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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).

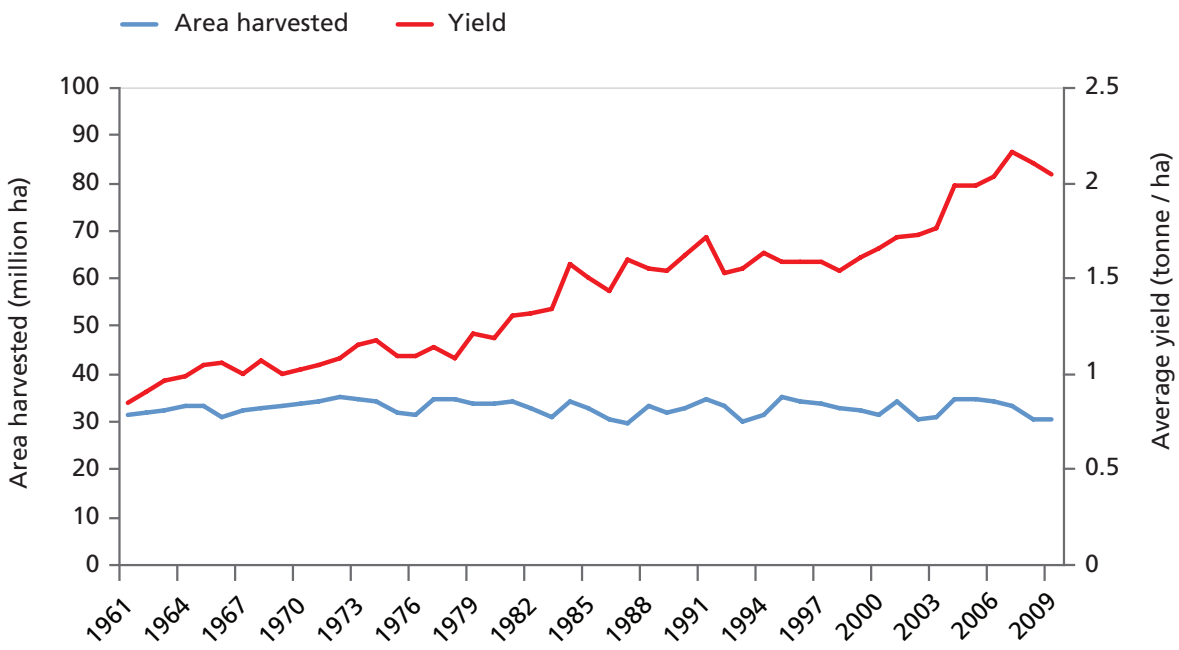
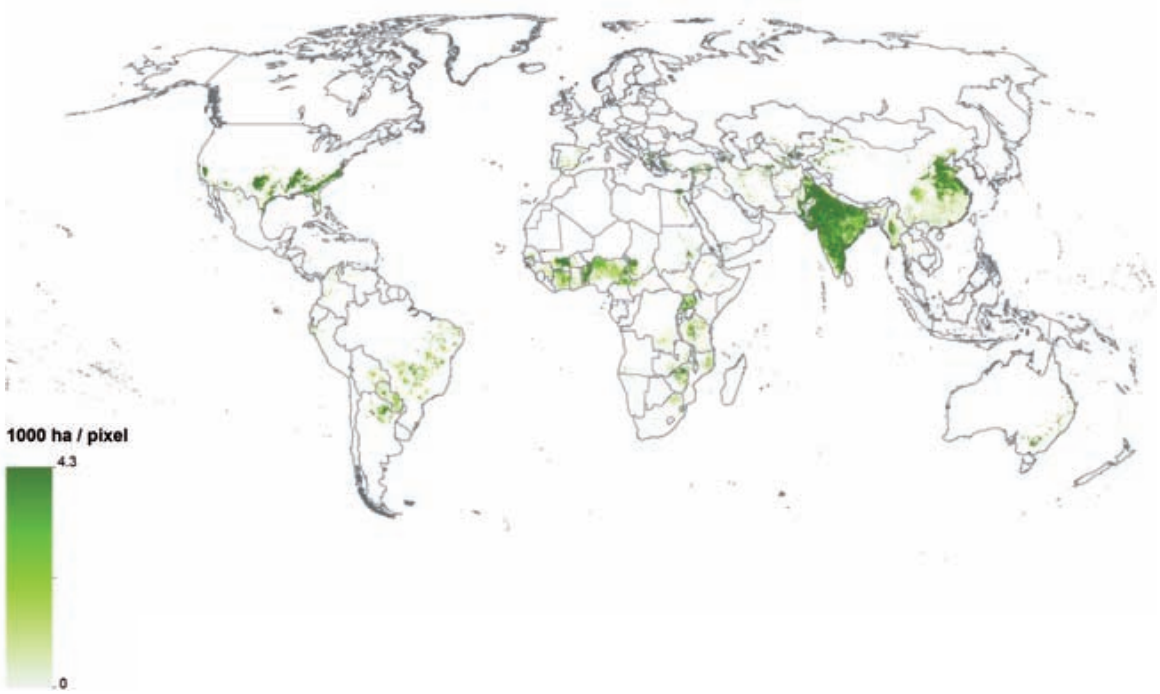


FIGURE 2 Cotton harvested area (GAEZ, 2011).



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.

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 f ower	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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