ARC-Institute for Industrial Crops

Desktop Studies

2016/2017

ARC • LNR

Excellence in Research and Development

Table of Contents

PROJECT TITLE	**:**	The influence on different foliar fertilizers (Zinc, Phosphorus and Potassium Nitrate) and soil applied potassium on cotton yield and fibre properties
PROJECT LEADER	**:**	JN de Bruin

INTRODUCTION

Supplying optimal quantities of fertilizers to growing cotton plants is one way to improve yield. Fertilizers need to be used rationally in order to avoid a negative ecological impact and undesirable effects on the sustainability of agricultural and cotton production systems (Zakaria, *et al*, 2008). Excessive application of fertilizers also affects the farmer's economy. In order to calculate the amount of fertilizers to be applied to cotton, it is necessary to develop recommendation programmes that adjust nutrient rates to crop requirements (Zakaria *et al.,* 2008).

Since cotton production covers a wide range of environments and economic circumstances, yields and, hence, nutritional requirements vary greatly. Supplying optimal quantities of fertilizers and using balanced macro- and micronutrient doses to growing cotton plants is one way to improve cotton yields (Zakaria, *et al*, 2008).

The goal of fertilizer programs for cotton should be to achieve maximum economic return for the fertilizer investment (Kerby and Adams, 1985), even though this may not necessary coincide with maximum yield, and it may change with time and with location. Fertilizer applications are made to meet the annual crop nutrient requirements and return to the soil those nutrients removed by the crop. Adequate fertilization is important to every cotton farmer because the amounts used, and therefore the cost, are slight compared to the dollars lost from yield limitations (Hake *et al.*, 1991). An effective economic fertilizer program must also keep in mind the optimum times when the different nutrients are needed as well as the fate of the nutrients when applied to the soil.

Potassium

Potassium (K) is the essential macronutrient for all living organisms required in large amounts for normal plant growth and development. Potassium deficiencies can limit the accumulation of crop biomass. This is attributed to the fact that potassium increases the photosynthetic rates of crop leaves, CO_2 assimilation and facilitates carbon movement. Also, potassium nutrition has pronounced effects on carbohydrate partitioning by affecting either phloem export of photosynthesis (sucrose) or growth rate of sink and/or source organs (Oosterhuis, 1976) .

If potassium is in limited supply during active fibre growth, there will be a reduction in the turgor pressure of the fibre resulting in less cell elongation and shorter fibres at maturity (Oosterhuis, 1976).

The uptake pattern for potassium by the cotton is well-documented (Bassett *et al.*, 1970; Halevy 1976) with the need for potassium rising dramatically when the boll load begins to develop (Halevy, 1976) because the bolls are the major sinks for this element. However, most fertilizer programs utilize a single pre-plant application of potassium with KCl being the predominant fertilizer used. However, this pre-plant application may not always be sufficient because the peak demand by the plant occurs much later during boll development, and because of the many factors that can affect potassium uptake by the cotton plant (the decline in root growth during boll development, nematodes, soil potassium fixation etc.).

There is a wealth of literature regarding foliar fertilization, which was used as long ago as 1844 to correct plant chlorosis with sprays of Fe. However, the practice has only caught on in cotton production in the last two decades. In 1991, it was estimated that about 9,000 tons of potassium fertilizer was foliar-applied to cotton in the US Cotton Belt. However, there is still considerable speculation about the benefits and correct implementation of this practice. While there are many reports on research involving soil applied potassium (e.g. Kerby and Adams, 1985), there are fewer studies available on the usefulness of foliar-applied potassium. Foliar applications of potassium offer the opportunity of correcting deficiencies quickly and efficiently, especially late in the season when soil application of potassium may not be effective or possible (Oosterhuis, 1995; Weir *et al.*, 1996). Foliar feeding of a nutrient may actually promote root absorption of the same nutrient (Keino *et al.*, 1999; Thorne, 1957).

Earlier research (Oosterhuis, 1976) indicated that foliar-applications of potassium significantly increased seed cotton yield. Halevy and Markovitz (1988) in Israel reported increased lint yield and average boll weight from foliar sprays containing nitrogen, phosphorus, potassium and sulphate in locations where the soil fertility was low. More recently Oosterhuis *et al.* (1990, 1991b, 1992, 1993) showed that foliar-applications of KNO_3 can increase yields and improve lint quality, i.e., by an average of 26 kg/ha compared to the standard soil potassium treatment.

Foliar-applications of potassium have also been shown to improve fibre quality (Oosterhuis *et al.*, 1990). The increase occurred primarily in fibre length uniformity and strength, with micronaire being increased only occasionally. In these studies, soil application of KCl alone did not enhance any of the fibre quality components. With the national emphasis on lint quality (Sasser, 1991) and the introduction of high volume instrumentation classification, the positive effect of potassium on lint quality may be of paramount importance.

The timing of foliar sprays, particularly in regards to the growth stage, can be critical in relation to the optimum efficacy of the foliar treatment, and more attention should be paid to it (Alexander, 1986). It was suggested that the optimal growth stages in cotton for foliar-applied potassium were pinhead square and first flower stages, and at peak boll development (Chokey and Jain, 1977). However, recent research has indicated that the optimum response to foliar applications of potassium was during the period of boll growth starting soon after flowering and continuing at weekly intervals past peak boll development (Oosterhuis, 1995) with the optimum stage occurring three weeks after first flower (Weir and Roberts, 1993). Application rates have averaged about 4 kg potassium/ha (Oosterhuis, 1995) with no visible injury of cotton leaves observed at foliar application rates of up to 22 kg KNO_3/ha (Oosterhuis *et al.*, 1990) in 94 l water/ha. However, solubility in cold water may be a problem at rates near 10 kg KNO_3/ha.

Phosphorus

Phosphorus (P) has been found to be the life-limiting element in natural ecosystems because it is often bound in insoluble compounds and hence it becomes unavailable for plant uptake or utilization (Ozanne, 1980). Phosphorus is an essential nutrient and an integral component of several important compounds in plant cells. These compounds include the sugar phosphates involved in respiration, photosynthesis and the phospholipids of plant membranes, the nucleotides used in plant energy metabolism and in molecules of DNA and RNA (Taiz and Zeiger, 1991). Phosphorus is also a necessary nutrient for the biosynthesis of chlorophyll, where phosphorus as pyridoxal phosphate must be present for the biosynthesis of chlorophyll (Ambrose and Easty, 1977). Phosphorus as a constituent of cell nucleus is essential for cell division and development of meristematic tissue (Russell, 1973). Phosphorus deficiencies lead to a reduction in the rate of leaf expansion and photosynthesis per unit leaf area (Rodriguez *et al*., 1998). The high soil pH (>7.6) and the high quantities of $CaCO_3$ result in precipitation of phosphorus, which reduces the soluble phosphorus supply.

Zinc

Crop yields are often limited by low soil levels of mineral micronutrients such as zinc (Zn), especially in calcareous soils of arid and semiarid regions (Cakmak *et al*., 1999). Zinc is an essential mineral nutrient and a cofactor of over 300 enzymes and proteins involved in cell division, nucleic acid metabolism and protein synthesis (Marschner, 1986).

Further, zinc is required in the biosynthesis of tryptophan, a precursor of the auxinindole-3-acetic acid (IAA), which is the major hormone inhibiting abscission of squares and bolls (Oosterhuis *et al*., 1991). Zinc deficiency symptoms include, i.e. small leaves, shortened internodes giving the plant a stunted appearance, reduced boll set and small boll size (Oosterhuis *et al*., 1991). Zinc deficiency is observed in cotton growing on high pH soils, particularly where the topsoil has been removed to alter the field slope for irrigation, exposing the zinc -deficient subsoil. In addition, zinc deficiencies have occurred where high concentrations of phosphorus are applied (Oosterhuis *et al*., 1991).

According to (Zakaria *et al.,* 2008)the dry matter yield, total chlorophyll concentration, potassium , zinc and phosphorus uptake per plant, number of opened bolls per plant, boll weight, seed index, lint index, seed cotton yield per plant, seed cotton and lint yield/ha and earliness of harvest increased with the application of potassium , zinc and phosphorus . Treatments generally had no significant effect on lint percentage and fibre properties. Potassium significantly increased the mean values of micronaire, the flat bundle strength, and uniformity ratio over the untreated control. When applying phosphorus at 1728 g/ha, the mean values of the micronaire readings were significantly increased over the untreated control. Applying potassium fertilization at 47.4 kg/ha combined with spraying cotton plants with zinc at 57.6 g/ha and with phosphorus at 1728 g/ha improved growth and yield of Egyptian cotton

Advantages and Disadvantages of Foliar Fertilization

The advantages of using foliar feeding with potassium include low cost, a quick plant response (increased tissue potassium concentration and fewer new deficiency symptoms), use of only a small quantity of the nutrient, quick grower response to plant conditions, compensation for the lack of soil fixation of potassium, independence of root uptake problems, increased yields and improved fibre quality (Snyder *et al.*, 1991). On the other hand, the disadvantages are that only a limited amount of nutrient can be applied in the case of severe deficiencies, and the cost of multiple applications can be prohibitive unless incorporated with other foliar applications such as pesticides. Other disadvantages when using high concentrations of potassium include the possibility of foliar burn, compatibility problems with certain pesticides, and low solubility of certain potassium salts, especially in cold water. Another disadvantage is that the potassium in fertilizers prepared for foliar application may cost as much as three times more per pound of potassium than in ordinary soil-applied fertilizers (Snyder *et al.*, 1991).

REFERENCES

Ambrose EJ, Easty DM. Cell Biology. The English Language Book Society and Longman, London 1977.

Bassett, D.M., AAnderson, W.D. and Werkhoven, C.H.E. 1970. Dry matter production and nutrient uptake in irrigated cotton (*Gossypium hirsutum* L.). *Agronomy Journal* **62:** 299-303.

Cakmak I, Kalayci M, Ekiz H, et al. 1999 Zn deficiency as a practical problem in plant and human nutrition in Turkey. A NATO-Science for stability project. Field Crops Res 60:175–88.

Hake, K., Cassman, K. and Ebelhar, W. 1991. Cotton nutrition - N, P and K. Physiology Today. National Cotton Council, Memphis, TN. Vol. **2** (3): 1-4.

Halevy, J. 1976. Growth rate and nutrient uptake of two cotton cultivars grown under irrigation. *Agronomy Journal* **68:** 701-705.

Halevy, J. and Markovitz. T. 1988. Foliar NPKS application to cotton from full flowering to boll filling. *Fertiliser Research* **15:** 247-252.

Keino, J., Beyrouty, C.A. and Oosterhuis, D.M. 1999 Differential uptake of potassium by plant roots. *In* D.M. Oosterhuis and G. Berkowitz (eds.) Frontiers in potassium nutrition: New Perspectives on the Effects of Potassium on Crop Plant physiology. Published Potash and Phosphate Institute and American Society of Agronomy.

Kerby, T.A. and Adams, F. 1985. Potassium nutrition of cotton. p. 843-860. *In* Potassium in Agriculture. American Society of Agronomy, Madison, WI.

Marschner H Functions of mineral nutrients: macronutrients. In: RJ Haynes (ed). Mineral Nutrition of Higher Plants. Academic Press,Orlando, FL., 1986 195–267.

Oosterhuis, D.M. 1976. Foliar application of fertilizer. pp. 11-12. *In* Annual Report Cotton Research Institute 1974-75, Gatooma. Government Printer, Salisbury, Rhodesia.

Oosterhuis, D.M. 1992. Cotton yield enhancement using foliar-applied potassium nitrate and PGR-IV. Better Crops with Plant Food. Phosphate and Potash Institute. Winter 1992-93.

Oosterhuis, D.M. 1995. Potassium nutrition of cotton with emphasis on foliar fertilization. pp. 133-146. In C.A. Constable and N.W. Forrester (eds.) Challenging the Future. Proc. World Cotton Research Conference 1. CSIRO, Australia.

Oosterhuis, D.M. and Bednarz, C.W. 1997. Physiological changes during the development of potassium deficiency in cotton. pp 347-351. In, T. Ando et. Al. (eds). Plant Nutrition for Sustainable Food Production and Environment. Kluwer Academic Publishers, Japan.

Oosterhuis, D.M., Hurren, R.G. Miley, W.N. and Maples, R.L. 1991b. Foliarfertilization of cotton with potassium nitrate. Proc. 1991 Cotton Research Meeting, University of Arkansas, *Arkansas Agriculture Experiment Station, Special Report* **149:** 21-25.

Oosterhuis D, Hake K, Burmester C 1991 Foliar feeding cotton. Cotton Physiology Today. National Cotton Council of America, 2, 1–7.

Oosterhuis, D.M., Miley, W.N. Janes, L.D. Baker, W.H. McConnell, J.S. Parker, P.W and Bryles, M.B. 1992. Foliar fertilization of cotton with potassium nitrate, Arkansas 1989-1991. Arkansas Fertility Studies. University of Arkansas, *Arkansas Agriculture Experiment Station, Bulletin* **421:** 135-139.

Oosterhuis, D.M., Miley, W.N. and Janes, L.D. 1993. A summary of foliar fertilization of cotton with potassium nitrate, Arkansas 1989-1992. Arkansas Fertility Studies. University of Arkansas, *Arkansas Agriculture Experiment Station, Bulletin* **425:** 97-100.

Oosterhuis, D.M., Wullschleger, S.D. Maples, R.L. and Miley, W.N. 1990. Foliar feeding of potassium nitrate in cotton. *Better Crops with Plant Food.* Phosphate and Potash Institute. Summer 1990, pp. 8-9.

Ozanne PG 1980 Phosphate nutrition of plants—a general treatise. In:FE Khasawneh, EC Sample, EJ Kamprath (eds). The Role of Phosphorus in Agriculture. Madiso n, Wisconsin: American Society of Agronomy, 559–89.

Russell EW 1973 Soil Condition and Plant Growth. The English Language Book Society and Longman, London.

Sasser, P.E. 1991. The future of cotton quality: Trends and implications —Fibre quality easurements. pp. 68-70. *In* Proceedings Beltwide Cotton Conferences. National Cotton Council, Memphis, TN.

Snyder, C.S., Miley, W.N. Oosterhuis, D.M. and Maples, R.L. 1991. Foliar application of potassium to cotton. University of Arkansas, Cooperative Extension Service. *Cotton Comments.* 4-91.

Taiz L, Zeiger E 1991 Plant Physiology: Mineral Nutrition. The Benjamin/Cummings Publishing Company, Inc. Redwood City, CA.

Thorne, G. 1957. The effect of applying a nutrient in leaf sprays on the absorption of the same nutrient by the roots. *Journal of Experimental Botany* **8** (24).

Weir, B.L., Kerby, T.A., Hake, K.D., Roberts, B.A. and Zelinski, L.J. 1996. Cotton fertility. pp. 210-227. *In* S. Johnson Hake, T.A. Kerby and K. D. Hake (eds.). Cotton Production Manual. University of California. Publication #3352.

Zakaria M.S., Mahmoud H.M. and Amal H.E. 2008. Influence of potassium fertilization and foliar application of zinc and phosphorus on growth, yield components, yield and fiber properties of Egyptian cotton (Gossypium barbadense L.). Journal of Plant Ecology Volume 1, Number 4, P 259–270.

ARC-Institute for Industrial Crops

Desktop Studies

2016/2017

ARC • LNR

Excellence in Research and Development

Table of Contents

PROJECT TITLE : Cotton irrigation

PROJECT LEADER : Dr T van der Westhuizen

CO-WORKERS : P Maja

INTRODUCTION

Water deficit, salinity and temperature extremes are the primary factors that limit crop productivity, accounting for more than a 50 % reduction in yields worldwide (Boyer, 1982). Water deficit is the major abiotic factor limiting plant growth and crop productivity around the world (Kramer, 1983). Approximately one third of the cultivated area of the world suffers from chronically inadequate supply of water (Massacci *et al*., 2008). Advances in irrigation technology have helped reduce the gap between potential and actual yield, but irrigation costs and limited water supplies constrain irrigation throughout the world. Water availability and quality affect the growth of all crops since water is the primary component of actively growing plants ranging from 70-90% of plant fresh mass (Gardner *et al*., 1984). Plant water stress depends both on the supply of water to the soil and the evaporative demand of the atmosphere. In general, plant water stress is defined as the condition where a plant’s water potential and turgor are decreased enough to inhibit normal plant function (Hsiao *et al*., 1973). The effects of water stress depend on the severity and duration of the stress, the growth stage at which stress is imposed, and the genotype of the plant (Kramer, 1983).

Cotton originates from warm arid areas and exhibits more drought tolerance than other row crops, such as maize and soybean (Oosterhuis and Wullschleger, 1998). However, cotton does not grow well without adequate water (Oosterhuis and Bourland, 2001). Consequently, the availability of water is one of the most critical factors for optimum cotton yields. As water availability is becoming a limiting factor for successful cotton growing, attention should be paid to water conservation, through correct land preparation, optimum planting times, and efficient use of irrigation water in order to decrease water consumption and conserve this precious resource.

South Africa receives an annual rainfall of 492 millimetres whereas the rest of the earth receives 985 millimetres (Bold, 2001). This is nearly half the earth’s average. South Africa is thus classified as a water-stressed country. Rainfall is distributed unevenly across South Africa (Hoffman et al., 2001). Rainfall in South Africa is also characterized by a high degree of variability. The country is, in general, frequently subject to droughts of shorter or longer duration (Tegniese mededeling, No 148). In South Africa the majority of cotton was produced under irrigation (5843 hectares) in the past production season, compared to 2510 hectare under dryland conditions. Climatic conditions in South Africa are such that irrigation management of cotton is of the utmost importance if optimum yields are to be achieved (Archibald, 1970).

In general, liberal water management occurs and can lead to excessive or rank vegetative growth that results in management problems. Irrigation water, if managed wisely, is an important tool to optimize productivity of the land and to ensure that no other inputs go to waste. Thus, it is an important tool that can be used in developing a sustainable crop management strategy. Basic principles of irrigations lead to two key questions, namely, when do I irrigate, and secondly, how much should I irrigate. A third important question is: Do I irrigate just because I have adequate water, or do I irrigate when the plant really needs the water.

Water shortages

Irrigated agriculture is the largest consumer of available water in South Africa and producers will experience increasing pressure to use less water (DWAF.1996). South Africa uses 60% of water in agriculture including irrigation (Ashwell *et al*., 2001). Irrigated agriculture plays a major role in the livelihoods of nations all over the world and South Africa is no exception. With irrigated agriculture being the largest user of runoff water in South Africa, there have been increased expectations from government that the sector should increase efficiency and reduce consumption in order to increase the amount of water available for other uses, in particular for human domestic consumption. Irrigation in South Africa is currently practised on 1.6×10^6 ha. In 2000, it used 62% of the runoff water that was used by all sectors, or 39.5% of the exploitable runoff water (DWAF, 2004). The increasing scarcity of water for agricultural production around the world is a major cause for concern. With the rapid growth of the population and the consequent rise in demand for water, water shortages will be an even greater concern in coming years (Dawood *et al.,* 1985). Only 2.5% of world's water is fresh water of which only a fraction is accessible, and agriculture accounts for two-thirds of the fresh water consumed. Concerns about scarcity of water have focused attention on irrigation, the largest water-using sector worldwide, which is widely seen as a low-value, wasteful and ‘‘inefficient’’ use for water. Therefore, protection of this precious natural resource, which becomes increasingly limited in supply, must be conserved through careful agricultural management. Within the concept of “more crop per drop”, this call for irrigation that is more efficient and planting of drought-and salt- tolerant crop varieties that require less water, must be implemented for sustainable use of water (Galanopoulo-Sendouca *et al., 2003*).

Effects of water stress on cotton growth

- Water stress reduces cell and leaf expansion, stem elongation, and leaf area index (McMichael and Hesketh, 1982)
- Leaf, stem and root growth rate are very sensitive to water stress because they are dependent on cell expansion (Hsiao, 1976; Hearn, 1994).
- Significantly fewer nodes and lower dry weights of stems and leaves of water-stressed plants compared to those of the control were reported by Pace *et al*. (1999)
- McMichael and Quisenberry (1991) observed decreased shoot-to-root ratios of plants grown under conditions of severe water stress.
- Malik *et al*. (1979) reported that root growth appears to be less affected by drought than shoot growth. Several researchers (McMichael and Quisenberry, 1991 and Pace *et al*., 1999) observed that seedlings of water stressed cotton showed increased root elongation, accompanied by a reduction in root diameter.
- A correlation between leaf abscission and low plant water potentials has been commonly reported. McMichael *et al*. (1972) identified a linear relationship between the rates of leaf abscission and the levels of the imposed water stress.
- Water stress has also been shown to alter cell ultrastructure. Ackerson *et al*. (1981) observed that leaves of adapted plants contained large starch granules in the chloroplast wherein the structure of the thylakoid membranes appeared to be damaged.
- In addition, Berlin *et al*. (1982) indicated that water stress caused significant changes in the grana and stroma lamellae, palisade cell walls, number and size of chloroplasts, and the structure of mitochondria.

To understand plant-water relation properly good knowledge is required of:

a. The soil characteristics that govern water holding capacity.
b. Change in water consumption by cotton and sensitive growth stages.
c. Evaporation demand of the atmosphere and factors that determine the rates.
d. Equipment available for irrigation, or methods to change the availability of water.
e. Management of all factors to minimise water stress and yield losses.

Water Holding Capacity of Soils

- Water holding capacity increases as clay and silt content increase. Water is more easily available from sandy soils.
- Effective rooting depth in a soil. Hard layers in a soil profile limited the growth of roots. Soil layers with abnormal chemical levels (pH, Al and salts) may stop root growth.
- Slope of a land site. Field on slopes increase runoff and erosion. Contouring is essential. Strip crop cultivation to reduce runoff.

Not all the water present in a soil profile is available to the cotton crop. The upper range, called field water capacity, is held against gravity at a suction of -10 to -30 kPa.

Table 1. Effect of water holding capacity and infiltration tempo of different soil types

Texture (Clay %)	Field water Capacity (mm.m)	Wilting point (mm.m)	Plant available water (mm.m)	Infiltration tempo (mm)
0 – 6	70	40	30	12 – 20
15 – 29	180	60	120	12
30 – 39	280	130	150	10
40 – 50	400	200	200	8
¬ 50	500	250	250	6

Cotton grown under irrigation provide higher yields at more economic levels than dryland production (Hake and Grimes, 2010).

Plant Water Requirement of Cotton

In many crops, reproductive development is most sensitive period to drought stress following seed germination and seedling establishment (Saini, 1997). In cotton, however, (Table 1) there is still a debate about the most sensitive period to water-stress during development in relation to yield, even though water sensitivity during flowering and boll development has been well established (Constable and Hearn, 1981; Cull *et al*., 1981 a and b; Turner *et al*., 1986). Water is an integrated part of any plant and all reactions in the plant is dependent on the presence of water. Sufficient and well-distributed rainfall can make or break dryland crop production (Dippenaar, 1994).

Table 2. Growth stages that are sensitive to water stress

Sensitive stage to water stress	**Author**
Flowering and boll development.	Constable and Hearn, 1981.
Beginning of flowering up to effective boll formation.	Dippenaar. 1987.
Early flowering period.	Reddell *et al*., 1987.
Peak flowering.	Orgaz *et al*., 1992.
Boll development, particularly well after the end of effective flowering.	(Radin *et al*., 1992; Plaut *et al*., 1992; de Kock *et al*., 1993).

From Table 3, it appears that the highest percentage of yield loss occurs during the flowering period, namely 32% yield loss.

Table 3. Important growth stages of cotton and its sensitivity towards water stress (Hile *et al*., 1973; Kattan and Flemming 1956)

Growth stage	**Time**	**Variation**	**Sensitivity %**
Emergence	5	3	
Vegetative	80	20	
Flower initiation	30	15	20
Flowering	50	20	32
Fruit set	52	20	32
Fruit set period	90	20	20
Maturing	140	40	
Harvest	160	40	

Time = days after planting when growth stage is reached

Variation = Variation in time to reach growth stage due to climate and cultivar differences.

Sensitivity = Sensitivity of the crop as % yield loss due to 1 water stress of total % yield loss due to drought over the time period.

Why irrigate cotton?

Proper irrigation management provides more consistent yield from year to year and protects the crop's yield potential. With rising production costs and the devastating effect of drought on yield, adopting irrigation to supplement rainfall and improving irrigation water management in the drier areas, is becoming increasingly essential to stay competitive. Irrigation has economic benefits to the producer by increasing yield per unit land area, and benefits to society by providing a consistent and dependable source of fibre. Irrigation offers safeguards against poor crop performance and/or failure due to insufficient and/or untimely rainfall.

The problem is that the occurrence of rainfall is random; one never knows if the right amount will come at the right time during the growing season. Drought periods could therefore occur at any time during the growing season with varying duration and severity. Risks associated with yield instability can be partially removed by irrigation, which leads to a more predictable season-ending yield (and return) year after year. Safeguarding against rainfall uncertainties is highly desirable in today's competitive markets where substantial investment has been committed at cotton planting time. There are two different ways in which cotton fields loose water: 1) Evaporation from the soil, and 2) transpiration from the leaves. Soil evaporation and plant transpiration are lumped together as "evapotranspiration" or ET. The terms evapotranspiration, crop water use, or crop water requirements are the same and are used interchangeably.

How much water does Cotton need?

Cotton required 450-800 mm water during growing season. Under full irrigation, 750 to 1100 mm water can be applied. The ideal amount of precipitation (irrigation + rainfall) requirement for growing cotton successful is between 500 to 1100mm per annum. Economic yields cannot be realized when precipitation is less than 500 mm (Dippenaar, 1980). Daily water consumption averages about 5 mm per day, with maximum daily usage from six to 10 mm at the peak of growth during mid-summer by transpiration and evaporation. Therefore, 609 to 812 mm water is required in the soil from rainfall and irrigation for use by the plant during the season. The soil should contain sufficient available moisture throughout the root zone, 1.2 to 1.8 meters deep, when cotton is planted. Irrigation before planting make this possible (Hewlett, 1971). Frequent irrigation keeping soil moisture levels from dropping below 50% of field capacity is necessary. Soil moisture content can be determined in the field with tensiometers.

Cotton does not need as much water during the first 6 weeks of growth. The critical irrigation time in cotton is when squares starts to develop, through flowering and up to early boll development. According to Dippenaar (1980), the period from the beginning of flowering up to effective boll formation is the most important stage in the development of cotton and is about 80 days long. When this critical stage is reached, it coincides with large leaf areas, total soil coverage and maximum root development (Metelerkamp & Cackett, 1965). Water stress during this stage can lead to yield losses of up to 32 %. Early square formation and flowering is most critical for yield formation. During peak flowering period the demand for water is very high, equivalent to A-pan evaporation of 12-15 mm/day and soil moisture is consumed very rapidly. Moisture stress can reduce yield by 3000 kg/ha if irrigation is delayed for two weeks. Fibre quality can also be affected. Moisture stress reduces the water use efficiency; therefore WUE is much lower on dryland than under irrigation.

Germination and emergence also are very sensitive stages. Lack of soil water in the top soil prevents establishing a good plant stand. Little water, but freely available, is needed by seedlings. Increase in leaf area accelerates water consumption. Transpiration is essential to keep the crop cool.

Archibald (1970) recommended that after completing the emergence irrigation cycles, it is extremely important to not irrigate the crop again for a period of at least 4 weeks. During this period, the root system is constantly expanding and tapping fresh supplies of water. It is also at this time that the cotton crop develops its potential for subsequent rank growth, and it is essential to subject the crop to a period of mild stress during the early growth stages to try to ensure a low, compact growth habit. This stress should not be continued later than six weeks, when the first flower buds, or ‘squares’ appear. The normal irrigation regime should be commenced after the initial 4 – 5 weeks ‘stress’ period, and thereafter irrigations should be carried out according to the daily evaporation figures obtained from the Class A Evaporation Pan. The amount of water to be applied at any one irrigation is determined by the available moisture in the root zone, which in the case of cotton may be depleted by 75%. When to apply an irrigation is governed by the available moisture and the stage of growth of the crop, which determines the evapo-transpiration ratio of the crop. The daily evaporation figures are accumulated until the evaporation deficit for the particular growth stage has been reached, and an amount of water as determined by the soil moisture capacity and the root depth is applied.

Bauer *et al*. (2017), in: “Cotton Incorporated review” summarises cotton irrigation requirements as follows:

Planting to emergence: water use by cotton – Low

Water is critical for germinating, and irrigating at this stage is primarily for stand establishment. If the seedbed is dry and irrigation is needed to establish a stand, it is preferable to irrigate before planting. Pre-irrigation reduces the possibility of seedling disease compared to irrigating shortly after planting. In addition, irrigation after planting will cool down the soil and may reduce seedling growth rates. Once the seeds germinate, sufficient moisture must be in close proximity of the seedlings until sufficient roots are developed to increase the area of water uptake. Establishment of the root system is quite fast, with taproots growing up to 6 mm per day after they emerged from the seed.

Emergence to first square: water use by cotton – 2.5 mm per day

Water demand at this time is low and young cotton plants partition significant resources to the roots. Unless soil water stress is extremely severe, irrigation at this time contributes relative little to yield. In fact, a mild water deficit early in the season can stimulate root production, especially encouraging deeper root systems. Primed Acclimation (PA) is an irrigation concept that uses intentional mild drought stress during early vegetative development to induce physiological changes in the plant to make it more drought tolerant during mid-season when detrimental effects of water are maximal. PA can maintain yield with significant water reduction. For cotton, PA period lasts about 36 days, starting at full stand establishment (14 days after planting) to late squaring/first bloom. During this time period water may be reduced by as much as 30 % with no yield loss. An additional benefit to properly applied PA is a reduction in plant growth regulator needed later in the growing season and a more uniform maturity.

First square to first flower: water use by cotton 2.5 – 5.1 mm per day

This approximately 21 day period from first square to first bloom is a critical time to avoid water stress.

First flower to peak bloom: water use by cotton increases from 5.1 – 7.1 mm water per day

Water deficit stress early in this growth stage reduces plant growth, which reduces the number of fruiting sites that are initiated. In addition, severe water stress can also reduce boll number through shedding of young bolls and results in substantial yield loss. Severe stress reduces fibre quality through shorter staple and higher micronaire.

Peak bloom to open bolls: water use by cotton – decreases from 7.1 mm of water per day

Water deficit stress during this growth stage is less critical than during squaring and early flowering. Water stress during this period can result in square and young boll shedding. However, these losses of late fruit have less impact on yield than loss of early season bolls. After bolls start opening, plants should be allowed to become water stressed to allow for better harvest conditions. Stress at this time hastens boll opening, makes defoliation easier, and reduces regrowth.

How to adopt to water limited situations

- Use irrigation systems such as lateral moves, centre pivot, or drip irrigation systems.
- Schedule irrigation by using technologies that continuously monitor weather, soil and plant stress. Scheduling should allow for differences in soil types, demands of the crop (crop stage) and climate (temperature and humidity).
- Improve soil management by adopting controlled traffic and reduced tillage practices to minimize compaction, and thereby improving soil structure and increasing the rooting zone.
- Change planting time to shift periods of maximum water use into periods of lower temperatures.
- Better utilization of stored soil water collected from crop fallows and employ practices to capture and retain soil moisture. Strategies such as reduced tillage and stubble retention are becoming standard practice for moisture conservation. Use of rainfall to establish crops rather than pre-irrigation or ‘watering –up’ are worth considering, especially if there is flexibility in planting time.
- Avoid excess nitrogen fertilizer, which encourages extra vegetative growth.
- Utilize supplemental irrigation strategies or modified row configurations (e.g. skip rows) to enhance crop access to soil moisture.
- Extend the length of fallows to capture rainfall, especially on soils with a greater plant available water holding capacity.

- Shorten the time of crop maturity. To cope with limited water availability, one option would be to reduce the time of maturity and then manage a crop to achieve a targeted economic yield threshold. Crop maturity can be manipulated by choice of cultivar, insect management, nutrition, growth regulators, or late-season irrigation management (Roberts and Constable, 2003).
- Explore the use of degradable polymer films as mulches in cotton systems, such as those described in Braunack *et al*. (2015). One mayor issue with using plastic film as mulch has been a problem of disposal as it is not degradable (Shorgren, 2001).
- Reduce the risk of waterlogging. This can be achieved through appropriate field design to ensure adequate drainage and runoff, growing cotton on well-formed hills, and avoiding irrigation before significant rainfall events by monitoring weather forecasts (Bange *et al., 2016).*

Water conservation practises

a. Start to accumulate rainfall during the previous rainy season.
b. Keep the soil surface in open and ruff condition to maintain a high infiltration rate for water.
c. Control all weeds and volunteer crops to conserve water. Reduce evaporation from the soil with a thick layer of dry organic crop residue or dry grass.
d. On sloping fields, runoff water from the higher portion of the hillside, can be converted to flood the lower portions.
e. Execute the primary cultivation when the preceding crop is been harvested. Prepare a seedbed timely to be able to plant with the first effective rain showers.

IRRIGATION SYSTEMS

Flood irrigation and sprinkle irrigation will not be discussed in this desktop study, but we refer readers to the book compiled by ARC-IC, “Important articles on irrigation in Cotton” (2017), which will be available from Cotton SA. Koegelenberg, (2006) states that cotton producers in South Africa will have to apply available water sources more effectively to be able to survive due to water shortages.

1. Drip Irrigation

Drip irrigation is the slow and frequent application of water to plants through mechanical devices called emitters, and at rates approximating the crop consumptive use. This method of irrigation is becoming increasingly favoured as there is the need for more efficient use of water in areas of scarcity (Mofoke *et al., 2004*). Drip irrigation is considered as the most efficient irrigation system, but there is proof from literature that this system can also be inefficient, because of water quality, mismanagement and maintenance problems. Currently, drip irrigation systems account for 140 000 hectares under irrigation in South Africa (*Koegelenberg et al., 2003)*. Drip irrigation was introduced in South Africa during the early 1970's. This irrigation method, although relatively expensive, offered significant advantages, particularly with respect to efficiency of irrigation, the effective application of plant nutrients, and the maintenance of a soil moisture regime, which is favourable to optimum plant production. This irrigation method therefore rapidly gained popularity for the irrigation of particularly high value perennial crops. While drip irrigation systems were originally only installed above the soil surface, underground installation of dripper lines is becoming increasingly popular for certain applications (see below). Since the conceptualisation of this irrigation method in the 1960's, the design and manufacture of emitters were considerably improved to attain better performance and to reduce some of the hazards that could affect the sustainable good performance of these devices (Uys, 2000).

Drip irrigation has expanding rapidly in Greece, especially in Thessaly where it covers approximately 50% of the cotton acreage. It is mainly only used in regions with intense water shortage problems and lack of irrigation delivery networks but with high crop yielding capacity, so that covering the expenses of buying the system can be achieved. Usually, a single dripper line supplies water to two adjacent rows. Drip irrigation is broadly used in Israel, where the shortage of water is very serious and where the drip irrigation system had its origin. Compared with sprinkler irrigation, yields of crops irrigated by drip irrigation are generally 15-20% higher, according to research work carried out for at least 15 years (Goren, 1994). The main advantages of drip irrigation are: effective use of water (approximately 40% less water in comparison to surface systems as there is not much waste due to evaporation or its movement below the root system), and more efficient and cheaper fertilization and weed control applied through the system (Goren, 1994). In South Africa cotton yield under drip irrigation was 24-65% higher than sprinkler irrigated cotton (*Dippenaar et al., 1994*). However, fertigation of cotton was slightly inferior to the conventional fertilization program but proved to be easy, accurate and labour saving.

Table 4. Advantages and disadvantages of drip (Bange *et al*., 2016)

Advantages of drip irrigation	***Disadvantages of Drip irrigation***
The most efficient irrigation system.	Sensitive to clogging.
Delivers the water directly to the crop root zone (savings on the losses of irrigation).	Moisture distribution problem.
Water losses through evaporation is minimised.	Salinity hazards.
Maximum use of available water.	High cost compared to furrow.
No water being available to weeds.	High skill is required for design, install and operation.
Maximum crop yield (extremely high yield potential).	
High efficiency in the use of fertilizers.	
Less weed growth and restricts population of potential hosts.	
Low labour and relatively low operation cost. No soil erosion.	

2. Subsurface Drip Irrigation

Subsurface drip irrigation (SDI) applies water directly to the crop root zone using buried polyethylene tubing, also known as a dripline, dripperline, or drip tape. Cost of the dripline is directly related to both diameter and thickness. Small holes called emitters are usually spaced every 8 to 24 inches along the length of the dripline. During irrigation, pressure forces the water out of the emitters drop by drop (Payero *et al*., 2005). Producers in South Africa will have to apply their available water sources more efficiently in future in order to survive, due to imminent water shortages in the country. Many producers are reverting to sub-surface drip, as experts (local and abroad) indicate that it may increase irrigation efficiency by more than 30% with associated increases in yield and quality (Koegelenberg, 2005). Numerous growers in the USA have been making use of sub-surface drip during the past ten years. Sub-surface drip lines are usually left in position for five to ten years with all cultivation taking place above the lines during this period. The only difference between subsurface and other drip irrigation systems is that the former is installed below the surface and has a flushing manifold. In most cases, thin-walled pipe (tube) is used (Koegelenberg, 2005).

Advantages of subsurface drip irrigation (Payero *et al.,* 2005)

One of the main advantages of SDI over other irrigation methods is that it has the potential to be the most efficient irrigation method available today. Since the driplines are usually installed in the soil between every other crop row, the system only wets a fraction of the soil volume, compared with other systems. This leaves space in the soil to store water from rainfall and may reduce the net irrigation requirements. Also, since driplines are buried, about 13-18 inches below the soil surface, the soil surface stays dry. A dry soil surface means that practically no irrigation water is lost due to evaporation and runoff.

- Potential Water Savings - Researchers in Kansas have reported that net irrigation needs could be reduced by 25 percent with SDI, while maintaining high corn yields.
- Potential Yield Increase - SDI can be automated to allow frequent water applications. It also can be used to frequently inject fertilizers and other chemicals such as acids, chlorine and even pesticides with the irrigation water.
- Labour Requirements - After the system is installed, the manual labour required to operate the system is similar to that required to operate a center pivot and is much less than required for a surface system. The SDI system also lends itself to automation, which could considerably reduce labor.
- System Underground - Having the irrigation system underground and keeping the soil surface dry, in addition to reducing evaporation, allows farm equipment to enter the field even during irrigation events.

Disadvantages of subsurface drip irrigation

- High investment cost is one of the main disadvantages of SDI. Cost per hectare varies widely, depending on field size and shape, location of the water source, and level of automation that is desired. Researchers in Texas estimated the investment cost for different irrigation system (Table 5).
- Water supply and system capacity - both water and nutrients can be applied frequently and in small amounts.

- Management time requirements for SDI can be higher than for other irrigation systems, especially the first couple of years when the learning curve is steep.
- Limited dripline lengths: In order to maintain high uniformity with SDI, dripline lengths have to be limited.
- Installation of a SDI system requires specialized equipment, is labour intensive and represents a significant portion of the initial cost of the system.
- Aside from cost, it is critical that SDI systems be properly designed, installed, operated, and maintained. During the design phase, decisions have to be made that cannot be reversed after installation.
- Emitter clogging is another main problem with SDI and other types of drip irrigation systems.
- Rodents can be one of the main problems limiting the successful use of SDI systems to irrigate.
- Since the underground SDI system keeps the soil surface dry, seed germination may be a problem and early growth can be limited by water stress.
- An important concern with SDI in arid regions is that soil salinity above the driplines can be increased with time.
- When driplines are installed parallel to the crop rows, as commonly done, it can be challenging to keep the driplines and the rows aligned from season to season.
- If water is applied at a rate greater than the infiltration rate of the soil, a saturated zone will develop around the dripline.
- Plant roots tend to grow towards the area of highest water content resulting in the danger of root intrusion.
- Chemical treatment of irrigation water is especially important with sub-surface drip irrigation to prevent clogging. Clogging of drippers takes place gradually; therefore, system efficiency can reduce, adversely affecting production, without the producer being aware of it.

Table 5. Investment cost for different irrigation systems (Amesson *et al.*, 2002)

		Cost $/Acre	
Irrigation systems	**Gross**	**Net[1]**	**Net[2]**
Conventional Furrow	165	153	142
Center Pivot	367	268	252
SDI	832	615	570

[1] Assuming tax rate of 15% and rate of 6%

[2] Assuming tax rate of 28% and rate of 6%

<u>Advantages of underground drip compared to surface drip:</u>

- Leads to an increase in water use efficiency,
- Longer lifetime of the system,
- Larger soil areas are wetted,
- Soil surfaces are kept dry,
- Two harvests are possible per year as one harvest can immediately be followed up with the planting of another crop,
- Mechanization of the harvesting process is easier,
- Infiltration tempos is not a problem especially where the soil surface tends to form a hard crust,
- Sewer water can be used,
- Less labour costs, especially for the roll out and rolling in of dripper lines at the end of the season.

CONCLUSION

The most common cases with cotton production in the world is one of limited water availability. Cotton is grown in many water-limited regions due to its high economic value per megaliter (approximately US$ 300 per megaliter) of applied water. Under limited water availability producers often rely on rainfall for a substantial part of the crop water supply. The element of uncertainty in rainfall events imposes an added level of complexity. Although comprehensive recommendations cannot be given for the many diverse conditions, several principles apply across many regions:

1. The water supply must be used in a way that ensures sufficient water reserves to mature bolls. Yield and quality require boll maturation. Unless rainfall during the last two months of crop development is certain, water must be held in reserve to support boll maturation either off the field in dams or underground reservoirs or in the field beyond the utilization of early season root growth.
2. The decision to spread the limited water over a large area or small area is based on the rain pattern and the relative cost of inputs that accrue on an area basis versus those that accrue on a yield basis. However, where rainfall is likely and purchased inputs per area are low, growers often plant substantial hectares that cannot be fully irrigated.

3. If more area is planted than can be fully irrigated, low-density stands or wide/skip row patterns are often used that limit leaf area below that which is required for maximum photosynthesis.
4. Field management practices are employed that capture and preserve soil moisture. Depending on local customs, field conditions and rainfall patterns, soils are managed to maximize infiltration while minimizing evaporation. Surface residues, where available, substantially increases infiltration due to the avoidance of surface crusts and maintenance of macropores. Surface evaporation is often controlled in fine texture soil by lowering the unsaturated hydraulic conductivity with shallow surface tillage.

Water is a scarce commodity that should be used with care. Over irrigation at the wrong time of the growing season when the crop does not really need the water can lead to problems such as roots that does not grow deeper to subtract water.

REFERENCES

Ackerson, R. C., and R.R. Hebert. 1981. Osmoregulation in cotton in response to water stress. I. Alterations in photosynthesis, leaf conductance, translocation, and ultrastructure. Plant Physiol. 67:484-488.

Archibald, R.I.M. 1970. Agronomist (Irrigated Crops).

ARC-Industrial Crops, 1980. Management guide for the Cotton Producer.

Bange, M.P, J.T. Baker, P.J. Bauer, K.J. Broughton, G.A. Constable, Q. Luo, D.M. Oosterhuis, Y. Osanai, P. Payton, D.T. Tissue, K.R. Reddy, and B.K. Singh. 2016. Climate change and cotton production in modern farming systems. A review. Int. Cotton Advisory Committee. Cotton Production Research-6.

Bauer, P., Faircloth, W., Rowland, D., Ritchie, G. 2017. Cotton Incorporated. Cotton Irrigation Management for Humid Regions.

Berlin, J., J.E. Quisenberry, F. Bailey, M. Woodworth, and B.L. McMichael. 1982. Effect of water stress on cotton leaves: I. an electron microscopic stereological study of the palisade cells. Plant Physiol. 70:238-243.

Bredell, G.S., Barnard, C.J. 1974. Bepaling van die waterbehoeftes van subtropiese vrugtesoorte. The Citrus and Subtropical Fruit Journal 487, 18 – 20.

Bruce, R.R., Shipp, C.D. 1962. Cotton fruiting as affected by soil moisture regime. Agron. J. 54, 15-18.

Bold, S. 2012. Water situation in South Africa. Rand Water.

Boyer, J.S. 1982. Plant productivity and environment. Science. 218:443-448.

Constable, G. A., and A.B. Hearn. 1981. Irrigation of crops in a subhumid climate, 6: effects of irrigation and nitrogen fertilizer on growth, yield and quality of cotton. Irrig. Sci. 2:17-28.

Cull, P.O., A.B. Hearn, and R.C.G. Smith. 1981a. Irrigation scheduling of cotton in a climate with uncertain rainfall. I. Crop water requirements and response to irrigation. Irrig. Sci. 2:127-140.

Cull, P.O., R.G.C. Smith, and K. McCaffery. 1981b. Irrigation scheduling of cotton in a climate with uncertain rainfall. II. Development and application of a model for irrigation scheduling. Irrig. Sci. 2:141-154.

Dawood, S.A, and S.N. Hamod. 1985. A comparison of non-farm irrigation systems. Drip/Trickle Irrigation in Action, Proc. of the third int. Drip/Trickle irrigation Congress, 240-545. Fresno, Calif.

De Kock, J., L.P. de Bruyn, and J.J. Human. 1993. The relative sensitivity to plant water stress during the reproductive phase of upland cotton. Irrig. Sci. 14:239-244.

Department of Water Affairs and Forestry. 1996. South African Water Quality Guidelines (second edition). Volume 4: Agricultural Use: Irrigation.

DWAF. 2004. National Water Resource Strategy. Department of Water Affairs and Forestry, Pretoria, South Africa. 150 pp.

Dippenaar, M.C, C. Barbard, and M.M. Pretorius. 1994. Yield potential of cotton under drip irrigation in South Africa. Proc. world cotton Research Conference-1, Brisbane Australia, Feb. 14-17.

Dippenaar, M.C. Plant water requirement of cotton. ARC-Tobacco and Cotton Research Institute, Rustenburg, RSA.

Galanoupoulou-Sendouca, S. and D. Oosterhuis. 2003. Agronomic concepts and approaches for sustainable cotton production. Proc. World Cotton Research Conference-3. Cape Town, South Africa, Mar.507-512.

Gardner, W.R., Gardner, H.R. 1983. Principles of water management under drought conditions. Agric. Water Manage. 7:143-155.

Gerard C.J., Namken, L.N. 1966. Influence of soil texture and rainfall on the response of cotton to moisture regime. Agron. J. 58, 39 – 42.

Goren, H. 1994. Drip irrigation. Proc. of the congress Greek cotton in Europe. Geotechnical chamber of Greece. Thessaloniki. Pp 97-100.

Guinn, G. 1981. Fruit age and changes in abscisic acid content, ethylene production, and abscission rate of cotton fruits. Plant Physiol. 69:349-352.

Hake, K.D. and D.W. Grimes. 2010. Crop water management to optimize growth and yield. Physiology of cotton. Pp. 263.

Hearn, A.B. 1994. The principles of cotton water relations and their application in management. pp. 66-92. In: Constable G.A., and N.W. Forrester (eds.), Challenging the Future. Proc. World Cotton Conf. Brisbane, Australia.

Hsiao, T.C. 1973. Plant responses to water stress. Annu. Rev. Plant Physiol. 24: 519-570.

Hsiao, T.C., Acevedo, E., Fereres, Henderson, D.W. 1976. Stress metabolism: Water stress, growth and osmotic adjustment. Phil. Trans. R. Soc. Lond. B. 273:479-500.

Hewlett, H.M. 1971. Field handbook. The Barberton cotton co-operative CO. LTD.

Hoffman, M.T and A. Ashwell. 2001. Nature divided: Land degradation in South Africa. Cape Town Press. Cape Town.

Hiler, E.A., Howell, T.A., Lewis, R.B., Boos, R.P. 1973. Irrigation timing by the stress day index method. ASAE meeting. Paper no 73-276. Anw. Kentucky, Lexington.

Jordan, W.R., Ritchie, J.T. 1971. Influence of soil water stress on evaporation root absorption and internal water status of cotton. Plant Physiol. 48, 783-788.

Kattan, A.A., Flemming, J.W. 1956. Cotton irrigation. Univ Arkansas Hort. Sci.

Koegelenberg, F.H. 2005. The engineering aspect of sub-surface drip irrigation. Agricultural Research Council. Institute for Agricultural Engineering, RSA.

Koegelenberg, F.H., F.B. Reinders, A.S. van Niekerk, R. van Niekerk & W.J. Uys. 2003. Performance of surface drip systems under field conditions. Water research commission.

Kramer, P.J. 1983. Water deficits and plant growth. pp: 342-389. In: P.J. Kramer (ed.). Water relations of plants. Academic Press, New York.

Loka, D.A., Oosterhuis, D.M. and Ritchie, 2016. Water-deficit stress in cotton. Stress physiology in cotton. Chapter 3. Number 7. The Cotton Foundation.

Malik, R.S., J.S. Dhankar, and N.C. Turner. 1979. Influence of soil water deficits on root growth of cotton seedlings. Plant Soil. 53:109-115.

Massaci, A., S.M. Nabiev, L. Petrosanti, S.K. Nematov, T.N. Chernikova, K. Thor, and J. Leipner. 2008. Response of the photosynthetic apparatus of cotton (Gossypium hirsutum L.) to the onset of drought stress under field conditions studied by gas-exchange analysis and chlorophyll fluorescence imaging. Plant Physiol. Biochem.46:189-195.

McMichael, B.L., W.R. Jordan, and R.D. Powell. 1972. An effect of water stress on ethylene production by intact cotton petioles. Plant Physiol. 49:658-660.

McMichael, B.L., and J.D. Hesketh. 1982. Field investigations of the response of cotton to water deficits. Field Crops Res. 5: 319- 333

McMichael, B.L., and J.E. Quisenberry. 1991. Genetic variation for root-shoot relationship among cotton germplasm. Environ. Exp. Bot. 31:461-470.

Mofoke,A.L.E, J.K. Adewumi, O.J. Mudiare and A.A. Ramalan. 2004. Structuring and characterisation of the medical infusion set as emitter for low-cost drip irrigation system. *Arid Zone Journal of Engineering, Technology and Environment. October, 2004; Vol. 4, 1-15.*

Metelerkamp, H.R.R., Cackett, K.E. 1965. Cotton evaporation in relation to pan evaporation and crop growth. Rhod. J. Agric. Res. 3.1. 9 – 13. (Tegniese mededeling, No 148).

Oosterhuis, D.M, Bourland, F.M. 2001. Management to reduce stress. Proc. 2001 Cotton Research Meeting. D.M.Oosterhuis (ed.). Arkansas agricultural Experimental Station, Univ. of Arkansas Special Report, 204: 13-19.

Oosterhuis, D.M., Wullschleger, S.D. 1988. Drought tolerance and osmotic adjustment of various crops in response to water stress. Arkansas Farm Research, 37(1): 12.

Orgaz, F., L. Mateos, and E. Fereres. 1992. Season length and cultivar determine optimum evapotranspiration deficit in cotton. Agron. J. 84:700-706.

Pace, P.F., H.T. Crale, S.H.M. El-Halawany, J.T. Cothren, and S.A. Senseman. 1999. Drought induced changes in shoot and root growth of young cotton plants. J. Cotton Sci. 3:183-187.

Payero, Jose O.; Yonts, C. Dean and Irmak, Suat. 2005. EC05-776 Advantages and Disadvantages of Subsurface Drip Irrigation". Historical Materials from University of Nebraska-Lincoln Extension. 4787.

Plaut, Z., M. Ben-Hur, and A. Meiri. 1992. Yield and vegetative growth as related to plant water potential of cotton irrigated with a moving sprinkler system at different frequencies and wetting depths. Irrig. Sci. 13:39-44.

Perry, C. 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrigation and Drainage 56: 367-378.

Radin, J.W., J.R. Mauney, L.L. Reaves, and O.F. French. 1992. Yield enhancement by frequent irrigation during fruiting. Agron. J. 84:551-557.

Reddell, D.L., J.F. Prochasca, and A.J. Cudrak. 1987. Sequential water stress in cotton: a stress day index model. ASAE 87, 2080, 23.

Reinders, F.B. 2011. Irrigation methods for efficient water application: 40 years of South African research excellence. Water SA vol.37 n.5 Pretoria.

Saini, H.S. 1997. Injuries to reproductive development under water stress, and their consequences for crop productivity. J. Crop Prod. 1:137-144.

Turner, N.C., A.B. Hearn, J.E. Begg, and G.A. Constable. 1986. Cotton (Gossypium hirsutum L.) physiological and morphological responses to water deficits and their relationship to yield. Field Crops Res. 14:153-170.

PROJECT TITLE : 2017 Desktop Study Spacing and Density

PROJECT LEADER : Dr T van der Westhuizen

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most important fiber crops in the world (Wang *et al*., 2016). Plant density can significantly affect plant habit, yield and quality of cotton (Jones and Wells, 1998). The main factor affecting cotton's growth and development is the environment (climate), and secondly management practices, which include cultivar choice, irrigation, spacing and density, weed control and insect and disease control (Bednarz *et al*., 2006). Irrigation and weed control has received a lot of attention the past few decades, whereas little or no attention has been given to plant spacing and density. This needs to be corrected as new cultivars have different plant structures and genetic potential which should be evaluated at different populations to optimize yields (Bednarz *et al*., 2006). Plant breeders have altered plant architecture in an effort to improve light interception by crop plants. The development of plants with columnar or bush-type architecture are examples of these types of manipulations to improve yield (Silvertooth, 1999).

Generally, cotton producers first look at seed costs, and to reduce seed costs, cotton producers aim to reduce plant populations without sacrificing yields (O'Berry *et al*., 2008). A statistical analysis on plant population of newer varieties is however essential, in order for producers to not inhibit yields when they buy less seed. With increases in cotton seed prices following the introductions of various transgenic and seed treatment technologies, determining optimal plant populations is increasingly important (Bednarz *et al*., 2006; Pettigrew and Johnson, 2005; Siebert and Stewart, 2006; Siebert *et al*., 2006). Siebert, (2005) also stated that choosing a seeding rate is one of the first decisions a grower must make each year and is a logical place to begin reducing input costs. However, the establishment of a good stand is paramount to obtaining a high yield (Christiansen and Rowland 1981). An acceptable plant population or what constitutes a "good" stand will vary with location, environmental conditions, cultivar, and grower preference (Silvertooth *et al*., 2001).

A proper space between plants and row spacing is a very important factor and remain the primary concern for many growers, in order to optimize the crop profit. Some researchers have introduced alternative cultivation systems such as a Narrow Row, (NR) or an Ultra Narrow Row, (UNR) system, from 19 to 75 cm, which has general operation expenses comparable to the Conventional Row system of 0.97 to 1.02 m (CR), (Atwell, 1996; Parvin et al., 2000; Jost and Cthern, 2000; Larson et al., 2004; Darawsheh et al., 2007; Bartzialis, 2004). An advantage of the NR or UNR production system is more canopy closure (Jost et al., 2001) which has led to better light interception, (Krieg, 1996; Heitholt et al., 1992), which in turn reduces weed competition (Snipes, 1996; Wright et al., 2004). Also, some researchers have reported that cotton grown in a narrow row system produced equal yield (Willcut et al., 2006; Nichols et al., 2004; Harrison et al., 2006), or even higher yield (Karnei, 2005; Wilson et al., www.SID.ir Archive of SID D. Zaxos et al. / International Journal of Plant Production (2012) 6(1): 129-148 131 2006; Buehring et al., 2006) than the conventional spacing system. For instance, Avgolas et al. (2005) found significant increase in yield up to 12.95% in 75 cm compared to 96 cm row distance under Greek environmental conditions.

Advantages of Ultra-Narrow Row (UNR) cotton (75 cm inter-row)

- Earliness is achieved since a plant produces only 5-7 bolls and the plant height at harvest is only 0.8m (Belot *et al*., 2010). The obvious advantage of this system is earliness (Rossi *et al*., 2007) since UNR needs less bolls / plant to achieve the same yield as conventional cotton and the crop does not have to maintain the late formed bolls to maturity.
- Higher productivity in Brazil was achieved through development of compact sympodial varieties suited for high density planting geometry.
- The UNR cotton plants produce fewer bolls than conventionally planted cotton but retain a higher percentage of the total bolls in the first sympodial position and a lower percentage in the second position (Vories and Glover, 2006).
- Other advantages include better light interception (Wright *et al.*, 2011), efficient leaf area development, (Wright *et al.*, 2011) and early canopy closure which will shade out the weeds and reduce their competitiveness (Wright *et al.*, 2011; Galanopoulou-Sendouca *et al*., 1980).
- Increases in yields is the most common rationale for using narrow-row cotton.
- Other benefits include water conservation (Galanopoulou-Sendouca and Oosterhuis 2004),
- better response to the growth regulator pix (Galanopoulou-Sendouca and Oosterhuis 2004),
- improved lint quality (Galanopoulou-Sendouca and Oosterhuis 2004),
- fewer pesticides applications (Galanopoulou-Sendouca and Oosterhuis 2004),
- and better use of solar radiation (Galanopoulou-Sendouca *et al*., 1980),

Disadvantage of narrow row cotton

- High seed costs
- Thirty percent more fertilizer (N) should be given, but this might not be seen as a disadvantage because of increased yields

A SUMMARY OF SPACINGS AND DENSITIES IN DIFFERENT COUNTRIES AND SOME YIELD RESULTS WILL FOLLOW

Argentina

Marcelo *et al. (2011)* in Argentina evaluated different N levels and water regimes at row spacing: 0.52 m and plant density, 200.000 plants/ha. Manipulating water, nitrogen and solar radiation may induce higher seed cotton yields under narrow rows cotton systems being a step forward to understand its potential for subtropical environments.

Australia

Quinn (2017) summarized that to optimise cotton yield you should aim for an evenly spaced plant population from 5–13 plants per metre. You need to avoid gaps greater than 50cm. This has been verified by many years of experiments under Australian conditions. There are some situations where growers should target the upper or lower end of this range.

Aim for the lower end of the range when:

- Planting dryland, and;
- Where you normally grow a larger plant size that can compensate well into spaces (e.g. in wetter, warmer climates and good soil types).

Aim for the higher end of the range when:

- Early crop maturing is essential (e.g. southern and eastern regions), and;
- Where you normally grow a smaller plant size that cannot compensate well into spaces (e.g. tight soils).

Brazil

Venugopalani *et al.* (2014) reported that in Brazil, cotton producers in the mid- west switched over to narrow row cotton (75cm spacing). At this spacing, 10 plants/m row was found to be optimum (Silva *et.al*. 2012). High yields are obtained under the high density system. High density planting with specification of 90X10 cm and 76X10 cm is done with zero monopodial (sympodial) varieties. High Density Planting method is practiced which enables higher number of plants at 150,000 to 250,000 per hectare. Thus, with more number of plants per hectare and with 8-14 bolls per plant at 4.0 gm per boll, the productivity is higher.

China

Wang *et al.* (2016) evaluated 3 different plant densities, namely (D1) 6.6 plants m-2, (D2) 8.9 plants m-2, and (D3) 12.3 plants m-2 and reported for plant density, 8.9 plants m−2 (D2) was appropriate for mechanical harvesting compared with 6.6 plants m−2 (D1), the local traditional density for manual harvesting, and 12.3 plants m−2 (D3). D2 showed a 2.5 cm greater height to the first fruiting branch and a 4.2 cm higher lowest boll, and exhibited 2.9–3.6 and 2.6–3.9 cm shorter lengths of lower and middle fruiting branches than D1, respectively. This type of compact plant habit is conducive to efficient mechanical harvesting. Moreover, D2 produced a similar yield to D1 for both the rainy 2013 and the dry 2014 seasons, indicating yield stability. Although D3 had a more suitable plant habit for mechanical cotton harvesting, its yield level and maturity varied across years.

Zhi, *et al*. (2016) evaluated three plant densities (15 000, 51 000 and 87 000 plants/ha) as the subplots in 2012 and 2013 in China and found that plant densities of 51000 and 87000 plants/ha increased lint yield by 61.3 and 65.3% in 2012 and 17.8 and 15.5% in 2013 relative to low plant density (15000 plants/ha). However, no significant difference was observed between 51000 and 87000 plants/ha.

Egypt

In Egypt plant populations are 120 000 to 150 000 plants per ha (Babiker, 2004).

Greece

Zaxosa *et al*. (2011) evaluated the effect of row spacings and irrigation levels on the earliness of seed production of cotton under the Mediterranean environment of central Greece. Two varieties of cotton, Celia and Hersi, were planted in two row spacings (93 and 75 cm) and two irrigation levels (normal and low levels 6160 and 3080 mm/ha). No significant difference in the yield was found among the two varieties, nor between the two row spacings.

Greece and Spain

Rossi et al (2007) reported that in Greece and Spain, the two cotton production countries within European Union, farming practices generally include high planting rates (above 20 Kg of certified seed per hectare), which usually results in high plant density, with more than 17 plants per meter for the common row space of 0.95 – 1.0 m. Despite the different studies showing that an excessively high plant density can depress yield (Bridge *et al*., 1973; York, 1983), farmers both in Greece and Spain are satisfied with their plant population, and average seed cotton yields in the two countries are among the highest in the world. Very dense plant populations can also create competitive pressure, strong enough to force plants to grow more compact. These compact plants would have a lower number of fruiting branches and subsequent shorter flowering periods, resulting in the desired earliness (Galanopoulou *et al*., 1980).

India

In India the distance between rows range from 30 to 60 cm (Venugopalani *et al* (2014). The seed rate was 17-23 kg/ha for *G. racticin* and 8-11 kg/ha for *G. hirsutum*. The distance between plants within row was 22 to 30 cm (Sikka *et al*. 1961). For traditional *G. hirsutum* varieties (Buri) a spacing of 60 x 30 cm was found to be optimum. Choufuli (square planting) at 35x35 cm also became popular in Vidarbha region since this method facilitated intercultural operations in both directions (Sikka *et al*., 1961). Before the advent of hybrid cotton, the highest plant density recommended for varieties of *G. hirsutum* and *G. racticin* were 55000 and 89000 plants/ha (Bonde and Raju, 1996).

Israel

Keren *et al*. (1983) studied cotton's response to 9.0 and 12.5 cm intra-row and 75.0 and 96.5 inter-row spacings under irrigation. They found that yield in plots with the conventional spacing (96.5 cm between rows and 12.5 cm between plants in the row) was 4863 kg/ha, whereas the yield in plots with 75 cm between rows was about 23% higher (5974 kg/ha).

Pakistan

Saleem *et al,* (2009) evaluated the effect of row spacing on earliness in cotton using 3 cultivars grown with three row spacings of 60, 75 and 90 cm. Cultivars as well as row spacing significantly affected almost all the characters related to earliness. Among row spacings, 60 cm apart rows took minimum days for the characters related to earliness. Earliness index was highest (50.9 %) with 60 cm row spacing, production rate index was highest (55.9 g/day) with 90 cm row spacing and seed cotton yield was highest (2603 kg/ha) with 75 cm row spacing. So, earliness in cotton can be achieved by growing a short duration cultivar and by decreasing the row spacing to a certain limit.

Siddique *et al*. (2007) evaluated three cultivars at three intra-row spacings, namely 15, 25 and 35cm and found that cotton with 25 and 35 cm spacings recorded satisfactory seed cotton yield. Yadav (1997) reported that a combination of 75x30 cm row and plant spacing gave more seed cotton yield and all the fiber quaity traits were superior.

South Africa

Irrigated cotton is planted at 1 m inter-row and 20 cm intra-row spacings (85 000 plants per hectare), and dryland cotton is planted at 1 m inter-row and 30 cm intra-row spacings (Dippenaar, Cotton SA). Although Darawsheh *et al*. (2009) summarized that increases of plant density with decreasing cotton row spacing has been suggested as an alternative strategy to optimize cotton profit, this practice would not work in South Africa, as mechanical pickers can only pick cotton that is either planted 0.75 m or 1 m apart.

Turkey

Mert *et al*. (2005) evaluated the response of cotton (*Gossypium hirsutum* L.) to different tillage systems and intra-row spacing and found that earliness is of great importance to cotton production in Mediterranean-type environments due to detrimental effects of autumn rainfall on lint quality. However, farmers commonly avoid early sowing due to risks of cold soil temperature and waterlogging after sowing in spring. Ridge-tillage system is one approach to increase soil temperature and mitigate adverse effects of waterlogging. The ridge-tillage system is also advantageous in reducing inputs in tillage operations. Field experiments were conducted in Turkey during 2000 and 2001. The experiment was laid out as a split-plot with 3 replications with tillage systems as main plots and intra-row spacing's (13, 17, 21 and 25 cm) as subplots. The effects of tillage systems on lint yield and earliness were inconsistent among years. The Ridge-tillage planting system resulted in 13.5% higher lint yield and 14.5% more earliness in 2001 when abundant rainfall occurred after sowing, while significant effects of tillage systems were not observed in 2000. The intra-row spacing's significantly affected lint yield and earliness in both years. The earliness increased with closer spacing, while the highest lint yield was obtained from 17 cm intra-row spacing in both years. However, tillage systems, intra-row spacing's and tillage system spacing interaction in both years did not significantly affect the fibre quality parameters. Recent investigations on row-spacing of cotton have shown that the highest yields produced from 76 cm row spacings regardless of tillage systems in a semi-arid Mediterranean environment in Turkey.

USA

In the USA, Galanopoulou-Sendouca and Oosterhuis (2003) summarized that researchers have made continued attempts to grow cotton at various row spacings and row configurations, including in double rows (15 -36 cm) and single rows (48 – 102 cm). Most narrow row cotton consists of 76 cm between rows. USA researchers have done this research on beds or flat soil. Raised beds has the advantage of better infiltration and an increase in soil temperature which leads to better emergence of cotton seedlings. Galanopoulou-Sendouca *et al*. (1980) Found that narrow row systems can be superior to conventional systems because they provide more suitable plant distribution for improved exploitation of resources, and early canopy closure for efficient radiation use.

Wright *et al* 2015 proposed that recommendations vary widely, but most researchers recommend from 80,000 to 150,000 plants per acre and stated that some of the best yields in Florida have come from final stands of 100,000 to 110,000 plants per acre. Investigations at Auburn University evaluated time of planting and plant density in UNR cotton. At 150,000 plants per acre, 3–4 bolls per plant set at the first or second fruiting position can yield 2–2.5 bales per acre. On sandy soils, or when moisture stress occurs late in the season, high plant densities may result in competition for moisture and this could cause yield reductions

Kohel and Lewis (1984) described in the book "Cotton" that planting rates for irrigated cotton are designed to give 10 to 15 plants per drilled meter of row which converts to 100 000 - 140 000 plants per hectare if rows are 1 m apart. More plants per hectare may cause excessive growth at the expense of yield (Wilkes and Corley, 1968). Planting rates for dryland cotton in the USA are designed to obtain 150 000 to 200 000 plants per hectare, i.e. 12 to 18 plants per meter of row in rows 1 m apart.

Silvertooth (1999) reported that in Arizona optimal plant populations (densities) for both conventional and narrow row cotton production systems often range between 30,000 to 60,000 plants per acre (ppa). Acceptable cotton plant populations have been reported between 20,000 to 75,000 ppa for irrigated cotton production systems in the desert Southwest. A conventional cotton production system in Arizona (e.g. an Upland cotton variety, 40 inch row spacing, and approximately 40,000 ppa) will commonly produce plants with an average of 21 fruiting branches by the time the crop experiences cut-out (end of primary fruiting cycle). Assuming the plants have at least two fruiting sites on each fruiting branch, the plants would have an average of at least 42 potential fruiting sites. With 50% retention of those sites at harvest and three plants/foot, this would provide approximately 63 bolls/foot of row. Using a general yield estimate of 20 bolls/foot equating to one bale lint/acre, this field would have a 3-bale yield potential. For a UNR system to be more profitable, a greater number of bolls would have to be produced per unit area, or an equal number produced with lower inputs. Seemingly, the goal of a UNR system would be to optimize the earliest (lower) fruiting sites on the plants. Thus, the emphasis in crop management will likely be oriented toward the early stages of the growing season and fruiting cycle.

Stephenson *et al*. (2011) evaluated three cotton planting patterns (19 or 38 cm twin rows and 97 cm single rows) at five plant densities (7, 9, 11, 13 and 15 plants m-2) on cotton growth, yield and fiber quality.

Recommendations made by DeltaPine Monsanto (2017) for USA cotton producers are as follows:

- Cotton is typically planted in wider 97 – 102 cm rows; however, narrower row spacing may provide yield benefits under ideal growing conditions.
- When planting in 75 cm 2:1 skip rows, the plant population within each row must be increased to fill in for the skip rows.

Uzbekistan

Uzbekistan is the fifth largest cotton producer in the world. Ibragimov *et al*. (2007) reported that cotton plants are thinned to achieve a population density of 9 plants/m^2.

DISCUSSION

Considerable research efforts have been ongoing for over 100 years to determine the optimum plant population for maximum yield and quality in cotton. Many studies report highest yields occur in plant populations ranging from 49,000 to 256,000 plants/ha (Kittock *et al*. 1986). A proper space between plants and row spacing is a key agronomic factor to optimize crop profit (Zaxosa *et al*., 2011). The manipulation of plant density is a time tested agronomic technique to improve yield and profitability (Venugopalan *et al*., 2014). Plant density directly influences the radiation interception, moisture availability, wind movement and humidity (Heitholt *et al*., 1992) that in turn affects the canopy height, branching pattern, fruiting behavior, crop maturity and yield. A decrease in row width resulted better light interception (Krieg, 1996) due to rapid canopy development and early canopy closure (Wright *et al*., 2011) which helped in weed suppression and a decrease in soil water evaporation.

Venugopalani *et al* (2014) reported that the manipulation of row spacing, plant density and the spatial arrangements of cotton plants, for obtaining higher yield have been attempted by agronomists for several decades in many countries and that the Ultra Narrow Row (UNR) system is popular in several countries like Brazil, China, Australia, Spain, Uzbekistan, Argentina, USA and Greece (Rossi *et al.*, 2004). The most commonly tested plant densities range from 5 to 15 plants/m^2 (Kerby *et al*., 1990) resulting in a population of 50000 to 150000 plants/ha.

Venugopalani *et al* (2014) further reported that the availability of compact genotypes, acceptance of weed and pest management technologies including transgenics, development of stripper harvesting machines and widespread application of growth regulators have made these high density cotton production systems successful in these countries.

Venugopalani *et al*. (2014) reported that world over, during the last 50 years, breeding efforts concentrated on developing sympodial varieties with fewer bolls per branch and more bolls closer to the main stem. The objectives were two fold, to fit in more plants per unit row length and to improve fibre quality. Bolls that were closer to the main stem received better nutrition, were more uniform and were expected to produce lint of good quality. As a result most of the varieties developed during the last three decades in many cotton growing countries except

India could be fitted to narrow row spacing (38 to 76 cm) with 8-10 plants/m row length and these systems become widely accepted in several countries.

Silvertooth (1999) summarized that variations in crop canopy architecture as effected by row spacing, plant population, and plant type have been topics of interest for many generations and will continue to be subjects of further study and development. Results with the UNR systems that are being developed and tested should be followed with great interest and be evaluated thoroughly and objectively to document the potentials they appear to offer.

Proper spacing of cotton plants can help maximize yield potential. Planting cotton seed at too high of a population can cause overcrowding of plants and may unnecessarily increase seed cost. High plant populations should be avoided unless very aggressive management practices are to be used in combination with proper variety selection.

When cotton plant populations are too high, the following can occur:

- Later initiation of fruiting with a somewhat shortened boll loading period due to running out of time at the end of the season.
- Decreased drought tolerance.
- Increased fruit shedding due to difficult to control plants during the mid to late season.
- Increased need for more aggressive plant growth regulator use during the cropping season.
- Increased number of small bolls. Plant populations that are too low can also reduce yield potential.

Reduced cotton stands can:

- Increase plant size.
- Delay reproductive development. Low populations typically fruit earlier but require time to accumulate a fruit load that allows for optimal yield. All of this takes time, which may or may not be beneficial, and can add management challenges in late planting and short-season scenarios.
- Shift more bolls to outer fruiting branches and vegetative branches.
- Increase boll size and micronaire at some fruiting positions.

CONCLUSION

When looking at all the above mentioned higher plant populations that is being used by numerous countries, it is worth the while to evaluate different inter-row and plant spacing of new cultivars in South Africa, where the advantage may result in a 25 – 30 percent yield increase.

REFERENCES

Babiker E.A. 2004. Plant density spatial arrangement for morphologically varying cotton varieties. World Cotton Research Conference – 3. Cotton production for the new millennium.

Bednarz, C.W., D.C. Bridges, and S.M. Brown. 2000. Analysis of cotton yield stability across population densities. Agron. J. 92:128-135.

Bednarz, C.W., W.D. Shurley, W.S. Anthony, and R.L. Nichols. 2005. Yield, quality, and profitability of cotton produced at varying plant densities. Agron. J. 97:235-240.

Bednarz, C.W., R.L. Nichols, and S.M. Brown. 2006. Plant density modifies within - canopy cotton fiber quality. Crop Sci. 46:950-956.

Belot, Jean-Louis and Salles, Alvaro O. (2010) – Second – cycle cotton growth with high plant density in Mato Grosso, Brazil – ICAC Recorder. June 2010.

Bridge, R.R., W.R. Meredith, Jr., and Chism J.F. 1973. Influence of planting method and plant population in cotton (*Gossypium hirsutum L.*). Agronomy Journal 65:104-109.

Buehring, N. and Dobbs, R. 2000. UNR Cotton Plant Population Effect on growth and Yield. Proceedings of the 2000 Beltwide Cotton Conference. National Cotton Council, 1: 660-661.

Darawsheh, M.K., [1*], E. M. Khah [2], G. Aivalakis [3], D. Chachalis [4] and Fatbardh Sallaku. 2009. Cotton row spacing and plant density cropping systems I. Effects on accumulation and partitioning of dry mass and LAI

DeltaPine Monsanto (2017). agKnowledge Spotlight. Shedding light on the concerns of your fields.

Dippenaar M.C. CottonSA. Cotton Production. Website: www.cottonSA.org.za

Galadima A., S.H. Husman, and J.C. Silvertooth. 2003. Plant population effect on yield and fiber quality of three upland cotton varieties at Maricopa Agricultural Center, 2002. http://www.cals.arizona.edu/pubs/crops/az1312/az13121e.pdf

Galanopoulou-Sendouka, A.G., Sficas, N.A., Gagianas, A.A. and Gerakis, P.A. 1980. Effect of Population Density, Planting Date, and Genotype on Plant Growth and Development of Cotton. Agronomy Journal, 72: 347-353.

Galanopoulou-Sendouca and Derrick Oosterhuis, D.M., 2004. Agronomic concepts and approaches for sustainable cotton production. World Cotton Research Conference-3. Cotton production for the new millennium.

Heitholt, J. J., W. T. Pettigrew, and W. R. Meredith. 1992. Light Interception and Lint Yield of Narrow-Row Cotton. CropSci: 32:728-733. doi:10.2135/cropsci1992.0011183X003200030030x

Husman, S.H.; McCloskey, W.B.; Teegerstrom, T. and Clay, P.A. 2000. Agronomic and Economic Evaluation of Ultra Narrow Row Cotton Production in Arizona in 1999. Proceedings of the 2000 Beltwide Cotton Conference. National Cotton Council, 1: 653-657.

Ibragimov, N., Evett, S.R., Esanbekov, Y., Kamilov, B.S., Mirzaev, L., Lamers, J.P.A. 2007. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agricultural water management, 90:112-120.

Jones, M.A., Wells, R. 1998. Fiber yield and quality of cotton grown at two divergent population densities. Crop Sci.38. 1190 – 1195.

Kerby, T.A., Cassman, K.G., and Keeley M. 1990. Genotypes and plant densities for narrow-row cotton systems: II. Leaf Area and dry-matter partitioning. Crop Science, 30: 649-653.

Kerby, T. 1998. UNR Cotton Production System Trial in the Mid-South. Proceedings of the 1998 Beltwide Cotton Conference. National Cotton Council, 1: 87-88.

Keren, R, Meiri, A and Kalo. Y. 1983. Plant spacing effect on yield of cotton irrigated with saline water. Plant and Soil, 74. P 461 – 465.

Kittock, D.L., R.A. Stelley, C.J. Cain, and B.B. Taylor. 1986. Plant population and plant eight effects on pima cotton lint yield. Agron. J. 78:534-538.

Krieg, D.R. 1996. Physiological Aspects of Ultra Narrow Row Cotton Production. Proceedings of the 1996 Beltwide Cotton Conference. National Cotton Council, 1: 66-66.

Marcelo, P., Luciano, M, Arturo, R, Omar, G. 2011. Narrow row cotton: can we increase yield by enhancing assimilate supply? 8º Congresso Brasileiro de Algodão & I Cotton Expo 2011, São Paulo, SP – 2011.

Mert, M., Aslan, E., Akiscan, Y., Caliskan, M.E. 2005. Response of cotton (*Gossypium hirsutum* L.) to different tillage systems and intra-row spacing. Soil and Tillage Research.

O'Berry, N.B., J.C. Faircloth, J.C., Edmisten, K.L., Collins, G.D., Stewart, A.M., Abaye, A.O., Herbert, D.A., Jr., Haygood, R.A. 2008. Plant Population and Planting Date Effects on Cotton (Gossypium hirsutum L.) Growth and Yield. The journal of cotton science 12:178-187.

Pettigrew, W.T., and J.T. Johnson. 2005. Effects of different seeding rates and plant growth regulators on early-planted cotton. J. Cotton Sci. 9:189-198.

Qiunn, J. 2017. Australian Cotton Production Manual.

Roche, R.; Bange, M.; Milroy, S.; Brown, E.; Caton, J. and Hammer, G. 2004. Why aren't ultra-narrow rows earlier than conventionally spaced rows in Hillston? 11th Australian Cotton Conference Proceedings. ACGRA.

Roche, R. and Bange, M. 2006. Do Ultra-Narrow Row Cotton Systems Offer Any Benefit to Australian Farmers? CSIRO Plant Industry, Cotton Catchment Communities Cooperative Research Centre: http://www.regional.org.au/au/asa/2006/concurrent/systems/4568_rocher.htm

Rossi, J. and Braojos, E. 2003. Cotton Response to Plant Population Densities in Spain. World Cotton Research Conference – 3. Agricultural Research Council, Institute for Industrial Crops. South Africa: 586-592.

Rossi,J., Braojos, E., Baxevanos D. 2007. Varietal Response to Ultra Narrow Row Cotton in Spain. World cotton research 2007.

Saleem, M.F., Anjum, A., Shakeel, A., Ashraf., M.Y., Khanh, Z. 2009. Effect of row spacing on earliness and yield in cotton. pak. j. b., 41(5): 2179-2188.

Siddiqui, M.H., Oad, F.C., Buriro, U.A. 2007. Plant spacing effects on Growth, Yield and Lint of cotton. Asian Journal of plant sciences, 6:415-418

Siebert B.S. 2005. Cotton (Gossypium hirsutum L.) response to plant density, insect pest management, and harvest-aid application strategies. PhD Dissertation. Louisiana State University.

Siebert, J.D., and A.M. Stewart. 2006. Influence of plant density on cotton response to mepiquat chloride application. Agron. J. 98:1634-1639.

Siebert, J.D., A.M. Stewart, and B.R. Leonard. 2006. Comparative growth and yield of cotton planted at various densities and configurations. Agron. J. 98:562-568.

Sikka S. M., Singh A., Singh A., Gadkari P. D., Balasubrahmanyan R., Iyengar N. K., Sawhney K., Bederker V. K., Patel G. B., Pandya P. S., Paranjpe V. N. and Panigrahi N. S. 1961. Cotton in India. A Monograph. Indian Central Cotton Committee (ICAC), Bombay. Pp. 1-375.

Silva P. T., Macedo, F. G., Camacho, M. A., Santos, C., Santi, A., Krause, W. and Rambo. J. R. 2012. Spacing and plant density effect on reproductive development of herbaceous cotton –Scientia Plena 8, 5: 1-9.

Silvertooth, J.C., K.L. Edmisten, and W.H. McCarty. 1999. Production Practices. In C.W. Smith ed. Cotton: Origin, History, Technology, and Production (pp. 463-465). JohnWiley & Sons, Inc. New York, NY.

Silvertooth, J.C. 1999. Row spacing, plant population, and yield relationships. http://ag.arizona.edu/crops/cotton/comments/april1999cc.html

Silvertooth, J.C. 2001. Plant population evaluation/management for cotton. http://cals.arizona.edu/pubs/crops/az1203.pdf

Stephenson, D.O., Barber, L.T, Bourland F.2011. Effect of twin-row planting pattern and plant density on cotton growth, yield and fiber quality. The Journal of Cotton Science, 15:243-250.

Venugopalan, M.V., Kranthi, K.R., Blaise, D., Shubhangi lakde and Sankaranarayana, K. 2014. High density planting system in cotton – The Brazil Experience and Indian Initiatives

Weir, B.L. 1996. Narrow Row Cotton Distribution and Rationale. Proceedings of the 1996 Beltwide Cotton Conference. National Cotton Council, 1: 65-66.

Wright, D.L., Marois, J.J., and Sprenkel, R.K. 2015. Production of Ultra Narrow Row Cotton. IFAS Extension, University of Florida

Wang, X., Hou, Y., Du, M., Xu, D., Lu H, Tian, X., Li, Z. 2016. Effect of planting date and plant density on cotton traits as relating to mechanical harvesting in the Yellow River valley region of China. Field Crops Research 198. 112–121.

York, A.C. 1983. Response of cotton to mepiquat chloride, varying N rates and plant populations. Agronomy Journal 75: 66-70.

Zelinski, L.J. 1997. Cotton Management Guide. Deltapine Seed: 38

Zaxosa ,D., Kostoulaa, S., Khaha, E.M. Mavromatisa ,A., Chachalisb, D, Sakellarioua, M. 2011. Evaluation of seed cotton (Gossypium hirsutum L.) production and quality in relation to the different irrigation levels and two row spacings.

Zhi, X., Han Y, Li, Y., WANG, G., Du Wi, Li,X., Mao, S., Feng, L. 2016. Effects of plant density on cotton yield components and quality Journal of Integrative Agriculture 2016, 15(7): 1469–1479