COTTON AND WATER – AN AGRICULTURAL PERSPECTIVE

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Without question fresh water resources are over allocated in many parts of the world where demand exceeds sustainable supply. Because cotton is a drought and heat tolerant crop, it is often grown in areas where water is limited. This can create the misperception that cotton requires excessive amounts of irrigation, but in reality, less than 50% of the world's cotton relies on irrigation. However, irrigation does stabilize and increase agricultural productivity, resulting in growing consensus that water shortages will be directly linked to unstable and decreased food supplies. This places importance on a crop like cotton because it has the ability to provide cash income through fibre, and add to the world's total feed and food supply – all while growing in harsh, water limited conditions. Furthermore, advances in science and technology will allow cotton's water use efficiency to continue improving, allowing it to make even better use of limited water resources.

Water is a key ingredient to human survival in direct use for drinking and sanitation, and water is also critical for power generation and food production (WWAP, 2012). Predictions on climate change will further challenge agricultural water resources and increase food insecurity beyond the impact of population growth alone (Elliot et al., 2013). Some company's shareholders are now asking that water risks be evaluated across the supply chains (Orr et al., 2011).There is expanding public scrutiny of water use coupled with an increasing awareness that water resources are over allocated. Because cotton is very heat and drought tolerant, it is commonly grown in areas with limited water supplies, and this is often improperly associated with excessive water use. While it is estimated that agriculture accounts for about 70% of humanity's freshwater use, water for cotton production only represents 3% of that water use (Hoekstra and Chapagain, 2007). The objective of this paper is to robustly document why the decreasing availability of water resources is a significant concern for cotton producers, and why limited water resources will result in the increasing importance of cotton to humanity in the future.

QUANTITY OF WATER USED BY COTTON

Cotton's water use is not unlike other agricultural crops, nearly proportional to its land use as illustrated in Figure 1, both of which are approximately 3% of global crop use. The crop water productivity (CWP = mass of economical beneficial product in kg per volume of water used in m^{-3}) is also similar to other crops as reported by Zwart and Bastiaanssen (2004). For example, wheat has a global mean value of 1.1 kg m^{-3} and seed cotton (harvested product before ginning) has a mean value of 0.65 kg m^{-3}. When considering the fibre only, Zwart and Bastiaanssen (2004) report a value of 0.23 kg m^{-3}, but considering only the fibre is technically not a correct definition of CWP as the seed is economically valuable as both animal feed and cooking oil.

In Life Cycle Assessment reports and in a concept referred to as a water footprint, the CWP is essentially inverted to report the volume of water needed to produce a unit mass of product.

Using the data from Zwart and Bastiaanssen (2004), 1.5 cubic meters of water is used to produce a kg of seed cotton fibre, and 4.3 cubic meters of water to produce a kg of cotton fibre. Sometimes units of litres per kg, or 4,300 litres per kg are reported. Using these units the water to produce cotton can be made to sound rather excessive but is quantitatively equivalent to saying 0.4 mm of rainfall on one ha of land will produce a kg of cotton. Units used for rainfall are a more accurate context for cotton production given that more than 50% of the cotton in the world is produced using just rainfall and nearly all cotton fields receive some rain.

Another challenge for interpreting water metrics used in product comparisons is that many of the metrics used only consider water that is evaporated and leaves a watershed (often referred to as consumption). A significant amount of water in the world is used for power generation, and because that water is returned to the stream or lake it was removed from, is not accounted for in some water footprint approaches and LCA measures. However, from a water risks perspective, the water needed to generate power cannot be ignored. If a river or lake goes dry due to prolonged drought, water is not available for cooling and power generation will stop. Therefore, it is important to consider all of the water associated with a product – not just consumption. Furthermore, it is not always the case that irrigation water that is evaporated leaves the watershed before being returned as rainfall (Lo and Famiglietti, 2013). Barnes et al. (2103) provide a more detail review of various water metrics and some of their limitations when applied to agricultural commodities.

In terms of total water used during the season, cotton is similar to other crops as illustrated in Figure 2. The data in that figure is for an extremely arid environment in the Arizona desert in the south-western U.S. where long season cotton varieties are grown; thus it represents one of the highest water use conditions in the world. But despite the climate, cotton will consistently use less water over the course of the year than the grass grown in someone's lawn. Seasonal water use for cotton varies from between 100 to 80 cm in arid regions such as Syria (Farahani et al., 2009) to a low of 45 cm in more humid regions (Bednarz et al., 2002). However, cotton yields follow the same trends as water – higher yields in more arid regions. Irrigation will almost always increase yields, and therefore, increases land use efficiency. Irrigation also provides a level of "insurance" against period droughts and prevents the investment in seed, fertilizer and land being lost in a dry year.

THE REASONS FOR COTTON'S DROUGHT TOLERANCE

There are several factors about the growth and development that when combined explain cotton's exceptional drought tolerance. The first attribute of cotton's drought tolerance is its extensive root system. Figure 3 illustrates the early formation of cotton root development based on the work of Oosterhuis (2001). Cotton devotes most of its early season development to growth of the root system so that it can benefit from greater areas of stored soil moisture as early as possible. When not limited by soil physical or chemical properties, cotton roots will extend to 1.8 meters below the surface by the middle of the growing season (Coelho et al., 2003). In addition to providing the ability to have a good reservoir of moisture, this also allows cotton to scavenge fertilizers left over from previous crops that are not as deeply rooted. For example, a common management practice is to decrease the amount of nitrogen following corn and soybeans.

In addition to a well-developed rooting system, cotton is also an "indeterminate" plant, meaning it produces flowers during most of the season (Ritchie et al., 2004). About 35 days after planting, flower buds referred to as squares begin to form, and cotton will continue to flower the entire year. The importance of this for drought tolerance is that when there are times of water stress, cotton will cease flowering, and then continue when rain or irrigation is provided. This is in contrast to determinate crops that only flower for a fixed time in their life cycle. If a determinate crop is deprived of water during its flowering period, it may produce no harvestable product.

Another feature that allows cotton to thrive in hot environments is its ability to cool itself via transpiration which continues under severe drought even during the hottest part of the day (Anderson et al., 1977), and the fact it has a relatively high optimal temperature for photosynthesis, estimated by Burke et al. (1988) to be optimal at 28^{o} C, and ranges from 23.5 to 32 ^{o}C. In arid environments, cotton with adequate soil moisture can reduce its canopy temperature by more than 12^{o} C through evaporative cooling to maintain the leaf at a temperature optimal for photosynthetic processes. Additionally, studies have also shown that under the increasing ambient concentration of carbon dioxide associated with global warming, cotton is even more water efficient (Mauney et al., 1994).

The inherent drought tolerance of cotton and the growing realization that water challenges of the future will have the biggest impact in meeting the world's food needs means cotton will be a more important food and fibre crop in a water limited world. Based on data from the USDA for the entire U.S., for every kg of cotton fibre produced, 1.4 kg of cottonseed is also created (USDA, 2013). The seed is high in protein and its oil is commonly used for cooking. Direct consumption of whole cottonseed has been limited to certain livestock species such as dairy cows due to the presence of a natural insecticide called gossypol. However, five years ago a breakthrough discovery was made by scientists at Texas A&M University, and a method was found to remove gossypol from the seed while keeping it in the plant to maintain protection from insect pests. Therefore in the future, cottonseed will be an even more significant high protein food source.

IRRIGATION OF COTTON IN WATER LIMITED REGIONS

The advances in geospatial technologies have now provided global estimates of the level of water stress in the world. An example of a water scarcity index is provided in Figure 4 from the World Resource Institute's Aqueduct database, showing an estimate of "baseline water stress" (BWS, Gassert et al., 2013). BWS is an attempt to estimate the amount of water stress in a region by comparing the water used to the water available. Therefore, BWS can be high even in areas with significant rainfall if the water demand in the region is also high. From Figure 4, it is apparent many parts of the cotton growing regions of the world are classified as under "High" and "Extremely High" BWS.

When viewing cotton through the lens of water scarcity indices, it is important to consider the importance of irrigation to cotton in the region in question, and if irrigation is required, what is the sustainability of the irrigation water source. Two examples from the U.S. illustrate this point. From Figure 4, two areas of U.S. cotton production with BWS rankings of "Extremely High" are western Texas and central California. In western Texas, a major aquifer in the region called the Ogallala is in a state of decline and is largely non-recharging. Some estimate it will no longer be economically feasible to use many areas of the aquifer as an irrigation source in the next 30 to 50 years. Even though this aquifer is used to irrigate cotton, it is more critical for corn production in the region and in a study by Gowda et al. (2007) it was determined that if producers were to convert half of the land from corn to cotton, the aquifer decline would be significantly reduced. Furthermore, while irrigation enhances and stabilizes yields in Texas, over 70% of cotton in the state is grown without irrigation; therefore, cotton will be one of the few crops producers in the region can grow after the aquifer is depleted.

In the case of central California, an even more arid environment, with average annual rainfall of approximately 25 cm, irrigation is essential for cotton production. The source for much of irrigation water is provided by snowmelt that varies year to year. Cotton is an important row crop for farmers in the region due to its heat tolerance; however, in years when the winter snow fall is limited, farmers will not plant cotton and leave the field fallow – saving what water they do have for permanent crops such as pistachios and grapes that require irrigation every year to survive. Such trends to fallow crops in water-limited years are seen in Figure 5 illustrating cycles of water use and fallow land for a water district in central California. Note the increase in fallowed acres (black line) in years when California Valley Project (CVP) water (red bar) is low. The CVP receives water from many sources including winter snowmelt and a large network of canals and storage reservoirs. For short term shortages the district has access to groundwater that be recharged after a wet year; therefore, even in a region where irrigation is required, cotton can still be grown in a responsible manner and provide growers with additional income in water plentiful years.

While the two previous examples were for the United States, similar examples can be found in other parts of the world where cotton requires irrigation. This is especially true in Australia where cotton acreage is highly responsive to available water supplies. While examples of responsible water use are common, past exceptions such as the Aral Sea dominate the Internet. And now because of better water management policies, there are signs the Aral Sea is showing signs of recovery (Walters, 2010).

FUTURE WATER STRATEGY

Even though cotton is drought tolerant, it will often provide a better yield under irrigated conditions, and predictions of increased erratic rainfall patterns in the future are of concern. Therefore it is very important that a holistic water strategy is developed for the future. Three key strategies to help farmers adapt to future climate uncertainties are to: 1) improve rainfall capture; 2) increase the precision of irrigation water delivery and scheduling; and 3) enhance the inherent high water use efficiency of the cotton plant. Each of these strategies is briefly outlined in the following sections.

RAINFALL CAPTURE

Often rainfall patterns do not match times when water is needed by the crop, or occur at such high rates it is not possible for the water to infiltrate the soil surface. Historically, one approach farmers have used to cope with rainfall leaving the field is the use of farm ponds to collect rainfall runoff water. These ponds will continue to be an important tool in the future and research is also being conducted to determine if the utility of the ponds can be increased in some hydrologic settings by allowing the pond to "leak" into the soil profile to recharge shallow water tables (Reba et al., 2013). This would allow increased water storage without sacrificing additional land to increase the surface area of the pond.

A second important opportunity to increase rainfall capture relates to the tillage system used. The adoption of conservation tillage and use of cover crops are increasing around the world (Goddard et al., 2008). Often the first motivation for a transition to these systems is to reduce input costs due to fuel and equipment savings, and secondarily reducing soil erosion and improving overall soil health. Soil erosion is typically reduced by decreased rainfall runoff, especially when a cover crop is used, thus increasing rainfall capture. And increased soil organic matter associated with reduced tillage also increases the ability of the soil surface to infiltrate water and more soil pore space to store water, meaning it is more likely to be there when the crop needs it.

PRECISION IRRIGATION DELIVERY AND SCHEDULING

Even in humid areas, irrigation can increase productivity when rainfall is delayed during the season or due to infrequent drought conditions (Vories et al., 2007). Precise management of irrigation water is an important tool to optimize productivity of the land and to ensure that no other inputs go to waste. New technologies have provided several new tools producers are now using to develop sustainable crop water management strategies. One example is companies who have taken advantage of widely distributed cellular networks to affordably transmit data from sensor networks monitoring water status in the field near-real time (for example, recent work at the University of Zimbabwe is reported by Marimbi et al., 2012). This allows farmers easy access to the water status of the plants in their fields so water is only applied when it is needed.

The precision of irrigation water delivery is also increasing with new technologies. One example that has been particularly successful for cotton in the south western United States had been subsurface drip irrigation where it is used on over 100,000 ha of cotton (Bordovsky and Mustian, 2012). In this system, water is delivered through tubes buried approximately 20 to 40 cm below the soil surface and under the planted row. The water can be applied frequently in small amounts as the crop needs it and essentially no water is lost due to evaporation.

Another example is the use of global position system (GPS) technologies to map changes in the soil within a field and then control sections of an irrigation pivot to apply the volume of water needed for the crop growing in that soil type (Kranz et al., 2012). The combination of sensors and irrigation controllers have resulted in systems that provide the option for completely automated control of the irrigation water. All major centre pivot manufacturers now offer integrated control and wireless data handling systems to farmers.

IMPROVED WATER USE EFFICIENCY

The final key strategy to be discussed is looking for all mechanisms possible to make the cotton plant even more drought resistant and water efficient. One way this can be accomplished is through traditional breeding techniques by crossing varieties that demonstrate superior performance under drought conditions. In the future there is also hope that progress already made in unlocking the cotton genome will provide new insights into the genes that contribute to drought tolerance.

An even more direct method to increase cotton's water productivity is better overall agronomic management. For example, if insect pests are not controlled in a cotton field productivity is lowered, but the same amount of water is still used. Evidence for cotton's increasing water productivity is provided by the upward trend in global cotton yields that have come without the increased use of irrigation water (see Figure 6). In the United States, data shows that average yields have increased over the last 20 years while total irrigation water used for cotton has decreased over the same time period (Field to Market, 2012)

SUMMARY AND CONCLUSIONS

There will be even greater competition for water resources in the future and water shortages will be tightly linked with a tightening of the world's food supply, and likely challenge our energy producing infrastructure. While cotton will not be immune to water resource challenges, the fact its water use is similar to other crops and its inherent drought tolerance will allow it to provide both food and fibre in environments where other crops cannot. Managed wisely, irrigation will be an important tool for farmers to cope with predicted erratic weather patterns in the future. It will be important to continue to implement a holistic water strategy that maximizes the benefits of rainfall, while precisely applying irrigation when rainfall is not sufficient, and developing future varieties of cotton that are even more drought tolerant. With these strategies in place, cotton is positioned to be a critical fibre and food crop for the future.

FIGURES AND TABLES

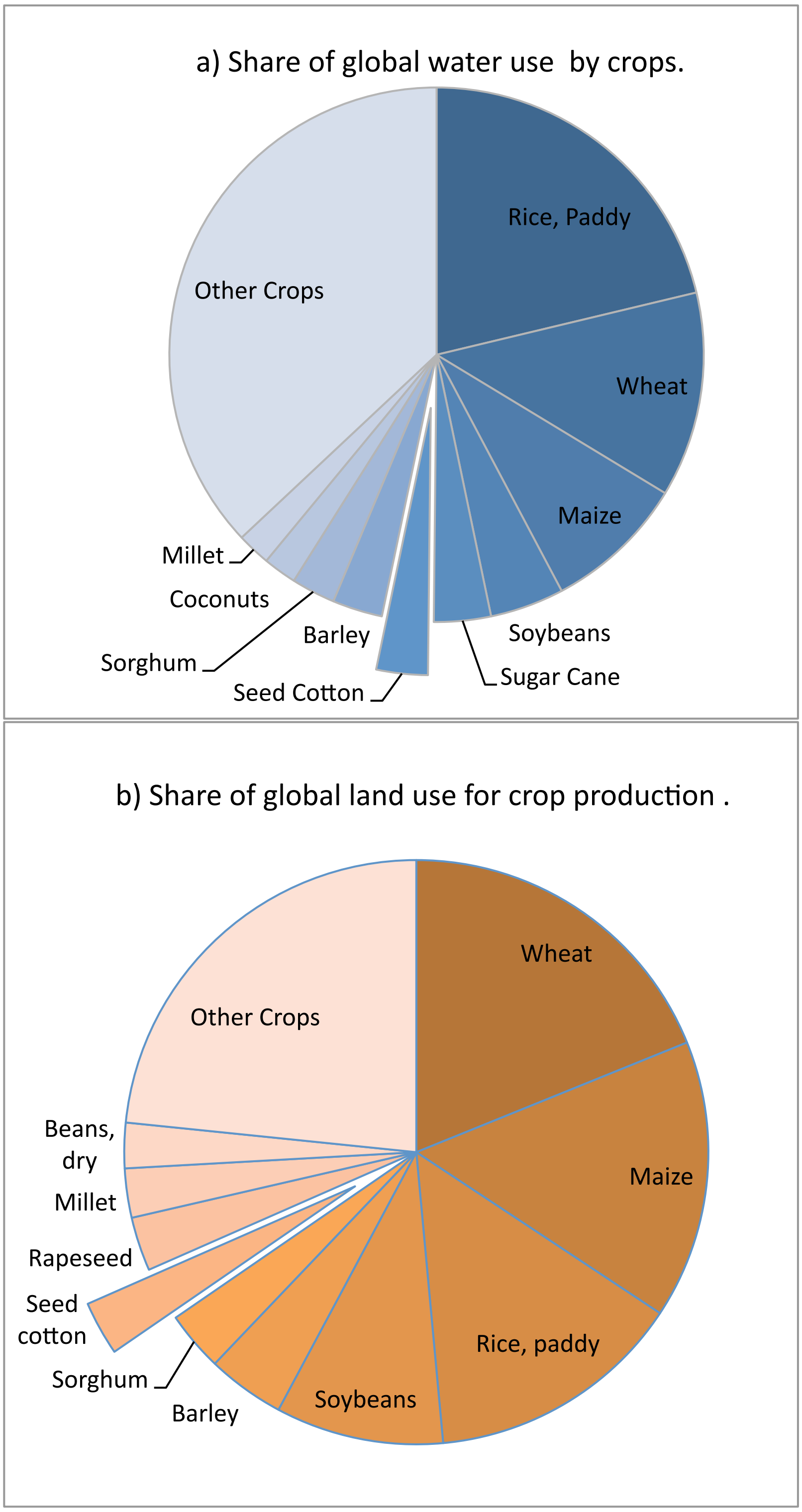

Figure 1. Global share of agricultural water (a) and land (b) by crop based on data from Hoekstra and Chapagain (2007) for water and FAOSTAT (2013) for land.

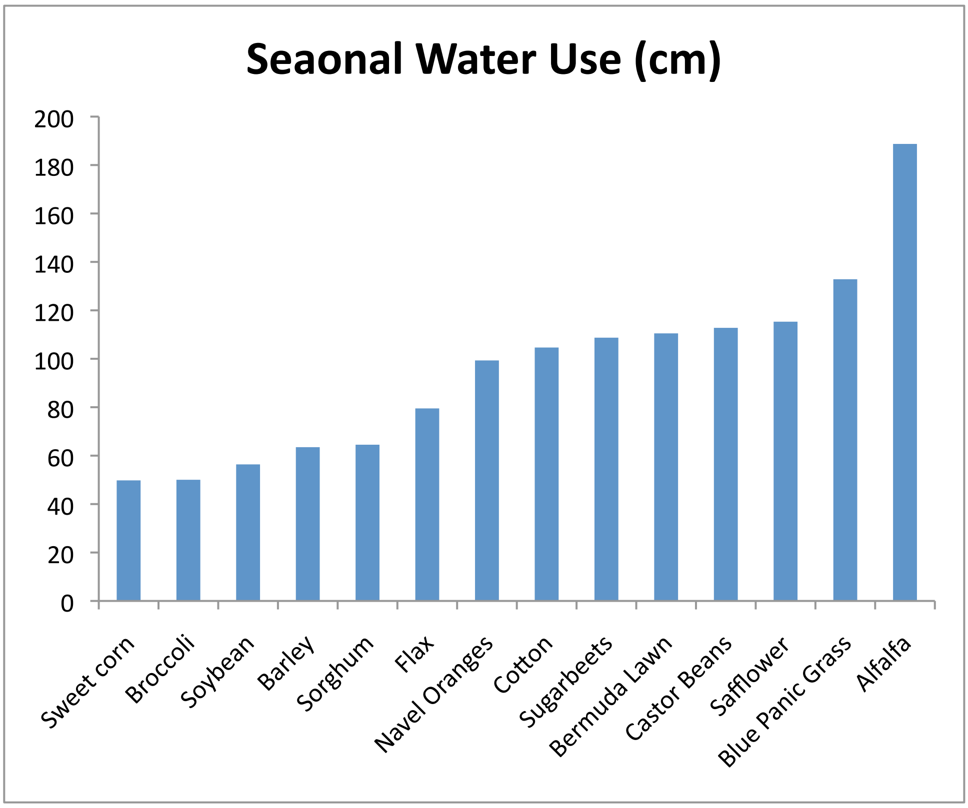

Figure 2. Total water used by crops in central Arizona, USA as reported by USDA (1982).

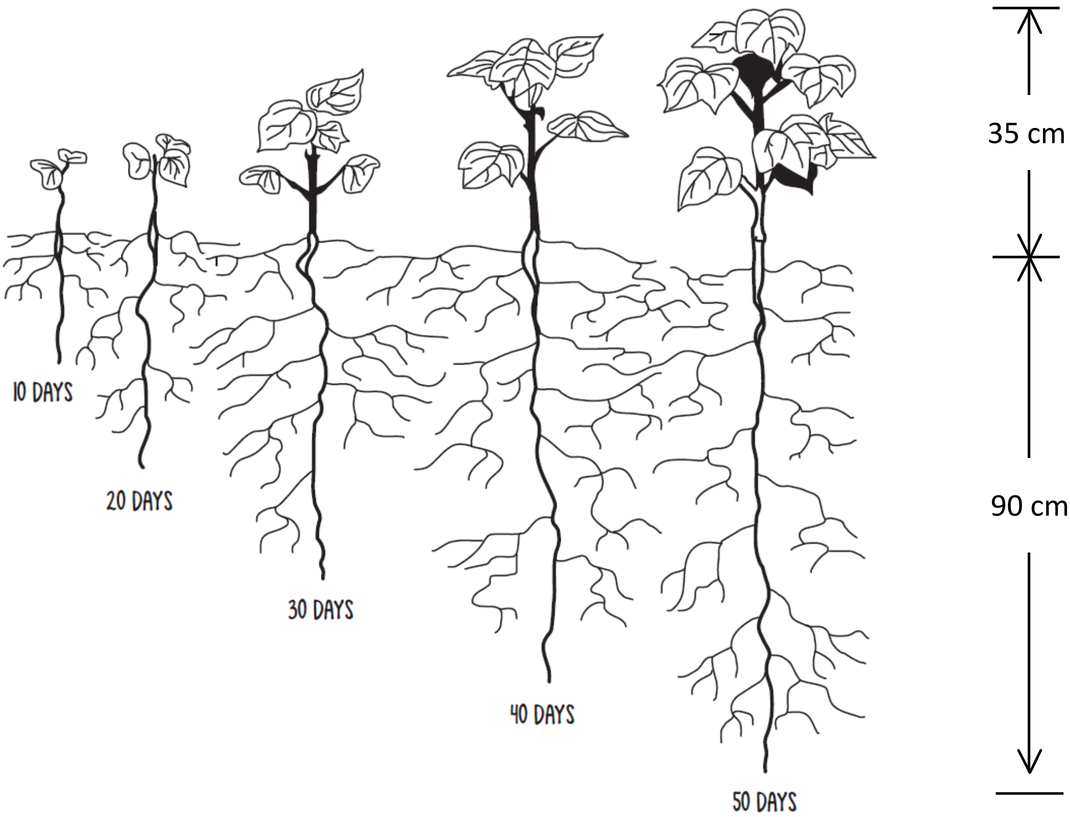

Figure 3. Cotton early season root develop (after Oosterhuis, 2001).

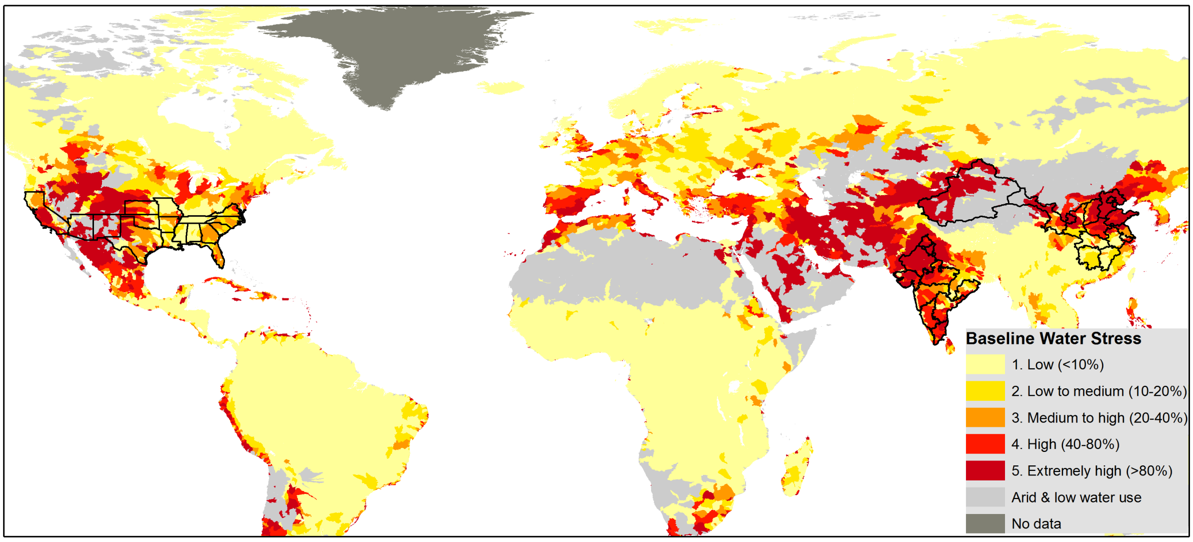

Figure 4. Baseline water stress from WRI's Aqueduct (Gassert et al., 2013) with the cotton producing provinces / states of the world's top three producing countries shown in black.

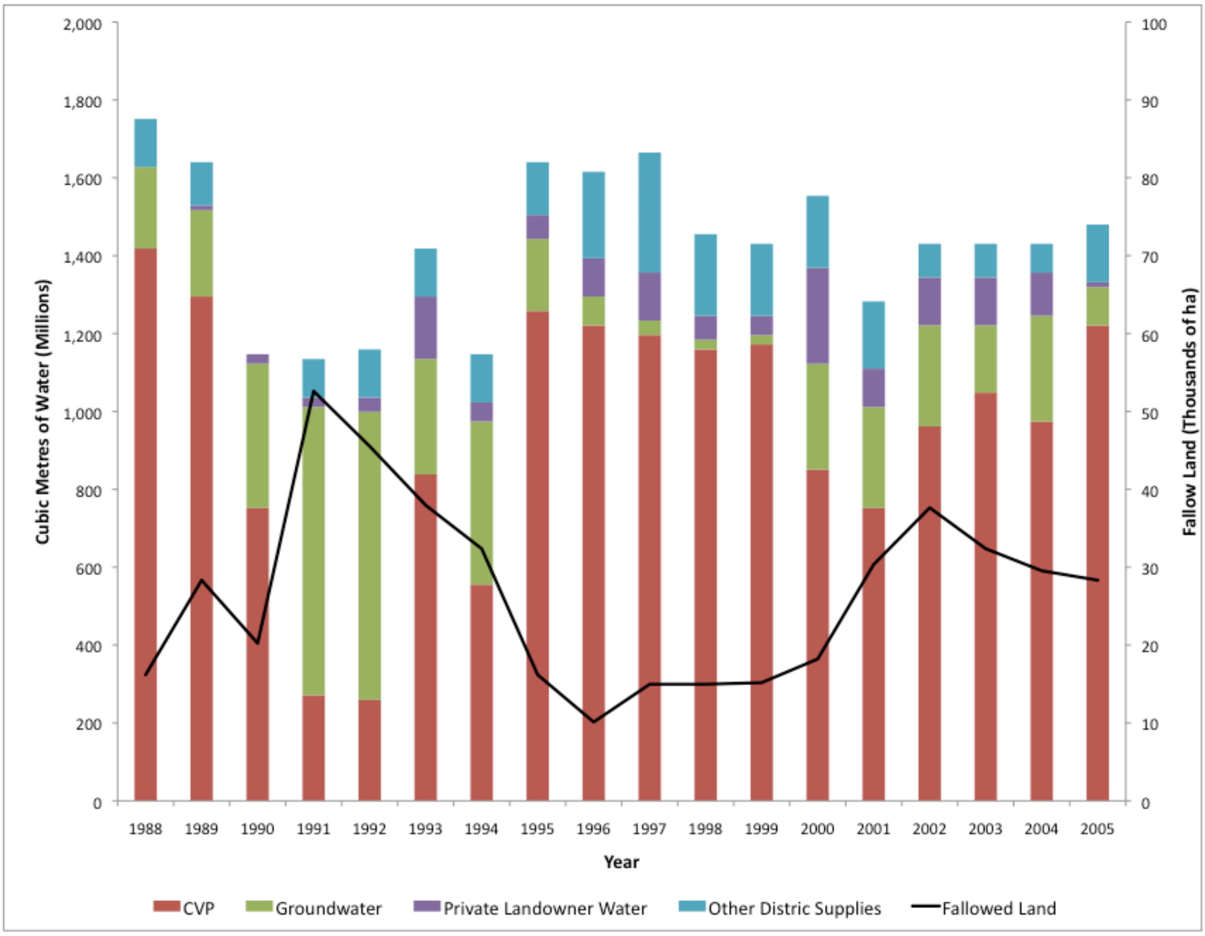

Figure 5. Westlands Water District Water Supply sources and fallowed land in the district from 1988–2005, taken from WWD (2006). "CVP" refers to water from the California Valley Project.

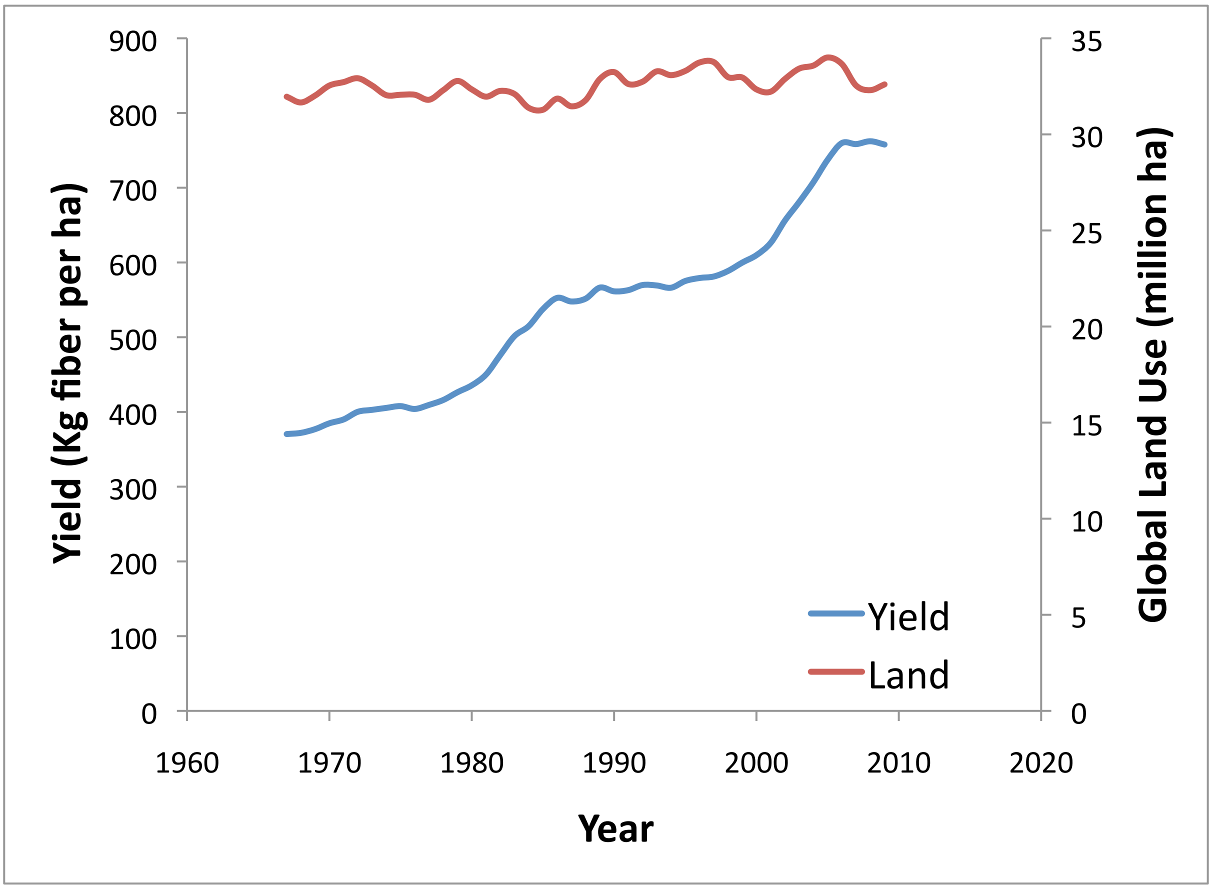

Figure 6. Global average cotton yield and land use from 1965 to 2011 smooth with a five year running average (data from Meyer et al., 2011)

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