A Perspective of Water Management for the Future

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ABSTRACT

Despite the reality that there is sufficient freshwater to support a much greater population, water is scarce in a growing number of locations. Consequently, the critical effects of long term salinity and possible industrial pollutants characteristic of recycled effluent necessitate that saline condition research should focus on drainage, irrigation technology and management on the one hand, and plant physiology, leading to plant stress tolerance and water use efficiency enhancement on the other. Agronomic management, including plant population, row spacing, plant growth regulators, land preparation and varietal selection continue to play a key role in water use efficiency for cotton production. Improved technology and scheduling methodology has promoted productivity and water use efficiency. Nevertheless, accuracy and control of water application in space, time and quantity remain constraints for enhancement of productivity and water use efficiency, regardless of the method applied. The hallmark of irrigation technique evolution is probably the inherent precision of water application in space and time. Further advances in precision agriculture contributing to crop uniformity are bound to improve productivity and consequently water use efficiency. These emerging technologies could also contribute to field monitoring and scheduling. This paper addresses knowledge-based considerations related to plant physiology, breeding and biotechnology that could facilitate water use efficiency. An increased substitution of information for water seem to be the most promising strategy to ensure water management in sustainable future irrigated agriculture.

Water availability

The global constant water amount on planet Earth is estimated at about 1,400 million cubic kilometers (km^3). Only a fraction of that comprising about 12,000 km^3, is available for human use. Unfortunately, despite the reality that there is sufficient freshwater to support a much larger population, water is considered scarce in a growing number of locations. Unequal distribution of rainfall, pollution and land degradation contribute to this (Kandiah, 1997). A recent UN report (CSD, 1997) clearly show widespread misuse with worsening water quantity and quality problems, largely due to inadequate management. Small communities, large cities, farmers and industries, developing countries and industrialised economies mismanage water with detrimental effects on quantity and quality.

Agriculture is in the eye of the storm. It has the largest water demand (FAO 1994), is relatively low value, and low efficiency but is highly subsidised and furthermore, it is unable to compete economically for scarce water among other competitors (Hutmacher *et al.*, 1995). Great expectations are aimed therefore at agricultural research to increase productivity with declining water availability. Thus, water use efficiency must be developed to improve productivity while releasing water for other uses (Kandiah, 1997).

This paper focuses on agronomic and physiological aspects of water management. Water resource development policy on national or global levels have a critical impact but are beyond the scope of this paper and will therefore be mentioned only briefly.

Cotton water usage

Cotton is irrigated with varying intensity (Hearn, 1995). Cotton is either fully irrigated (Western USA, Mediterranean, Central Asia, Punjab of India and of Pakistan and parts of China), fully rainfed - including ex-seasonal rainfall dryland and seasonal rainfed production (South and parts of North America, most of Africa, most of India and South East Asia) or receives supplementary irrigation (Australia, North America and parts of

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Asia). Overall, irrigated cotton accounts for 7.3% of irrigated land (61% accounts for rice). Hearn (1995) concludes that 73% of the cotton fiber in the world is produced under irrigation from 53% of the total cotton land.

Drainage and marginal water usage

High water tables and related salinisation are a major constraint in many parts of the world. Lowering water table depths by installing sub-surface drainage and appropriate maintenance has been reported to increase cotton and maize production by up to 43% (Finney, 1997). Reclamation using basic drainage methods should be utilized to effectively alleviate these problems (Martinez-Beltran *et al.*, 1996).

As a crop with xerophytic origins, cotton is tolerant to saline conditions with an EC threshold of nearly 8 dS/m (Maas, 1986). This type of tolerance has been the background for the exploitation of various water resources such as saline water and reclaimed wastewater for cotton production. Alas, despite extensive research on saline and sodic conditions in water and soil and despite short-term success in managing them, the long term effects of salinity seem detrimental to soil properties and to yield (Sadan, 1997). This is especially true in areas with low rainfall and insufficient leaching of salts.

Methods for alleviation salinity and sodium hazards have included soil treatments, drip irrigation systems (Hanson and Bendixen, 1995) and augmented water schedules (Meiri and Plaut, 1985), changes from flat bed to furrow irrigation (Choudhry *et al.*, 1994) and varietal selection (Munk and Wroble, 1995). Gypsum managed soils seem to be losing tolerance and negative effects are evident after about 10 - 20 years (Sadan, 1997).

As an industrial crop, cotton has been a suitable candidate for application of treated effluent from urban origin. Calculating that one adult generates approximately 100 litres of effluent per day, in a developed urban environment, a city of 2 million could generate recycled wastewater to cultivate 15-20 thousand hectares of cotton. The cost of this cannot be ignored but purification of effluent in developed societies is an issue to be addressed quite apart from irrigation water for agriculture. In the long run, research emphasis should aim at cheaper, higher levels of purification at the source and cost effective methods of desalinising saline water, to avoid exhausting soil and environment with highly polluted and salinised water.

In the case of salinised agricultural land, great care should be taken to avoid high salt contamination that in the long term causes wasteland. Management through crop rotation and natural rainfall leaching should be employed. Due to the critical effects of long term salinity and possible industrial pollutants characteristic of recycled effluent, saline condition research should be focused on irrigation technology and management on the one hand, and plant physiological functioning leading to plant stress tolerance and water use efficiency enhancement on the other.

Agronomic practices – interacting with water management

Agronomic management probably accounts for a significantly high percentage of variation in cotton yield. The interaction between various agronomic practices and water management is highly important.

Plant population and density

Cotton has a well-documented potential to compensate for loss of fruiting forms and lack of stand (Jones and Wells, 1997). Thus it is often difficult to demonstrate the advantages of alternative management systems, or the conditions best suited to their expression. Narrow rows and high populations comprise a sound theoretical basis for early, high yield. Rapid canopy cover for enhanced compensation potential, early and augmented irradiation interception and potential for earliness, to mention a few, are the basis for yield increase. Frequently, previous work from various origins does not demonstrate this but with precise management, suitable varieties and high uniformity, there could be an opportunity to manage the cropping system by means of plant density combined with irrigation to improve water use efficiency. Reports from the US (Best *et al.*, 1997) show that the narrower the row spacing, the more plants generate additional dry matter per area and improve harvest index.

Chinese production is traditionally narrow row with 60cm between two row beds and 35cm between rows on the bed, giving plant populations of up to 180,000 plants per hectare. This spacing proved to be most efficient for short season production under water constraints in the cool deserts of Xinjiang province.

Experience in Israel using drip irrigation shows that the narrower the row spacing, the higher the yield and the greater the water use efficiency. This was achieved under saline conditions (Keren *et al.*, 1983), and with plant populations of 55,000, 80,000 and 105,000 plants per hectare for 2 X 1 meter single skip row, 100cm and 76cm regular row spacing respectively (Bosak *et al.*, 1991). Although not always cost effective, much the same has been demonstrated for other environments. Narrow and ultra narrow rows therefore have potential to improve productivity and water use efficiency. This usually depends on appropriate management, suitable cultivars, technical solutions other than broadcast stripping, lint quality stability and demonstrable of cost effectiveness (Kerby, 1998; Brown *et al.*, 1998).

Other examples of positive interaction between management practices and water use efficiency such as plant growth regulators in some situations, land preparation and tillage versus no-till systems have been demonstrated. Obviously varietal selection also determines water management fine tuning.

So much for agronomic management which will obviously continue to play an important role in water use efficiency for cotton production.

Development of irrigation systems – towards precision irrigation

Irrigation systems can be categorized as (1) surface-gravity-flow systems such as furrow, border or level basin and (2) pressurized flow systems such as sprinkler systems (including solid set, centre pivot, linear move, sideroll) and micro-irrigation systems (drip and micro-spray) (Hutmacher *et al.*, 1995).

Constraints

Constraints for surface gravity flow systems include:

- excess use of water resulting in
- oxygen deprivation from soil saturation,
- square and small boll shed,
- leaching of nitrates and of course
- water loss due to both runoff and drainage below the root zone.

Constraints for advanced pressurized systems include:

- management complexity;
- labour intensive, especially for surface systems;
- high capital investment;
- high variable maintenance costs.

In characterizing the evolution of irrigation methods, the development of water use efficiency can be demonstrated (Derived from Hearn, 1995). Nevertheless, comparable water use efficiency has been demonstrated for various irrigation methods. The hallmark of irrigation technique evolution is probably the inherent precision of water application in space and time.

- Higher engineering efficiency for water conservation - a higher percentage of the pumped water actually reaching the root zone and being utilized for transpiration.
- Increased potential for precise spatial uniformity
- Precision metering and high level of control

Development in each of the various methods has followed this course. For example:

- The development of small basins and microcatchments for surface gravity flow systems;
- Surge valve application for row water systems can approach 80% efficiency (Krieg, 1998).
- Low Energy Precision Systems (LEPA) for sprinkler related methods now exceed 95% efficiency (Krieg, 1998); and
- Self regulating emitters and sub-surface installation for drip irrigation increase productivity and water use efficiency.

Improved methodology has definitely promoted productivity and water use efficiency. Growers who have adopted drip methods in various environments have obtained increased yields, enhanced water use efficiency and economic advantages (Shiyani and Kuchhadiya, 1996; Fedler, 1996; Dipenaar *et al.*, 1997), especially where water costs are high. Sub-surface drip irrigation has partially challenged these issues (Camp et al, 1997; Hutmacher *et al.*, 1993), but cost-effectiveness is yet to be demonstrated.

Nevertheless, consensus concerning the necessity of higher technology such as drip irrigation is far from being wide (Anthony and Namoi, 1996), and the ability to obtain uniformity by drip irrigating has also been scrutinized (Amali *et al.*, 1997). Increased uniformity in spatial distribution of water and increased application frequency have been demonstrated by other irrigation means, with results comparable to those achieved with advanced drip systems (Radin *et al.*, 1992).

Accuracy and control of water application in space, time and quantity remain constraints for improved productivity and water use efficiency, regardless of the method in question. Thus new irrigation techniques should be manageable, precise in water application and cost-effective for the environment in question. Due to the many factors involved, new or alternative methodology should be carefully scrutinized for marked economic advantage before adoption into an existing, balanced environment.

The theoretical basis linking field variation to productivity has been demonstrated (Tanji and Yaron, 1994). Lack of uniformity in water application coupled to soil variability could definitely contribute to low uniformity in plant development, associated with lower expected average yields and lower profits. Cotton is a highly demanding crop for optimum water management, both shortage and excess of water being detrimental to yield. A desirable irrigation system applies water at a rate that allows all water to infiltrate, and distributes the water in space and time to match crop requirements in each parcel of the field. Resulting field variability as reflected through cotton foliage temperatures for example, generally demonstrates low uniformity in current leaf temperature (Wanjura and Upchurch, 1994). A large number of measurements or measurements from larger areas are therefore required to reach an average field value within an acceptable tolerance. Other reports demonstrate the disadvantage of temporary diurnal stress for both low and high frequency irrigation systems and potential benefits of frequent, low volume irrigation (Moreshet *et al.*, 1996; Chu *et al.*, 1995; Landivar *et al.*, 1995). Hence, multi-dimensional uniformity in application timing, space and quantities seem to be imperative. With enhanced engineering, computer capabilities and improved knowledge of the soil–plant-water continuum, irrigators could adopt “prescription” irrigation that apply precisely the prescribed amounts of water to match production capacity on each parcel of land (Hoffman and Martin, 1993). Mechanized linear or central pivot irrigation could be suitable candidates for testing this concept.

Further advances in precision agriculture contributing to crop uniformity are bound to improve productivity and consequently water use efficiency. These emerging technologies could contribute to field monitoring and scheduling.

Water management scheduling and control - the secret of how much and when

Cotton is a highly demanding field crop in management, water management is probably being a major knowledge-based component. Water application has to be optimized. Deficient irrigation generates water and carbohydrate stress leading to yield shortfall, whereas excess irrigation ends in rank growth, low harvest index leading to yield loss and a waste of a valuable resource. Water management optimization is understanding plant necessities and responding precisely.

Plant development and sensitivity to water status have been investigated intensively. Plant measurements and related calculations such as height, nodes, fruiting formations, plant vigour, nodes above first position white flower, dry weight measurements, boll opening rates have been consolidated into specific, optimum development curves for various situations and environments. Sensitivity of cotton plants to water stress during the various reproductive development phases, is well-documented (Krieg *et al.*, 1993). Three basic stages are identified: square formation and early flowering; flowering peak and boll development; and boll ripening. It is well established that water stress during boll development has the most pronounced inhibiting effect on yield and quality. Both the early and later development periods are less affected by water stress (de Kock et al, 1990).

Contrary to historical water management methods, early season water stress is no longer recommended practice, providing the availability of water and a given aim to maximize yields. The basic goal is to refill the soil profile to the moisture holding capacity in order to diminish stress risks. Optimum water amounts for application can be calculated using the water budget method in which prevailing climatic conditions are reflected in evapotranspiration rates. Evapotranspiration estimation has been intensively investigated (Doorenbos and Pruitt 1977; Meron *et al.*, 1990) and good approximations of real evapotranspiration by using pan evaporation or by long term approximation have been reached.

Cotton crop coefficients reflecting plant development are estimated using a variety of methods. A midday sunfleck method to measure row crop cover (Meron *et al.*, 1990) is simple and usually adequate. Other methods have been developed in California using regression analysis over time on long term data (Kerby and Hake, 1996). Further data analysis has shown close correlation between plant height and leaf dry weight (LDW) (Bosak, 1992; Sadan, 1990). Assuming good correlation between LDW, leaf area index (LAI) and transpiration, plant height has been is used as a parameter for coefficient estimation (Bosak, 1992). Thus, periodic cotton coefficients have been defined to reflect plant canopy, ground cover and transpiration.

Multiplying a measured or estimated evapotranspiration rate by the appropriate cotton canopy coefficient provides a value representing the amount of irrigation water needed to replace the volume depleted through evapotranspiration. In addition, criteria for early season and irrigation termination have been proposed and implemented (e.g. Johnson Hake *et al.*, 1996; Munk *et al.*, 1997).

Additional methods for irrigation scheduling and plant water status monitoring include:

- the pressure chamber (Seymour *et al.*, 1996)
- canopy temperature measurement (Wanjura, 1997)
- sap flow gauge technology
- other plant growth monitoring methods such as height development, height-to node ratio (HNR), retention rates, nodes above white flower (NAWF) (Kerby and Hake, 1996)
- computerized cotton simulation models based on developmental knowledge
- soil moisture measurement methods and soil sensor actuated systems

Computerized cotton simulation models – the game of "playing God" - and numerous other specific algorithms are developing rapidly, and exist for many production environments. Calibration and validation are constantly underway with the discovery of new knowledge. These tools developed as experimental research aids designed to highlight missing knowledge. They are now evolving into crop management tools used by growers for water management. New knowledge and further modification of these programs are expected to improve their usage and value.

Advance information on soil moisture is important in management. Gravimetric measurements are common and relatively reliable, but tedious and time consuming. Neutron probes that pose significant calibration problems and soil tensiometers of various types and other soil moisture metering devices, all suffer critically from soil variability. With all due respect for soil moisture advance information, the best tensiometer in a field for management purposes is a cotton plant. In short, a good representative, reliable, manageable and cost effective means for soil moisture measurement is still lacking.

Cotton irrigation scheduling still relies heavily upon plant, field and soil sampling. Once again, representative monitoring for field assessment is closely associated with uniformity. Further enhancement of correct scheduling demands broader field information and increased field uniformity. Precision agriculture developments could play a role in water scheduling if proven feasible and cost-effective. Developments such as thermal imagery (Garrot, 1997) or Multispectral remote sensing and site specific agriculture (Barnes *et al.*, 1996) for example, if further refined, could provide insight into consolidated, representative field information on water status. Methodology such as this could possibly contribute to water conservation, to transpiration efficiency and to cotton productivity in a cost effective manner.

Furthermore, present water management practices are based upon the onset of stress symptoms such as growth decline, leaf water potential drop, sap pressure and flow change and leaf temperature increase. Since these symptomatic responses are not necessarily related to water stress, they could prove misleading if used as management tools.

Advanced stress information could facilitate water management. New concepts of stress signaling (Hearn, 1995) could provide the advance warning and be harnessed as novel indicators of plant water status, associated with the biochemistry of plant water stress and hormonal balance. Further knowledge of stress physiology and biochemical pathways could possibly provide a reliable and timely water management tool.

The physiology of water use efficiency

Understanding basic cotton water stress physiology has facilitated applied water management. Understanding retention and abscission patterns has determined variation in seasonal tolerance to water deficit and has thus assisted in defining irrigation schedules. Periods of increased sensitivity, such as peak flowering have been discovered, thus determining preferred water management emphases. Similarly, cotton has been shown to precisely balance reproductive to vegetative ratios by mechanisms of retention and shedding (Jordan, 1986), control partitioning of photo-assimilates in response to water stress (Krieg and Sung, 1986), which also play a role in irrigation management and its optimization.

Water transpiration from cotton leaves cools the plant, the optimum temperature being 30$_o$C. Inability to cool, related to stomata closure, results in decreased net photosynthesis and high respiration rates, shifting of hormone levels within the plant, slowing translocation (Gerik *et al.*, 1995) and thus less photo-assimilates for boll retention and growth (Jonhson Hake *et al.*, 1996). The gas exchange complex in leaves is better understood. Limiting factors for photosynthesis are at the mesophyll tissue level. Breeding for yield, as demonstrated in Pima cotton, has been inadvertent breeding for heat tolerance (Radin *et al.*, 1994) in the form of high stomatal conductance and thus high cooling values. In this sense, plants seem to offset water for yield in high temperature extremes. This development has been productive, has promoted heat tolerance and has been shown to generate higher photosynthetic capacity, as new varieties were released (Faver et al, 1997). Further improvements to cotton yield could be achieved through assimilatory modification that could hopefully enhance water use efficiency. Tools such as carbon isotope discrimination (Δ) if further understood could facilitate breeding for transpiration efficiency. Good negative relationships between Δ and transpiration efficiency have been established and positive relationships between leaf Δ and crop yields. (Gerik *et al.*, 1995). Unfortunately, relatively little progress has been made in increasing productivity per unit of water by methods such as these, or by selection for increased photosynthesis, stomatal conductance or any other plant physiological parameter per se (Gerik *et al.*, 1995), probably due to the many inconsistencies and confounding factors, linked to this methodology.

Further knowledge-based considerations related to uncoupling of transpiration and photosynthesis through biotechnology, breeding and novel plant growth regulators could facilitate water use efficiency. In the long range these approaches seem more promising than direct modification of water management or irrigation scheduling. At a grower level they may well be more cost effective.

Generally, an increased substitution of information for water seem to be the most promising strategy to ensure a sustainable future for irrigated agriculture and water management (Stanhill, 1997). This means investment in irrigation science, stress physiology and biochemical pathways, new plant and genetic material, with higher crop water use efficiency. Genetic engineering for salinity or drought resistance requires an even clearer view of the physiological and biochemical pathways involved in cellular adaptation to osmotic stress. This biotechnology is now about to break through more than at any time before. Nevertheless, despite publications of over a decade ago (Valentine, 1984) regarding genetic engineering with osmoprotectants such as proline, glycine betaine, proline betaine and other mentioned materials this is still a fertile and highly important area for basic and applied research. It seems that natural osmotic adaptation in cotton is hard to beat. Nevertheless, recent work (Nepomuceno *et al.*, 1998) has identified and isolated numerous genes connected to osmotic adjustment, relative water content, photosynthetic rates, carbon discrimination and other physiological parameters. The development of new water deficit tolerant cultivars can be significantly improved with this information.

Quisenberry (1986) postulated methodology based on understanding basic physiology that demonstrated the potential of linkage between new physiological ideas and knowledge and the search for genetic variation related to specific physiological traits. This could lead to significant developments in the production system. "…applying basic physiological research to develop new cotton cultivars is an application worthy of the efforts." (Quisenberry, 1986). This will hopefully be followed beyond breeding and genetics into plant growth regulation, hormonal control of water management, development of new knowledge on photosynthesis and transpiration and biotechnology related research to confront water stress, plant osmotic adaptation and improved water use efficiency.

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A Perspective of Water Management for the Future

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ABSTRACT

Despite the reality that there is sufficient freshwater to support a much greater population, water is scarce in a growing number of locations. Consequently, the critical effects of long term salinity and possible industrial pollutants characteristic of recycled effluent necessitate that saline condition research should focus on drainage, irrigation technology and management on the one hand, and plant physiology, leading to plant stress tolerance and water use efficiency enhancement on the other. Agronomic management, including plant population, row spacing, plant growth regulators, land preparation and varietal selection continue to play a key role in water use efficiency for cotton production. Improved technology and scheduling methodology has promoted productivity and water use efficiency. Nevertheless, accuracy and control of water application in space, time and quantity remain constraints for enhancement of productivity and water use efficiency, regardless of the method applied. The hallmark of irrigation technique evolution is probably the inherent precision of water application in space and time. Further advances in precision agriculture contributing to crop uniformity are bound to improve productivity and consequently water use efficiency. These emerging technologies could also contribute to field monitoring and scheduling. This paper addresses knowledge-based considerations related to plant physiology, breeding and biotechnology that could facilitate water use efficiency. An increased substitution of information for water seem to be the most promising strategy to ensure water management in sustainable future irrigated agriculture.

Water availability

The global constant water amount on planet Earth is estimated at about 1,400 million cubic kilometers (km^3). Only a fraction of that comprising about 12,000 km^3, is available for human use. Unfortunately, despite the reality that there is sufficient freshwater to support a much larger population, water is considered scarce in a growing number of locations. Unequal distribution of rainfall, pollution and land degradation contribute to this (Kandiah, 1997). A recent UN report (CSD, 1997) clearly show widespread misuse with worsening water quantity and quality problems, largely due to inadequate management. Small communities, large cities, farmers and industries, developing countries and industrialised economies mismanage water with detrimental effects on quantity and quality.

Agriculture is in the eye of the storm. It has the largest water demand (FAO 1994), is relatively low value, and low efficiency but is highly subsidised and furthermore, it is unable to compete economically for scarce water among other competitors (Hutmacher *et al.*, 1995). Great expectations are aimed therefore at agricultural research to increase productivity with declining water availability. Thus, water use efficiency must be developed to improve productivity while releasing water for other uses (Kandiah, 1997).

This paper focuses on agronomic and physiological aspects of water management. Water resource development policy on national or global levels have a critical impact but are beyond the scope of this paper and will therefore be mentioned only briefly.

Cotton water usage

Cotton is irrigated with varying intensity (Hearn, 1995). Cotton is either fully irrigated (Western USA, Mediterranean, Central Asia, Punjab of India and of Pakistan and parts of China), fully rainfed - including ex-seasonal rainfall dryland and seasonal rainfed production (South and parts of North America, most of Africa, most of India and South East Asia) or receives supplementary irrigation (Australia, North America and parts of

Asia). Overall, irrigated cotton accounts for 7.3% of irrigated land (61% accounts for rice). Hearn (1995) concludes that 73% of the cotton fiber in the world is produced under irrigation from 53% of the total cotton land.

Drainage and marginal water usage

High water tables and related salinisation are a major constraint in many parts of the world. Lowering water table depths by installing sub-surface drainage and appropriate maintenance has been reported to increase cotton and maize production by up to 43% (Finney, 1997). Reclamation using basic drainage methods should be utilized to effectively alleviate these problems (Martinez-Beltran *et al.*, 1996).

As a crop with xerophytic origins, cotton is tolerant to saline conditions with an EC threshold of nearly 8 dS/m (Maas, 1986). This type of tolerance has been the background for the exploitation of various water resources such as saline water and reclaimed wastewater for cotton production. Alas, despite extensive research on saline and sodic conditions in water and soil and despite short-term success in managing them, the long term effects of salinity seem detrimental to soil properties and to yield (Sadan, 1997). This is especially true in areas with low rainfall and insufficient leaching of salts.

Methods for alleviation salinity and sodium hazards have included soil treatments, drip irrigation systems (Hanson and Bendixen, 1995) and augmented water schedules (Meiri and Plaut, 1985), changes from flat bed to furrow irrigation (Choudhry *et al.*, 1994) and varietal selection (Munk and Wroble, 1995). Gypsum managed soils seem to be losing tolerance and negative effects are evident after about 10 - 20 years (Sadan, 1997).

As an industrial crop, cotton has been a suitable candidate for application of treated effluent from urban origin. Calculating that one adult generates approximately 100 litres of effluent per day, in a developed urban environment, a city of 2 million could generate recycled wastewater to cultivate 15-20 thousand hectares of cotton. The cost of this cannot be ignored but purification of effluent in developed societies is an issue to be addressed quite apart from irrigation water for agriculture. In the long run, research emphasis should aim at cheaper, higher levels of purification at the source and cost effective methods of desalinising saline water, to avoid exhausting soil and environment with highly polluted and salinised water.

In the case of salinised agricultural land, great care should be taken to avoid high salt contamination that in the long term causes wasteland. Management through crop rotation and natural rainfall leaching should be employed. Due to the critical effects of long term salinity and possible industrial pollutants characteristic of recycled effluent, saline condition research should be focused on irrigation technology and management on the one hand, and plant physiological functioning leading to plant stress tolerance and water use efficiency enhancement on the other.

Agronomic practices – interacting with water management

Agronomic management probably accounts for a significantly high percentage of variation in cotton yield. The interaction between various agronomic practices and water management is highly important.

Plant population and density

Cotton has a well-documented potential to compensate for loss of fruiting forms and lack of stand (Jones and Wells, 1997). Thus it is often difficult to demonstrate the advantages of alternative management systems, or the conditions best suited to their expression. Narrow rows and high populations comprise a sound theoretical basis for early, high yield. Rapid canopy cover for enhanced compensation potential, early and augmented irradiation interception and potential for earliness, to mention a few, are the basis for yield increase. Frequently, previous work from various origins does not demonstrate this but with precise management, suitable varieties and high uniformity, there could be an opportunity to manage the cropping system by means of plant density combined with irrigation to improve water use efficiency. Reports from the US (Best *et al.*, 1997) show that the narrower the row spacing, the more plants generate additional dry matter per area and improve harvest index.

Chinese production is traditionally narrow row with 60cm between two row beds and 35cm between rows on the bed, giving plant populations of up to 180,000 plants per hectare. This spacing proved to be most efficient for short season production under water constraints in the cool deserts of Xinjiang province.

Experience in Israel using drip irrigation shows that the narrower the row spacing, the higher the yield and the greater the water use efficiency. This was achieved under saline conditions (Keren *et al.*, 1983), and with plant populations of 55,000, 80,000 and 105,000 plants per hectare for 2 X 1 meter single skip row, 100cm and 76cm regular row spacing respectively (Bosak *et al.*, 1991). Although not always cost effective, much the same has been demonstrated for other environments. Narrow and ultra narrow rows therefore have potential to improve productivity and water use efficiency. This usually depends on appropriate management, suitable cultivars, technical solutions other than broadcast stripping, lint quality stability and demonstrable of cost effectiveness (Kerby, 1998; Brown *et al.*, 1998).

Other examples of positive interaction between management practices and water use efficiency such as plant growth regulators in some situations, land preparation and tillage versus no-till systems have been demonstrated. Obviously varietal selection also determines water management fine tuning.

So much for agronomic management which will obviously continue to play an important role in water use efficiency for cotton production.

Development of irrigation systems – towards precision irrigation

Irrigation systems can be categorized as (1) surface-gravity-flow systems such as furrow, border or level basin and (2) pressurized flow systems such as sprinkler systems (including solid set, centre pivot, linear move, sideroll) and micro-irrigation systems (drip and micro-spray) (Hutmacher *et al.*, 1995).

Constraints

Constraints for surface gravity flow systems include:

- excess use of water resulting in
- oxygen deprivation from soil saturation,
- square and small boll shed,
- leaching of nitrates and of course
- water loss due to both runoff and drainage below the root zone.

Constraints for advanced pressurized systems include:

- management complexity;
- labour intensive, especially for surface systems;
- high capital investment;
- high variable maintenance costs.

In characterizing the evolution of irrigation methods, the development of water use efficiency can be demonstrated (Derived from Hearn, 1995). Nevertheless, comparable water use efficiency has been demonstrated for various irrigation methods. The hallmark of irrigation technique evolution is probably the inherent precision of water application in space and time.

- Higher engineering efficiency for water conservation - a higher percentage of the pumped water actually reaching the root zone and being utilized for transpiration.
- Increased potential for precise spatial uniformity
- Precision metering and high level of control

Development in each of the various methods has followed this course. For example:

- The development of small basins and microcatchments for surface gravity flow systems;
- Surge valve application for row water systems can approach 80% efficiency (Krieg, 1998).
- Low Energy Precision Systems (LEPA) for sprinkler related methods now exceed 95% efficiency (Krieg, 1998); and
- Self regulating emitters and sub-surface installation for drip irrigation increase productivity and water use efficiency.

Improved methodology has definitely promoted productivity and water use efficiency. Growers who have adopted drip methods in various environments have obtained increased yields, enhanced water use efficiency and economic advantages (Shiyani and Kuchhadiya, 1996; Fedler, 1996; Dipenaar *et al.*, 1997), especially where water costs are high. Sub-surface drip irrigation has partially challenged these issues (Camp et al, 1997; Hutmacher *et al.*, 1993), but cost-effectiveness is yet to be demonstrated.

Nevertheless, consensus concerning the necessity of higher technology such as drip irrigation is far from being wide (Anthony and Namoi, 1996), and the ability to obtain uniformity by drip irrigating has also been scrutinized (Amali *et al.*, 1997). Increased uniformity in spatial distribution of water and increased application frequency have been demonstrated by other irrigation means, with results comparable to those achieved with advanced drip systems (Radin *et al.*, 1992).

Accuracy and control of water application in space, time and quantity remain constraints for improved productivity and water use efficiency, regardless of the method in question. Thus new irrigation techniques should be manageable, precise in water application and cost-effective for the environment in question. Due to the many factors involved, new or alternative methodology should be carefully scrutinized for marked economic advantage before adoption into an existing, balanced environment.

The theoretical basis linking field variation to productivity has been demonstrated (Tanji and Yaron, 1994). Lack of uniformity in water application coupled to soil variability could definitely contribute to low uniformity in plant development, associated with lower expected average yields and lower profits. Cotton is a highly demanding crop for optimum water management, both shortage and excess of water being detrimental to yield. A desirable irrigation system applies water at a rate that allows all water to infiltrate, and distributes the water in space and time to match crop requirements in each parcel of the field. Resulting field variability as reflected through cotton foliage temperatures for example, generally demonstrates low uniformity in current leaf temperature (Wanjura and Upchurch, 1994). A large number of measurements or measurements from larger areas are therefore required to reach an average field value within an acceptable tolerance. Other reports demonstrate the disadvantage of temporary diurnal stress for both low and high frequency irrigation systems and potential benefits of frequent, low volume irrigation (Moreshet *et al.*, 1996; Chu *et al.*, 1995; Landivar *et al.*, 1995). Hence, multi-dimensional uniformity in application timing, space and quantities seem to be imperative. With enhanced engineering, computer capabilities and improved knowledge of the soil–plant-water continuum, irrigators could adopt "prescription" irrigation that apply precisely the prescribed amounts of water to match production capacity on each parcel of land (Hoffman and Martin, 1993). Mechanized linear or central pivot irrigation could be suitable candidates for testing this concept.

Further advances in precision agriculture contributing to crop uniformity are bound to improve productivity and consequently water use efficiency. These emerging technologies could contribute to field monitoring and scheduling.

Water management scheduling and control - the secret of how much and when

Cotton is a highly demanding field crop in management, water management is probably being a major knowledge-based component. Water application has to be optimized. Deficient irrigation generates water and carbohydrate stress leading to yield shortfall, whereas excess irrigation ends in rank growth, low harvest index leading to yield loss and a waste of a valuable resource. Water management optimization is understanding plant necessities and responding precisely.

Plant development and sensitivity to water status have been investigated intensively. Plant measurements and related calculations such as height, nodes, fruiting formations, plant vigour, nodes above first position white flower, dry weight measurements, boll opening rates have been consolidated into specific, optimum development curves for various situations and environments. Sensitivity of cotton plants to water stress during the various reproductive development phases, is well-documented (Krieg *et al.*, 1993). Three basic stages are identified: square formation and early flowering; flowering peak and boll development; and boll ripening. It is well established that water stress during boll development has the most pronounced inhibiting effect on yield and quality. Both the early and later development periods are less affected by water stress (de Kock et al, 1990).

Contrary to historical water management methods, early season water stress is no longer recommended practice, providing the availability of water and a given aim to maximize yields. The basic goal is to refill the soil profile to the moisture holding capacity in order to diminish stress risks. Optimum water amounts for application can be calculated using the water budget method in which prevailing climatic conditions are reflected in evapotranspiration rates. Evapotranspiration estimation has been intensively investigated (Doorenbos and Pruitt 1977; Meron *et al.*, 1990) and good approximations of real evapotranspiration by using pan evaporation or by long term approximation have been reached.

Cotton crop coefficients reflecting plant development are estimated using a variety of methods. A midday sunfleck method to measure row crop cover (Meron *et al.*, 1990) is simple and usually adequate. Other methods have been developed in California using regression analysis over time on long term data (Kerby and Hake, 1996). Further data analysis has shown close correlation between plant height and leaf dry weight (LDW) (Bosak, 1992; Sadan, 1990). Assuming good correlation between LDW, leaf area index (LAI) and transpiration, plant height has been is used as a parameter for coefficient estimation (Bosak, 1992). Thus, periodic cotton coefficients have been defined to reflect plant canopy, ground cover and transpiration.

Multiplying a measured or estimated evapotranspiration rate by the appropriate cotton canopy coefficient provides a value representing the amount of irrigation water needed to replace the volume depleted through evapotranspiration. In addition, criteria for early season and irrigation termination have been proposed and implemented (e.g. Johnson Hake *et al.*, 1996; Munk *et al.*, 1997).

Additional methods for irrigation scheduling and plant water status monitoring include:

- the pressure chamber (Seymour *et al.*, 1996)
- canopy temperature measurement (Wanjura, 1997)
- sap flow gauge technology
- other plant growth monitoring methods such as height development, height-to node ratio (HNR), retention rates, nodes above white flower (NAWF) (Kerby and Hake, 1996)
- computerized cotton simulation models based on developmental knowledge
- soil moisture measurement methods and soil sensor actuated systems

Computerized cotton simulation models – the game of "playing God" - and numerous other specific algorithms are developing rapidly, and exist for many production environments. Calibration and validation are constantly underway with the discovery of new knowledge. These tools developed as experimental research aids designed to highlight missing knowledge. They are now evolving into crop management tools used by growers for water management. New knowledge and further modification of these programs are expected to improve their usage and value.

Advance information on soil moisture is important in management. Gravimetric measurements are common and relatively reliable, but tedious and time consuming. Neutron probes that pose significant calibration problems and soil tensiometers of various types and other soil moisture metering devices, all suffer critically from soil variability. With all due respect for soil moisture advance information, the best tensiometer in a field for management purposes is a cotton plant. In short, a good representative, reliable, manageable and cost effective means for soil moisture measurement is still lacking.

Cotton irrigation scheduling still relies heavily upon plant, field and soil sampling. Once again, representative monitoring for field assessment is closely associated with uniformity. Further enhancement of correct scheduling demands broader field information and increased field uniformity. Precision agriculture developments could play a role in water scheduling if proven feasible and cost-effective. Developments such as thermal imagery (Garrot, 1997) or Multispectral remote sensing and site specific agriculture (Barnes *et al.*, 1996) for example, if further refined, could provide insight into consolidated, representative field information on water status. Methodology such as this could possibly contribute to water conservation, to transpiration efficiency and to cotton productivity in a cost effective manner.

Furthermore, present water management practices are based upon the onset of stress symptoms such as growth decline, leaf water potential drop, sap pressure and flow change and leaf temperature increase. Since these symptomatic responses are not necessarily related to water stress, they could prove misleading if used as management tools.

Advanced stress information could facilitate water management. New concepts of stress signaling (Hearn, 1995) could provide the advance warning and be harnessed as novel indicators of plant water status, associated with the biochemistry of plant water stress and hormonal balance. Further knowledge of stress physiology and biochemical pathways could possibly provide a reliable and timely water management tool.

The physiology of water use efficiency

Understanding basic cotton water stress physiology has facilitated applied water management. Understanding retention and abscission patterns has determined variation in seasonal tolerance to water deficit and has thus assisted in defining irrigation schedules. Periods of increased sensitivity, such as peak flowering have been discovered, thus determining preferred water management emphases. Similarly, cotton has been shown to precisely balance reproductive to vegetative ratios by mechanisms of retention and shedding (Jordan, 1986), control partitioning of photo-assimilates in response to water stress (Krieg and Sung, 1986), which also play a role in irrigation management and its optimization.

Water transpiration from cotton leaves cools the plant, the optimum temperature being 30_{o}C. Inability to cool, related to stomata closure, results in decreased net photosynthesis and high respiration rates, shifting of hormone levels within the plant, slowing translocation (Gerik *et al.*, 1995) and thus less photo-assimilates for boll retention and growth (Jonhson Hake *et al.*, 1996). The gas exchange complex in leaves is better understood. Limiting factors for photosynthesis are at the mesophyll tissue level. Breeding for yield, as demonstrated in Pima cotton, has been inadvertent breeding for heat tolerance (Radin *et al.*, 1994) in the form of high stomatal conductance and thus high cooling values. In this sense, plants seem to offset water for yield in high temperature extremes. This development has been productive, has promoted heat tolerance and has been shown to generate higher photosynthetic capacity, as new varieties were released (Faver et al, 1997). Further improvements to cotton yield could be achieved through assimilatory modification that could hopefully enhance water use efficiency. Tools such as carbon isotope discrimination (Δ) if further understood could facilitate breeding for transpiration efficiency. Good negative relationships between Δ and transpiration efficiency have been established and positive relationships between leaf Δ and crop yields. (Gerik *et al.*, 1995). Unfortunately, relatively little progress has been made in increasing productivity per unit of water by methods such as these, or by selection for increased photosynthesis, stomatal conductance or any other plant physiological parameter per se (Gerik *et al.*, 1995), probably due to the many inconsistencies and confounding factors, linked to this methodology.

Further knowledge-based considerations related to uncoupling of transpiration and photosynthesis through biotechnology, breeding and novel plant growth regulators could facilitate water use efficiency. In the long range these approaches seem more promising than direct modification of water management or irrigation scheduling. At a grower level they may well be more cost effective.

Generally, an increased substitution of information for water seem to be the most promising strategy to ensure a sustainable future for irrigated agriculture and water management (Stanhill, 1997). This means investment in irrigation science, stress physiology and biochemical pathways, new plant and genetic material, with higher crop water use efficiency. Genetic engineering for salinity or drought resistance requires an even clearer view of the physiological and biochemical pathways involved in cellular adaptation to osmotic stress. This biotechnology is now about to break through more than at any time before. Nevertheless, despite publications of over a decade ago (Valentine, 1984) regarding genetic engineering with osmoprotectants such as proline, glycine betaine, proline betaine and other mentioned materials this is still a fertile and highly important area for basic and applied research. It seems that natural osmotic adaptation in cotton is hard to beat. Nevertheless, recent work (Nepomuceno *et al.*, 1998) has identified and isolated numerous genes connected to osmotic adjustment, relative water content, photosynthetic rates, carbon discrimination and other physiological parameters. The development of new water deficit tolerant cultivars can be significantly improved with this information.

Quisenberry (1986) postulated methodology based on understanding basic physiology that demonstrated the potential of linkage between new physiological ideas and knowledge and the search for genetic variation related to specific physiological traits. This could lead to significant developments in the production system. "…applying basic physiological research to develop new cotton cultivars is an application worthy of the efforts." (Quisenberry, 1986). This will hopefully be followed beyond breeding and genetics into plant growth regulation, hormonal control of water management, development of new knowledge on photosynthesis and transpiration and biotechnology related research to confront water stress, plant osmotic adaptation and improved water use efficiency.

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