top-down water extraction pattern throughout the growing season for seedling and regrowth crops. Reductions in water extraction rates are observed in situations of water shortage. In the absence of other measurements, it can be assumed that alfalfa can extract about 3 percent of the plant available water from the soil on any day. Effectively the potential daily water supply can be estimated from the available water capacity of the soil and the rooting depth of the alfalfa crop. The extraction rate coefficients of alfalfa are low compared with other crops (Dardanelli *et al.*, 1997) so alfalfa will prolong the use of the soil water it has access to, mainly because its deep rooting enlarging the supply reservoir.

Alfalfa is less tolerant of waterlogging (saturated soils) than other forage (grass) species. Anaerobic conditions for more than 7-14 days lead to root death and secondary disease infection, particularly from *Phytophthora* species.

SOIL FERTILITY

Successful alfalfa stands are grown on deep (>1.0 m) free-draining soils, to take advantage of its taproot, with a pH of 6.0–8.0. Adequate phosphorous (P), Sulphur (S), Boron (B) and Molybdenum (Mo) are usually required depending on soil nutrient status. Potassium (K) based fertilizers are recommended, particularly under intensive cutting, because leaves of alfalfa, a natrophobe, have a higher potassium and lower sodium (Na) content than many other forage species.

TEMPERATURE

At temperatures less than 5 °C or greater than 45 °C, alfalfa development is negligible. Between these thresholds, alfalfa development rates increase linearly to reach a maximum at ~30 °C. Low temperatures also limit net canopy photosynthesis rates. Radiation use efficiency was shown to increase linearly from 0.6 g/MJ at 6 °C to 1.6 g/MJ at 18 °C (Brown *et al.* 2006).

SALINITY

Alfalfa is tolerant to relatively high salinity in the lower root zone provided the upper zone is saline free. It is more sensitive to Na^+ than Cl^- so that sodium accumulation is the dominant reason for yield decreases when irrigating with saline water. Irrigation, even with moderately saline water, can cause salts to accumulate deeper into the soil profile which enables roots to proliferate in regions of relatively low salinity. At salt concentrations above 10 dS/m significant yield reductions are expected. In these conditions, the absolute yield of alfalfa may still be greater more than 'salt-tolerant' grasses.

YIELD AND QUALITY

The diversity of climate and soil types used to grow alfalfa means reported yields range from less than 1 tonne DM/ha in rainfed systems, on soils of low water holding capacity combined with low annual rainfall (<300 mm/year) to over 28 tonne DM/ha per year in well watered deep silt loam soils in New Zealand (Brown *et al.,* 2005). A similar maximum yield has been reported in Africa, with yields of 10 to 20 tonne DM/ha commonly produced in Europe, China and North America under irrigated conditions. Under rainfed conditions with 500-800 mm of annual rainfall, yields of 5 to 17 tonne DM/ha have been reported. The productivity and persistence of alfalfa stands are affected by management and location with a decline in plant population expected over the first 4–5 years. Stands can persist for over 20 years in low rainfall climates that have a distinct winter dormant period, provided soils do not freeze and cause plant death.

For alfalfa, the quality of herbage is directly related to the fraction of leaf and palatable stem compared with lower quality lignified stem. During vegetative crop growth, the first 2 tonne DM/ha is predominantly high quality forage with a crude protein content of at least 25 percent. As alfalfa matures beyond this stage the proportion of lower quality stem material increases and the overall leaf to stem ratio declines (Marten *et al.,* 1988). So for high quality hay, alfalfa is cut normally at the early flowering stage or sooner. When alfalfa is grazed in a rotational system it is recommended that each paddock is rested for 35–42 days before re-entry of livestock (Moot *et al.* 2003). Continuous grazing (or set stocking) contributes to a decline in root reserves and consequent death of weakened plants. Allowing a period of extended autumn regrowth is beneficial to replenish root reserves and aids persistence of the stand.

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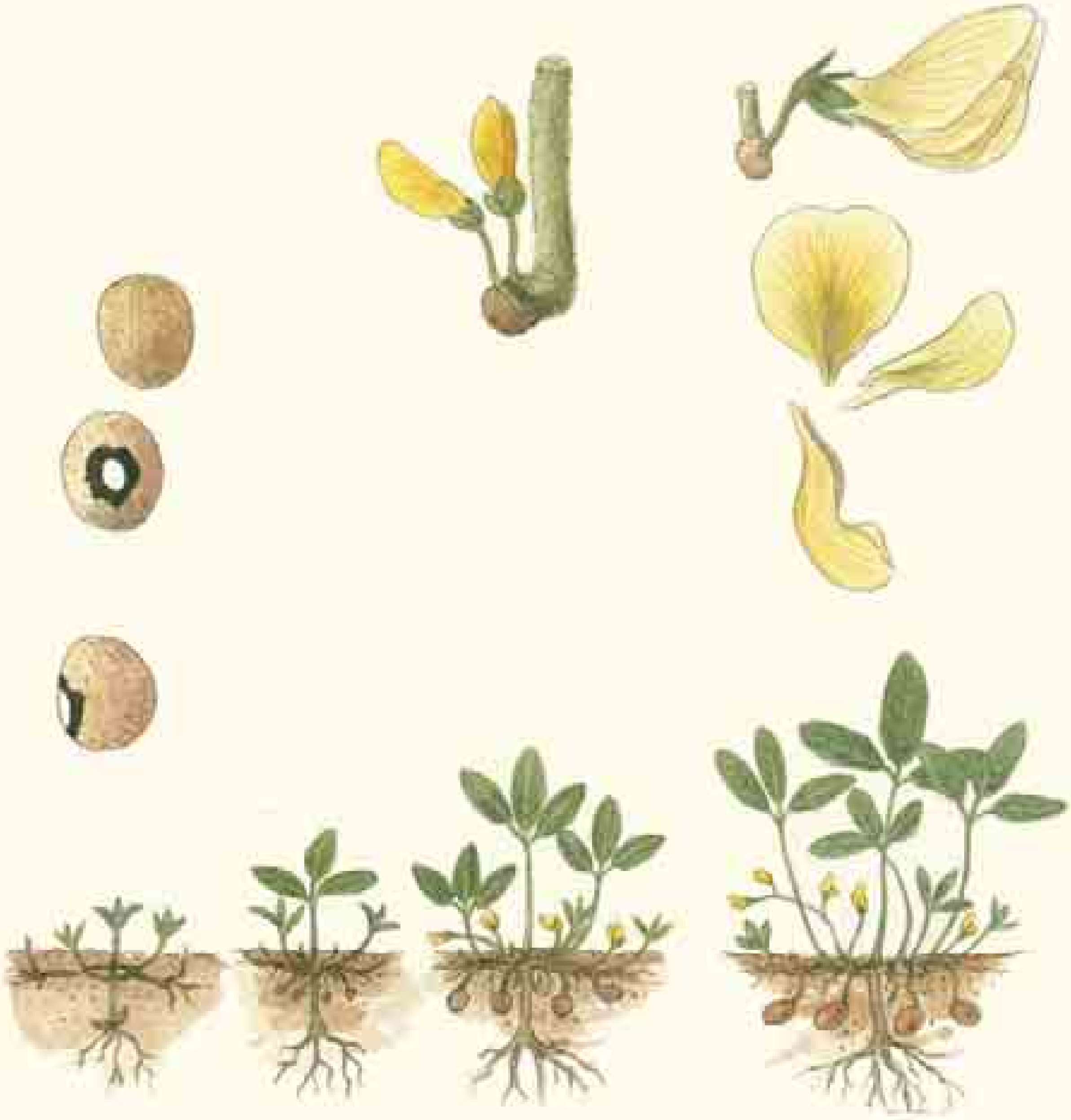

Bambara Groundnut

Bambara Groundnut

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GENERAL DESCRIPTION

Bambara groundnut (*Vigna subterranea*) is an indigenous food legume crop that originated in the regions between the Jos Plateau in northern Nigeria and Garu in Cameroon. The variety *subterranea* is the cultivated form with wild forms belonging to variety *spontanea* (Pasquet *et al.*, 1999). No established varieties exist and, to date, there have been no coordinated programmes of crop improvement, resulting in high genetic variability within cropped fields. Marginal and subsistence farmers in Africa grow locally selected 'landraces', which are often grown from seeds stored from previous harvests or from unregulated supplies of seeds bought from local markets.

Bambara groundnut has been grown widely in Africa for many centuries and now plays a significant role in cropping systems in semi-arid sub-Saharan Africa. It is mainly grown by women farmers for the subsistence of their families, often intercropped with cereals, tuber crops, vegetables, and other legumes (Linnemann, 1991). Bambara groundnut has been introduced through historical migrations to Indonesia, Thailand and Malaysia. More recently, the crop has been experimentally evaluated in India. (See Figure 1 for area harvested and yield).

GROWTH AND DEVELOPMENT

Because pod formation occurs at or just below the soil surface, this crop benefits from a well-prepared seedbed. The planting density is variable and there seems to be significant plasticity in response to planting density. In Swaziland, five plant densities between 33 000 to 267 000 plant/ha were investigated (Edje *et al.*, 2003). Across this range, the number of pods per plant varied between 40.5 and 5.8. However, there was no effect of these planting densities on seed yield.

FIGURE 1 World bambara groundnut harvested area and average yield over the period 1961-2009 (FAO, 2011).

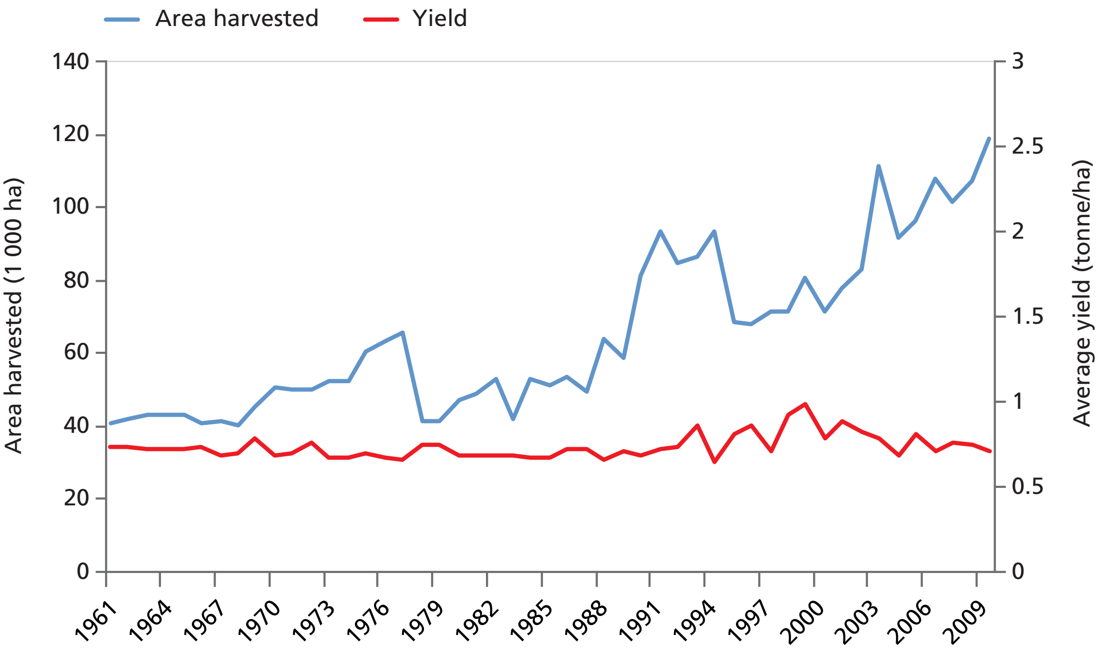

TABLE 1 Duration of developmental stages in bambara groundnut landrace-UniswaRed with different sowing dates in Botswana and Swaziland.

Region		**Notwane, Botswana**		**Malkerns, Swaziland**
Landrace		**Uniswa Red**		**Uniswa Red**
		Sowing date		**Sowing date**
	21 Dec 2006	**18 Jan 2007**	**1 Feb 2007**	**26 Nov 2002**
Days after sowing to:				
Emergence	7	7	7	11
Flowering	55	55	57	74
Max rooting depth	58	58	60	79
Max canopy	68	69	72	93
Canopy senescence	77	80	84	105
Maturity	127	130	135	130
Duration of yield formation	40	48	66	58
Duration of flowering	23	25	28	31

Generally, the growing season begins in December in most of the Southern African region whereas in parts of Eastern African farmers may plant in two seasons around December and June. When water supply is unlimited, the rate of germination is dependent on temperature, genetic variability, and seed size and age. Germination generally takes 7 to 15 days and the maximum rate of seed germination occurs around 30 °C, with no germination below 9 °C or above 45 °C (Massawe *et al.*, 2003). The length of the main growth stages is reported in Table 1. Once established, the seedling enters a period of leaf initiation with very little root growth. By about 35 days, the plant has 6-10 leaves with a shallow root system. From this stage onward leaf and root growth occur simultaneously with the above ground parts making up an increasing proportion of total plant dry weight. The evolution of canopy cover (CC) is temperature dependent and, at optimal temperature, maximum CC (CC_x) is reached after about 60 days in field conditions. Onset of flowering ranges between about 45 and 70 days after sowing. Bambara groundnut is an indeterminate crop, with overlapping of vegetative and reproductive phases, as leaf production continues alongside flowering and podding. The total growing period ranges from 120 to 140 days. Across landraces, stands of bambara groundnut effectively extract water down to at least 0.90 m under drought whilst when water is unlimited most extraction occurs in the top 0.50 m of the soil profile.

A major labour requirement is the practice of earthing up, also known as ridging, which involves covering the developing pods with soil. Different reasons are given for this practice, including better pod development, protection of the pods against pests and disease and avoidance of waterlogging where rainfall intensities are high. However, there is no clear quantitative evidence for the benefits of earthing up across different environments.

WATER USE & PRODUCTIVITY

Seasonal transpiration under adequate water supply varies between 500 to more than 600 mm, depending on land races and environment. There is little information on the transpiration of water-limited crops. Water productivity ($WP_{Y/ET}$) varies with landrace and possibly ranges from 2-3 kg/m^3.

RESPONSE TO STRESSES

Bambara groundnut tolerates a wide range of agroecological conditions and poor soils and this resilience to variable and low-input systems makes it popular among farmers with limited resources. In particular, it exhibits a number of drought tolerance traits that confer agronomic advantages over other legumes in low and variable rainfall areas. Nevertheless, severe drought during the vegetative phase affects leaf and dry matter production. Water availability influences the allocation of dry matter to reproductive yield with harvest index (HI) reduced by up to 16 percent under water limitation.

There are reports of significant effect of heat stress on pod formation in some landraces (e.g. Uniswa Red from Swaziland). Experimental evidence from controlled environment glasshouses at Nottingham, United Kingdom showed that, whilst Uniswa Red produced a massive vegetative canopy through unrestricted leaf production and expansion, it exhibited a 45 percent reduction in HI when exposed to temperatures above 33 °C. Whilst high temperatures clearly influence reproductive performance disproportionately more than vegetative performance, it is not known how temperature stress reduces pod formation. Whether the maintenance of leaf production and expansion at high temperatures may be a cause or a consequence of poor pod formation, it results in the major proportion of biomass being allocated to vegetative development. The reduction in pollen viability due to heat stress may be associated with poor pod set.

Bambara groundnut is a short-day species. While flowering is generally set by thermal time, very unusually, the onset of pod growth is affected by photoperiod (Harris and Azam-Ali, 1993). At daylengths longer than 12 hours, the crop will take longer to initiate pod filling, delaying maturity.

IRRIGATION PRACTICE

Generally, bambara groundnut is grown as a rainfed crop in semi-arid Africa. Where available, irrigation practices enhance the total productivity of the crop. However, even when water is not limiting yield is still subjected to the daylength control of pod growth. This has important implications both for rainfed and irrigated production as sowing date needs to be set by the optimal daylength for pod filling and seasonal rainfall and/or irrigation need to fit within this production interval. When water resources are limited and daylength is not a constraint, any available water should be applied during the late vegetative period (up to flowering) to ensure that the maximum numbers of pods are set, provided that water is not so restricted as to shorten the crop life cycle markedly.

YIELD

Yields under favourable conditions may range from 3.0 to 3.8 tonne/ha (Collinson *et al.*, 2000). However, as a result of genetic variability and because the environments in which bambara groundnut is grown are characterized by various biotic and abiotic stresses, typical yields are extremely low and vary between 0.65 and 0.85 tonne/ha for most of the semi-arid tropics (Hampson *et al.*, 2000). In practice, there are large differences in reported yields between and within countries, with yields as low as 0.06 to 0.11 tonne/ha (Zambia), 0.05 to 0.66 tonne/ha (Swaziland), and 0.07 to 0.86 tonne/ha (Zimbabwe). At harvest, the ratio of pods to total dry matter (Harvest Index, HI) is in the range of 0.30 to 0.45. The HI decreases under drought, temperature stress and longer day lengths, and is maximal when applied water is sufficient for maximum canopy cover to be achieved and daylength and temperatures are optimal. The nutritional composition of bambara groundnut (protein content is 16-25 percent) is comparable or superior to other legumes (Linnemann and Azam-Ali, 1993), providing an important supplement to cereal-based diets.

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Quinoa*

*Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyans, this colour varies from green-yellowish to deep purple and even black throughout quinoa varieties.

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Quinoa

GENERAL DESCRIPTION

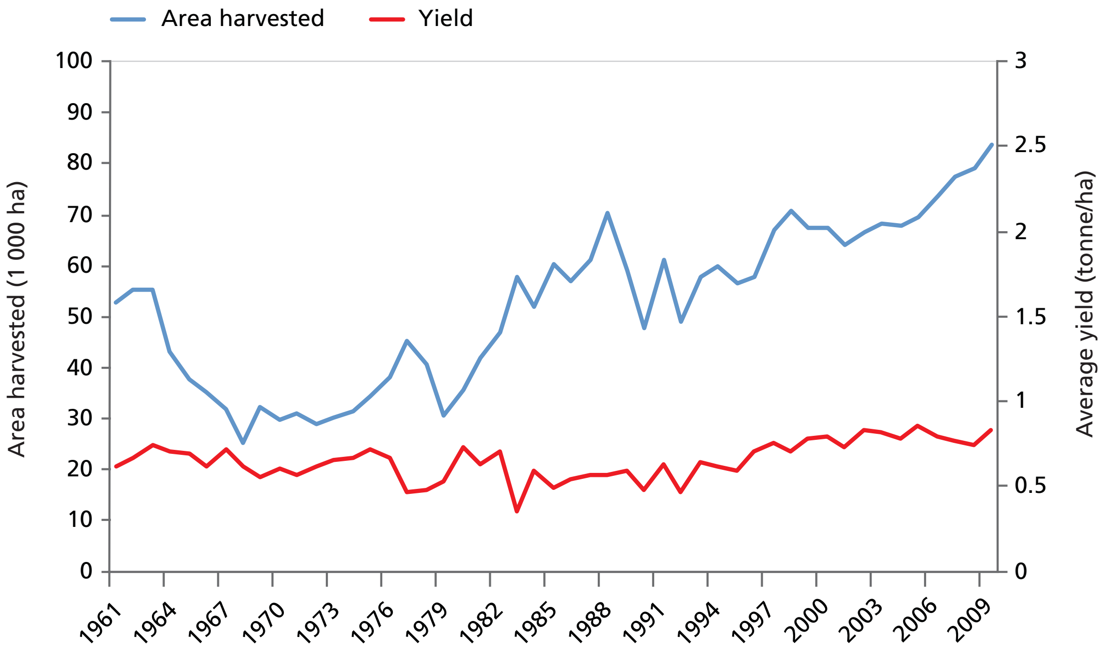
Quinoa (*Chenopodium quinoa* Willd.), a species of the goosefoot (*Chenopodium*) genus of the family of sugar beet, beetroot, mangold and spinach, is a grain-like crop grown primarily for its edible seeds. It is a seed crop, rather than a true cereal, or a grain, as it is not a member of the grass family. It is native to the Andean mountains where this traditional seed crop has been cultivated in the Peruvian and Bolivian Andes for more than 7 000 years. Although the production declined significantly during the Spanish conquest, popularity of quinoa rose again in the last century. Production is now widespread in the Andes, covering Bolivia, Peru, Ecuador, Colombia and the north of Argentina and Chile. As a crop with a large food utilization potential, it is rapidly gaining interest globally, being already fairly known in North and Central America, Brazil, Europe and Asia (Schulte auf'm Erley *et al.*, 2005). First results also indicate the potential of quinoa in Africa. In 2009, 83 thousand hectares were sown to quinoa, producing 69 000 tonne of grain at an average grain yield of 0.8 tonne/ha (FAO, 2011). The worldwide trend for cropping area and production over the last 50 years is shown in Figure 1.

Quinoa is characterized by an enormous intra-species variety and plasticity that allows the crop to grow under highly diverse climatic and agronomic conditions. It is well adapted to arid and semi-arid locations and grows from sea-level to high altitudes, up to Andean Altiplano at around 4 000 m above sea level, where its cultivation is of special importance. Quinoa is cultivated as a mono-culture (e.g. Southern Bolivian Altiplano) or in rotation with potato and barley, and sometimes with wheat and maize at the low altitudes. When cultivated as mono-culture, fields are left fallow for 1 to 3 years and sometimes even longer (up to 10-12 years) for pest control, soil fertility regeneration and build up of the soil water reserve. Traditionally, a range of quinoa landraces is cultivated in the same vicinity, though for export purposes a few local cultivars sown in monoculture are generally preferred (e.g. quinoa var. Real Blanca). Daylength neutral cultivars of quinoa can be grown under the long day conditions of northern Europe (Christiansen *et al.*, 2010).

GROWTH AND DEVELOPMENT

Quinoa is a C_3 annual dicot of 0.5 to 2 m height, terminating in a panicle consisting of small flowers, and with only one seed of around 2 mm

FIGURE 1 World quinoa harvested area and average yield over the period 1961-2009 (FAO, 2011).



produced per flower. In the Andean highlands, quinoa is grown from September to May, and normally without any fertilizer or pesticide. In the Bolivian Altiplano, the sowing date varies between the beginning of September and the end of November, according to the crop cycle length of the different cultivars and local climate, particularly when the soil is moist enough for germination. Sowing practice is the key for the success of quinoa. Superficial sowing runs the risk of seed dehydration or sunburn whereas deep sowing can prevent emergence; in both cases, a poor stand and uneven canopy cover occurs with detrimental effects on final yield. Common practice is to sow between 8 to 15 kg of seeds per hectare in rows 0.4 to 0.8 m apart, either on top of the bed or in the furrow, with plants spaced about 10 cm apart within the row after thinning. Another practice, adapted to arid environments where commercial production is widespread, is to group several plants each in pits spaced about 1 m apart. Less common are transplanting (Inter-Andean valleys) or broadcasting of the seeds. As nutrients are often scarce in the Altiplano, early weeding (± about 30 days after sowing) and thinning of excessive plants are important activities in the areas where rain is sufficient to allow for rapid plant growth. In arid areas, instead, weeding and thinning are not practised, even in commercial production.

Phenological development is highly variable among varieties. Additionally, phenology is highly flexible in response to water stress, with differences in time to maturity of as much as 30 days for the same cultivar (Geerts *et al.*, 2008c). Under no stress conditions, time from sowing to emergence is 3 to 10 days. The time to maximum canopy cover (CC_x) depends on plant density and temperature regime. Phenology is further complicated by a response to photoperiod — a short day response for duration of emergence to flowering, and for the duration of all developmental phases in some cultivars (Bertero, 2003). The time from emergence to physiological maturity varies between 100 and 230 days, again because of wide variation among cultivars. Flowering starts between 60 to 120 days, and lasts around 20 days. Canopy senescence starts generally about one month before physiological maturity, and progresses relatively fast. It is important to note that these indicative values are given for cultivars cultivated at high elevations, and could be biased because growing conditions (temperature, fertility, water supply) are not optimal. Roots, often with numerous ramifications, can deepen to 1.80 m depth in cases of drought stress in light soils.

In the southern Andes, quinoa is harvested in April-May, mainly by pulling out or cutting the plants and leaving them in stacks on the field to dry. Harvest can take up to 1.5 months because of asynchronous flowering and ripening. In principle, realistic simulation of such production practice with *AquaCrop* would entail simulations runs for each maturity group, and then summing up the yields of all groups in proportion to their population density or land area occupied (Figure 2. Example of quinoa).

WATER USE & PRODUCTIVITY

In midseason, quinoa reaches maximum canopy cover (CC_x), shortly after first anthesis. CC_x is largely dependent on the management conditions and, to a large extent, determines quinoa transpiration. For a complete canopy cover of the ground and under non-limiting nutrient conditions, quinoa transpires at a rate similar to the reference evapotranspiration (ET_o). Seasonal ET values for quinoa with a normal season length of 150-170 days are around 500 mm under non-stressed conditions. As a C_3 crop, normalized crop water productivity (WP*) is low,

FIGURE 2 Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyanins, this colour varies from green-yellowish to deep purple and even black throughout quinoa cultivars.

with typical values around 10.5 g/m^2 under the low, natural fertility in the Bolivian Altiplano (Geerts *et al.*, 2009). Still-under poor fertility conditions, a decrease of the reference biomass water productivity (WP*) value only occurs at higher total transpiration sums, and only by 10 percent. The C_3 pathway is well adapted to the prevailing low average temperatures in the Altiplano. Reported values of seed yield per unit of water consumed ($WP_{Y/ET}$) are rather low and lie between 0.3 and 0.6 kg/m^3 because of the generally prevailing low fertility conditions (Geerts *et al.*, 2009). On the other hand, it is a crop with a large nitrogen-sink thus causing an increased metabolic cost or higher glucose-equivalent per unit dry matter produced. To our knowledge, no research has been conducted on the response of quinoa to increases in atmospheric CO_2.

RESPONSE TO STRESSES

Quinoa is highly resistant to a number of abiotic stresses (Jacobsen *et al.*, 2003). Several drought resistant mechanisms are present in quinoa. Drought in early vegetative stages may prolong its life cycle, allowing the plant to make up for growth lost during the early drought if water is available later. Also, the availability of cultivars with different season length makes it possible to match the water requirement of the quinoa crop to the available rainfall or the stored soil water at a given location. Quinoa tissue is relatively high in osmotic solutes and undergoessubstantial osmotic adjustment under drought, which enable stomata to remain somewhatopen down to a leaf water potential range of -1.5 MPa. During soil drying the plants are able to maintain leaf water potential and photosynthesis due to the complex stomatal response, resulting in an increase of leaf water use efficiency. Root originated ABA plays a role in stomata performance during soil drying. ABA regulation seems to be one of the mechanisms utilized by quinoa when facing drought inducing decrease of turgor of stomata guard cells (Jacobsen *et al.,* 2009). The plant also avoids negative effects of drought through fast and deep rooting particularly in dry soils. Quinoa also reduces its leaf area by controlled leaf senescense under drought.

Quinoa is a facultative halophyte (Bosque-Sanchez *et al.,* 2003) and can grow in non-saline to extremely saline conditions, depending on the cultivar. Seed production is enhanced by moderate salinity (EC in the 5-15 dS/m range) and may not be drastically reduced even at EC of 40 to 50 dS/m in some cultivars (Jacobsen *et al.,* 2003). Osmotic adjustment by the accumulation of salt ions in tissues enables the plant to maintain cell turgor and transpiration under saline conditions.

Apart from drought, frost and cold are the other major growth limiting factors in the Altiplano. Quinoa is tolerant to frost, partly because of the protection provided by its heterogeneous canopy (Winkel *et al.,* 2009), although the tolerance varies with cultivar and appears to diminish at the late phenological stages (Jacobsen *et al.,* 2005). Leaf freezing of quinoa occurred only between -5 and -6 °C, and is delayed in case of mild water stress (Bois *et al.,* 2006). The resistance to frost is associated with super cooling of tissue water and tolerance of extracellular ice formation (in the cell wall), as is common for most winter crops.

Linked to frost resistance is a low base temperature (T_{base}) for plant processes. In a study of the leaf appearance rate of different quinoa cultivars originating from various altitudes and latitudes, T_{base} averaged 2 °C and the temperature at which maximum rate was reached averaged 22 °C. Other studies found a T_{base} of 3 °C, T_{opt} of 30-35 °C and T_{max} estimated to 50 °C

(Bertero *et al.*, 2000; Jacobsen and Bach, 1998).Temperature sensitivity of quinoa was highest in cultivars originating in cold and dry climates and lower in cultivars from warmer and humid climates (Bertero *et al.,* 2000).

Because soil fertility is generally poor in its centre of origin, cases of quinoa cultivation under non-limiting soil fertility are very rare. Research into nitrogen and phosphorus requirements conducted in Colorado, United States, found that maximum yields over 4.5 tonne per ha are possible when 170 to 200 kg N/ha were applied (Oelke *et al.,* 1992). If these results are confirmed in other studies, the WP* of quinoa under non-limiting fertility would be much higher than the value of 10.5 g/m^2 reported earlier for the low fertility natural conditions of the Andean Altiplano. No effect on yield was observed when 34 kg of phosphorus (as phosphoric acid) per ha was applied, in comparison to an untreated field plot (Oelke *et al.,* 1992). In areas of traditional cultivation, some sheep or lama dung is applied when available; but mostly, quinoa is sown in unfertilized fields. If sown after potato, nutrient supply is generally better because of the nutrients left over from the potato fertilization.

IRRIGATION PRACTICE

As quinoa is drought resistant, it is traditionally cultivated under rainfed conditions, even in semi-arid locations. Researchers, though, started to study the impact of additional water on quinoa production and found that deficit irrigation (DI) was highly beneficial in various experimental locations. DI is already practised for the reintroduction of quinoa in arid regions of Chile. On the other hand, currently quinoa is rarely cultivated under full irrigation, as research of quinoa under full irrigation gave only slightly better results than quinoa cultivated under deficit irrigation (Geerts *et al.*, 2008a and b), besides the issue that sufficient water for full irrigation is mostly unavailable.

YIELD

Quinoa produces nutritious seeds (Alvarez-Jubete *et al.,* 2009) with high protein content (from 12 up to 20 percent), as compared to maize, rice or even wheat. The balanced amino acids composition makes the protein quality comparable to that of milk, making it an effective meat and milk substitute. Additionally, quinoa is gluten free, which is advantageous for commercial food manufacturing for celiac consumption. On the other hand, the seeds also contain the anti-nutritional component saponin (Mastebroek *et al.,* 2000), that the plant produces as an inherent protection against pests. Saponin is removed by washing or dry polishing before consumption.

Although high yields (up to 4.5 tonne/ha and more) have been occasionally reported for some quinoa cultivars under non-limiting fertility and water conditions, rainfed yields in the Peruvian and Bolivian Altiplano do not exceed 0.85 tonne/ha as an average. Pests, including birds and rodents, and diseases are major causes of yield loss, in addition to low fertility and water deficits. Harvest index (HI) of quinoa in the field ranges between 0.3 and 0.5. Building up of HI takes a short time for the short season cultivars, and up from 80 to 100 days for the long season cultivars. Individual grain size is quite variable among cultivars, with 1 000 grain weight ranging from 1.2 to 6.0 g in non-stress conditions (Rojas, 2003).

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Tef

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Tef

GENERAL DESCRIPTION

Tef (*Eragrostis tef* [Zucc.] Trotter) is a C_4 annual grass (Holden, 1973; Hirut *et al.,* 1989) also known as bunch grass, which originated and diversified in Ethiopia (Vavilov, 1951). It is one of the most important cereal crops in that country, ranks first in cultivated area among all annual crops and occupies about 29 percent of the land devoted to cereals. Tef yield is quite low (averages around 1 tonne/ha or less), but accounts for about 20 percent of the total cereal production (in most cases second to maize) in Ethiopia. The trend there over the last decade is an increase in cultivated area (about 25 percent) and a 45 percent increase in yield per hectare. Outside Ethiopia, tef is also traditionally grown in Eritrea, and to a lesser extent in India.

Tef is predominantly grown alone, though it is intercropped occasionally with oil crops such as rapeseed, safflower and sunflower or relay-cropped with maize and sorghum (Seyfu, 1997). In Ethiopia, tef is often rotated with pulses, such as field pea, faba bean, chickpea, or oil crops like linseed depending on location and the type of soil. In most cases a 4 or 5-year rotation is common, with pulse/tef/tef, wheat or barley/pulse, and pulse/tef/tef/other cereal/pulse.

Tef is predominantly produced as a staple food for local consumption and an important cash crop for farm households. The grain is grounded into flour to make a pancake-like local bread called *Injera*. It provides about two-thirds of the daily dietary protein intake for most Ethiopians (NRC, 1996). The protein content of the grain is about 9-11 percent, slightly higher than sorghum, maize or oats, but lower than wheat or barley. Tef is also appreciated as a fodder crop, with nutritious straw preferentially given to lactating cows and oxen used for traction. Moreover, its straw is the preferred binding material in Ethiopia for walls, bricks and household containers made of clay.

Tef grain contains gluten lacking the gliadin fraction that causes coeliac disease; therefore it can be consumed by gluten intolerant people. The amino acids of protein in tef grain are fairly balanced. These properties make tef an attractive potential crop for cultivation outside its traditional areas. Countries like the United States, Canada, Australia, South Africa, and Kenya began production of tef for different purposes, as a forage crop, as a component of porridges and pancakes, and as a thickener for soup and gravy, probably because tef flour imparts the product a short, stiff texture and a slight molasses-like sweetness.

GROWTH AND DEVELOPMENT

The common method of sowing tef is hand broadcasting. The tef seeds are extremely small, weighing 250 to 350 mg per 1 000 seeds (*NRC, 1996*). Hence, special care is necessary to prepare a fine and smooth seed bed. This entails ploughing the field between 3 to 6 times (Aune *et al.*, 2001) to pulverize the soil and cover the seeds lightly after sowing. A seeding rate of 25-30 kg/ha is recommended for broadcast sowing (Fufa, *et al.*, 2000 and Seyfu, 1997). Sowing period in Ethiopia ranges between mid-July to early August, depending on local climate, soil type and life cycle length of the cultivar, and usually when the soil water is near field capacity.

Emergence takes a few days or longer (between four and 11 days), depending on soil moisture and temperature. Soil temperature below 19 °C slows the rate of emergence. Vegetative growth and canopy development (Alemtsehay *et al.*, 2011) follows the common pattern for other crops, as does biomass accumulation. Because tef is usually planted at high density (e.g. 2 000 plant/m^2), full canopy cover (CC_x) is reached early. Final height of the plant ranges from 0.6 m to just above 1 m.

Tef is self-pollinating, with very small inconspicuous flowers typical of grasses borne on panicles (Figure 1), which can range from loose to compact (Seyfu, 1997). It is photoperiod sensitive and its time to flowering is accelerated by short days. Under certain conditions, flowering can start as early as 40 days after sowing or even earlier. Since the stem terminates at the panicle, the earlier the flowering, the fewer the leaves produced on the stem. Time to flowering ranges from about 35 to 65 days, as observed in various studies. Canopy senescence starts

FIGURE 1 Tef showing panicle type of inflorescence on the left and panicles bearing seeds on the right.

about 55 days or more after planting, depending on genotype and environmental conditions. Rooting depth of tef grown in plastic tubes differs with genotype and ranges from 0.6 to 1.0 m at heading (Mulu *et al.*, 2001).

As tef grain fills and approaches maturity, lodging is often a problem, especially if the grain is bountiful and there is strong wind and heavy rain. Tef is harvested when the vegetative part turns yellow or brown. Depending on the maturity group of the cultivar and photoperiod, tef may be harvested between 60 and 150 days after sowing (Fufa *et al.*, 2001).

WATER USE & PRODUCTIVITY

In Ethiopia, tef performs well with annual rainfall of 750-850 mm and 450-550 mm during its growing season, but reasonable yield can be obtained with 300 mm of rainfall in its growing season (Seyfu, 1997). There is very little reported research on its water productivity (WP) other than the first attempts to estimate normalized WP (WP*) of tef for use in *AquaCrop* simulations. The values arrived at in two studies (Araya *et al.*, 2010; Alemtsehay *et al.*, 2011) fell in the range of 14 to 20 g/m^2, similar to values common for C_3 species but much lower than the 30 g/m^2 found for other C_4 species. The low WP* of tef is attributable at least partly to low N fertilization, as the crop was fertilized with only 60 kg/ha of N, in both studies. The general WP* values noted above for C_3 and C_4 species are for crops grown with optimal mineral nutrition (receiving 150 to 250 kg N/ha). Additional and more definitive study of tef WP is much needed.

RESPONSE TO STRESSES

Tef is genetically diverse, grown at elevations of 1 000 to 2 500 m and a mean temperature range of 10°C to 27°C (Seyfu, 1997). The crop is considered to be tolerant to both drought and waterlogging (Mulu *et al.,* 2001). This feature is valuable to poor farmers in locations with highly variable environmental conditions.

With regard to water stress, at least one of the coping mechanisms is apparently osmotic adjustment. In a study (Mulu *et al.,* 2001) with many genotypes, it was found that most of the tef lines osmotically adjusted by more than 0.4 MPa to slowly developing drought. However, under water stress canopy senescence is accelerated (Araya *et al.,* 2010) as in most crops. Many cultivars require 200 to 300 mm of water during their early growth (NRC, 1996). Seyfu (1997) mentioned that 300 to 500 mm of rainfall is adequate in a growing season and even less than 300 mm seasonal rainfall may be sufficient for early-maturing cultivars. This is the reason why tef is often planted after a cereal fails because of early drought, as a rescue crop in the same season, taking advantage of later rains to yield some grain and straw. Seasonal ET of early maturing tef estimated using *AquaCrop* or other simulation models for Ethiopian high lands would fall in the range of 280 to 300 mm. Hence, a short life-cycle tef may not even experience water stress in such a situation, albeit the yield would be less compared to longer cycle cultivars.

Tef grows on a wide range of soil types. To improve the yield where nutrients are limiting, one recommendation is to apply phosphorus at the rate of 60 kg P_2O_5/ha at sowing to both light and heavy soils, and 40 kg and 60 kg of nitrogen per hectare, respectively, to light and heavy soils (EARO, 2002). Tef has some tolerance to frost and flooding, and to high temperatures up to 35 °C, but cannot survive a prolonged freeze (NRC, 1996).

IRRIGATION PRACTICE

Irrigation is not commonly practised in the traditional culture areas, though water scarcity is the major limiting factor for tef growth in arid and semi-arid regions of Ethiopia because of inadequate and erratic rainfall. Research shows clearly that tef benefits from supplementary irrigation in locations prone to terminal drought by maintaining the green canopy longer (Araya *et al.,* 2010).

YIELD

The national average yield under rainfed condition in Ethiopia is around 1 tonne/ha, although yields more than 2 tonne/ha may be attainable with good agronomy. One reason for the low yield is the nitrogen limitation. In one study (Tulema *et al.,* 2005) on two soil types and three locations in Central Ethiopia, a late-maturing cultivar of tef yielded 0.77, 1.6 and 1.9 tonne/ha, and the measured N (grain plus straw) totaled 58, 103 and 126 kg/ha, at the three locations. 64 kg/ha of N was applied to the soil in all cases. For the highest yield, the amount of N applied was only about half of the N removed by 1.9 tonne/ha crop. These results indicate that N may be a major factor limiting current yields. Nevertheless, increasing N fertilization may increase lodging, and another likely reason for low yield is tef's tendency to lodge while the canopy is still green. The potential for yield increase by minimizing lodging was shown in a study (Teklu and Tefera, 2005) where many cultivars were optimally grown in the field through fixed nettings to provide support for the stems and prevent lodging. The yields varied from 2.9 to 4.6 tonne/ha, with a mean of 3.8 tonne/ha. Efforts are apparently underway to breed for lodging resistance (van Delden *et al.,* 2010).

Still another reason for the low yield of tef is its low harvest index (HI). As a national average for Ethiopia, an HI of 0.24 is reported by Seyfu (1997). Teklu and Tefera (2005) found HI to be in a similar range for their many tef cultivars. On the other hand, Temesgen *et al.* (2005) reported mean HI ranging from 0.33 to 0.38 for different clusters of germplasm accessions, but did not specify the plant density. In contrast, HI of modern cultivars of other cereal crops fall around 0.45 to 0.50.

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