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AGRONOMY AND SOILS

In-Season Cotton Drought-Stress Quantification: Previous Approaches and Future Directions

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ABSTRACT

Cotton producers in the Mid-South and southeastern regions of the U.S. have two approaches to manage drought stress: irrigate or plant drought-tolerant cultivars. Still, timing irrigations and defining the amount to be applied have been challenging in humid regions. Additionally, little information is available on varietal drought tolerance. An index capable of quantifying drought stress at a given location could be used to compile yield responses across variety trials to give robust insight into varietal drought tolerance and define irrigation thresholds for irrigated fields or provide information required to better place varieties in dryland scenarios, thereby increasing the water-use efficiency and sustainability of the production system. The objectives of this review are to cover past research conducted on developing drought-stress indices, examine the potential of soil moisture measurements to provide insight into cotton water status, and highlight cotton-specific data that likely will be used to construct a drought-stress index capable of providing insight into cotton water status. Although multiple approaches have been taken, each relies on some measure of drought stress coupled with susceptibility of the crop to the stress at a given point in the season. From this review, it is clear that new advancements in sensor technology and a better understanding of cotton's susceptibility to drought stress should support the development of a more accurate, reliable drought-stress index capable of providing insight into varietal drought tolerance and driving irrigations.

The physiological processes associated with the onset and progression of drought in cotton (Gossypium hirsutum L.) have been well characterized (Ball et al., 1994; Grimes et al., 1970; Guin and Mauney, 1984a, b; Loka et al., 2011; Pettigrew, 2004a, b). Each of these processes ultimately aggregate to curtail yield, resulting in a gap between yield potential and realized yield driven by water-deficit stress. In other cotton producing regions, producers have several management tools at their disposal to increase the soil water reserve or attempt to avoid water-deficit periods during the year. However, cotton producers in the Mid-South and southeastern regions of the U.S. only have two primary approaches to mitigate or manage drought stress: irrigate or plant drought-tolerant cultivars.

Ease of access and low-overhead cost associated with the furrow system coupled with a relatively long growing season and fertile soils have allowed the number of irrigated acres in the Mississippi Delta to drastically increase during the past 40 years. However, row crop production in the Mid-South region of the U.S., traditionally characterized by an over-abundant water supply, recently has seen an emphasis placed on water-use efficiency. Factors contributing to this shift include escalating conflicts in the western U.S. between rural and urban water demand exacerbated by dwindling water supplies (Gleick et al., 2003); unsustainable depletion of several nonrenewable aquifers located across the Cotton Belt, even in the Mississippi River Delta (Konikow, 2013; Scott et al., 1998); and record drought in the 2011 and 2012 seasons, resulting in the most extensive drought since the 1950s (USDA-ERS, 2012). As a result, a large number of researchers currently are working on increasing the net return produced from a given measurement of water in the production system (sometimes referred to as water-use efficiency [WUE] but more appropriately referred to as water productivity [WP]) (Molden et al., 2009). These approaches can be categorized in three main goals: (1) increase the efficiency of the irrigation system, (2) better time each irrigation event, and (3) select cultivars that are more drought tolerant.

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Approaches to increase the efficiency of the furrow-irrigated system are somewhat limited compared to other, more controllable irrigation systems. Most of these programs are focused on increasing the uniformity of each application, decreasing the amount of water allowed to run off the field, and increasing water infiltration into the profile. Methods to accomplish these goals vary, but can include the use of surge flow, computerized hole selection, land grading, proper pipe placement, and tail water recovery. Programs such as the Pipe Hole and Universal Crown Evaluation Tool (PHAUCET) and Pipe Planner™ by Delta Plastics (Little Rock, AR) are designed to accomplish many of these aforementioned goals.

In contrast to increasing the efficiency of the application, another method to increase WUE currently being explored is irrigation timing. Irrigation events are frequently scheduled by "balance sheet" or "checkbook" methods, which calculate water to be applied by subtracting modeled evapotranspiration from rainfall. Although better than an arbitrary time-interval-based irrigation regime, many of these programs are based on estimated levels of crop water use instead of experimental verification (Vories et al., 2004). These methods can fail to estimate soil water at planting, runoff, or deep percolation.

Another method of increasing the irrigation efficiency of the production system would be the selection of drought-tolerant cultivars. Numerous studies in the recent past have attempted to define cultivar-specific responses to drought, but these efforts involve a limited number of cultivars that typically are not available for commercial production (Gerik et al., 1996; Loka et al., 2015; Pace et al., 1999; Quisenberry et al., 1981). Subsequently, varietal drought tolerance is derived by the producer/retailer/consultant from yield responses noted in dryland cultivar trials. Although there are a large number of these trials located throughout the Cotton Belt, drought stress experienced at each location is rarely characterized; if specific information on drought stress is reported, it typically consists solely of accumulated rainfall. As defined by Salas (1993), necessary parameters required to accurately define drought include the deficit duration, magnitude, intensity, severity, geographic extent, and frequency. Unfortunately, accumulated rainfall does not provide the information required to define the aforementioned parameters. Subsequently, accumulated rainfall can fail to characterize experienced drought at a given location and therefore does not provide an accurate, reliable characterization of a cultivar's susceptibility or tolerance to drought. For these reasons, producers lack the tools required to evaluate the drought tolerance of current commercially available cultivars. It is hypothesized that failure to collect and rapidly disseminate information on cultivar-specific tolerance to drought is limiting WP; a more robust quantification of experienced drought at a given location could provide insight into cultivar-specific drought tolerance. This measurement would provide the information necessary for placement of more drought-tolerant cultivars on dryland acres and provide cultivar-specific information on magnitude, timing, frequency, and longevity tolerance to drought stress and subsequently support more educated irrigation practices.

Therefore, the objectives of this review are to: (1) cover past research conducted on developing drought-stress indices, (2) examine the potential of soil water measurements to provide insight into crop water status, and (3) highlight cotton-specific data that likely will be used to construct a drought-stress index capable of providing insight into cotton water status.

LITERATURE REVIEW

Water-deficit Stress Indices. A drought-stress index, in the most basic sense, is an accumulated measure of drought experienced through the growing season calculated for some management purpose. In addition to providing end-of-year insight into experienced stress, this index could serve as a tool for irrigation scheduling through embedded thresholds. Success of the accumulated stress/yield concept is based on the negative correlation between yield and water-deficit stress. If no water stress is experienced during the growing season, yield will be a function of other genotypic and environmental limitations. As water-deficit stress occurs and stress units are accumulated, yield penalties ensue. Most agriculture-based stress indices have been developed to increase WUE by more efficient irrigation scheduling. The index framework is fairly consistent from author to author; however, authors typically diverge on stress definition and determination as well as the incorporation of a crop susceptibility factor.

Early Development. Two of the first authors to develop a primitive water-stress index concept were Nix and Fitzpatrick (1969). Through soil-water modeling and estimated potential evapotranspiration, they determined periods of water stress and correlated these stress index units to yield of wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* L.). The defined stress index represents the time in weeks that the current level of available water would sustain the crop if the rate of potential evaporation remained consistent. Noted yields of grain sorghum and wheat were positively correlated to increases in the stress index. This stress index, which more appropriately should have been deemed an available water index, is determined at the beginning of the predetermined, critical growth stage. Therefore, water stress experienced prior to, or after, the critical period is not included in the calculation.

A more refined, season-encompassing stress day index (SDI) was introduced by Hiler and Clark (1971) as a method of increasing water-use efficiency by optimizing irrigation scheduling. Accumulated SDI values are calculated by summing the product of a stress day factor (SD) multiplied by a crop susceptibility factor (CS). Length, magnitude, and timing of stress are dictated by the SD factor. Authors suggested possible parameters that could be used to calculate SD included coarse-resolution plant measurements or estimated meteorological data; both of these parameters were evaluated in a preliminary analysis within the publication. The CS factor served as a method of weighting SDI depending upon species and growth stage sensitivity to stress. Authors found this index to be acceptable for irrigation scheduling and predicting yields under crop water stress conditions. Weaknesses of this index hinged on the large number of samples required to define changes in plant water potential (the author-selected SD factor) over time restricted its use in most production systems. Still, the SDI successfully advanced the stress index concept to include seasonal stress and growth stage sensitivity.

Canopy Temperature and the SD Concept. A few years prior, Wiegand and Namken (1966) examined the influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. They used an infrared thermometer to measure leaf temperature and a thermocouple in each plot to determine air temperature. Results indicated increases in leaf temperature were associated with decreases in relative turgidity, the authors' chosen indicator of plant moisture stress. Leaf temperature was also sensitive to solar radiation and air temperature. Conclusions stated plant moisture stress significantly altered leaf temperature with respect to ambient air temperature, but caution should be taken under cloudy conditions due to the influence of solar radiation on leaf temperature. Several years later, Aston and van Bavel (1972) published research examining the relationship between soil surface-water depletion and leaf temperature to determine the feasibility of remote detection of cropped-field water depletion. Specifically, the authors tested the theory that increases in leaf temperature were associated with increases in shortwave radiation from drying soil. Although this publication failed to consider transpiration as the major control for leaf temperature, the authors suggested drought onset could be detected remotely through measurement of canopy temperature. These publications, along with several others, served as the framework for the incorporation of other drought-stress indicators to serve as the SD factor.

Recognizing the shortcomings of the SD component of the SDI and the ability of canopy temperature to indicate stress, Idso et al. (1977) and Jackson et al. (1977) proposed canopy air temperature differences to be an appropriate SD indicator. Both publications referred to this index as a stress degree day (SDD). According to the authors, this measurement could be monitored remotely and prevented the labor intensive, plant water potential measurements of Hiler and Clark (1971). To test this new SD indicator, Idso et al. (1977) predicted final wheat yield with accumulated stress units determined from canopy temperature. As predicted, strong negative relationships were noted between grain yield and accumulated stress units. Jackson et al. (1977) further tested this method by examining stress thresholds on which to base irrigations. Authors used a derived evapotranspiration equation to relate canopy air temperature differences to soil water depletion. Even though several parameters in this equation were estimated, results suggested canopy air temperature differences could serve as irrigation scheduling tools for large irrigation districts. In a later critique, however, Idso et al. (1981) found the SDD to be sensitive to several parameters beyond the parameter of interest, soil moisture.

During this time, other indices were being developed. Similar to the SDD, the temperature stress day (TSD) developed by Gardner et al. (1981), utilized no atmospheric measurements. The TSD also differed from the SDD by utilizing a well-watered canopy temperature instead of an ambient air temperature for index calculation. Authors noted moderate relationships between cumulated TSD and relative yields of sorghum. Clawson and Blad (1982) were successful in scheduling corn (*Zea may* L.) irrigations from measured TSD, but a critique of the TSD method by Clawson et al. (1989) displayed the sensitivity of the TSD to changes in vapor pressure deficits at a constant stress level, similar to the findings of Idso et al. (1981) concerning SDD.

Crop Water-Stress Index. In an effort to reduce sensitivity of these indices to parameters other than soil moisture, Jackson et al. (1981) and Idso et al. (1981) modified the SDD introduced in 1977 and introduced this modified index as the crop water-stress index (CWSI). These papers diverge on calculation of baselines; Jackson et al. (1981) proposed a theoretical approach to calculating the CWSI rooted in energy balance of foliage. Calculation of the theoretically derived index also required wet-bulb air temperature and an estimation of net radiation in addition to the standard dry-bulb air temperature and canopy temperature measurements required by the SDD. These measurements are used to determine lower and upper limits of the canopy air temperature difference, which represent well-watered and completely water-deficit stressed conditions, respectively. The index is then calculated by normalizing readings, resulting in values from zero (no water-deficit stress) to one (complete water-deficit stress). Idso et al. (1981), in contrast, demonstrated the utility of an empirical approach. Instead of relying upon wet-bulb temperatures, this approach utilizes the temperature difference of the foliage temperature of a well-watered crop and air temperature at varying vapor pressure deficits to derive the upper and lower thresholds of CWSI. Regardless of method of calculation, the CWSI was intended to be calculated from a single measurement taken between 1340 and 1400 each day. Studies examining the sensitivity of this index indicated the CWSI correlates strongly to extractable soil water and is less sensitive to other environmental factors (Idso et al., 1981).

One major limitation of adoption of the CWSI is the requirement for a wet-bulb temperature, which must be either estimated or determined experimentally. Estimation of this baseline requires information on multiple environmental parameters, which can be difficult to measure. Furthermore, experimental determination of the nonwater-stressed baseline is site- and season-specific and is only valid during clear skies. As a result, Berliner et al. (1984) modified the CWSI to include instead a well-watered canopy temperature and found this method buffered measurements against wind gusts and resulted in strong correlations with leaf water potential and stomatal resistance. Clawson et al. (1989) proposed a merging of the CWSI and the TSD. Specific modifications included the theoretical and empirical replacement of several difficult to determine CWSI parameters with a well-watered canopy temperature reading of the TSD. Each of the two methods displayed stability to changes in environmental factors at constant levels of experienced stress, suggesting both could be acceptable crop water stress indicators. Similar work was conducted by Alves and Pereira (2000), who proposed and tested replacement of the wet-bulb temperature with monitored canopy temperature of a well-watered irrigation control. Conclusions were similar to other mentioned studies. Alves and Pereira (2000) concluded this adjustment would allow for crop water stress monitoring even under overcast conditions. More recently, Bockhold et al. (2011) evaluated canopy temperature data in a humid environment and noted utility of the approach when solar radiation exceeded 200 W m^{-2}, which suggested some cloud cover might not degrade data quality, but the authors concluded more research was necessary to accommodate excessive cloud cover and high vapor pressure deficits.

Additionally, Colaizzi et al. (2003a) conducted a trial comparing the CWSI to a soil water stress index (SWSI) based on available water in the effective rooting zone in Maricopa, AZ. Results showed a strong linear correlation between the CWSI and SWSI ($r^2 = 0.86$), confirming the ability of canopy temperature to serve as an indicator of available soil water and therefore crop water stress in arid environments. However, the authors were forced to remove four growing season days from the analysis, three of which corresponded to rainfall events of 5, 3, and 5 mm, and one of which resulted in no rainfall but was characterized by overcast conditions.

Water-deficit Index. Another weakness of many canopy temperature measurements, and therefore the CWSI, is the inclusion of soil in the field of view, particularly prior to canopy closure (Moran et al., 1994). This has led some investigators to attempt to include only plant foliage in the field of view or exclude time periods in which canopy development was not sufficient enough to prevent soil interference (Wanjura et al., 2004). Unfortunately, full canopy closure in many environments occurs at a point well past irrigation initiation, and due to the substantial influence of soil water on soil temperature, a linear canopy closure and soil temperature correction often fails to accurately remove soil interference. In an attempt to increase the utility of CWSI prior to canopy closure, Moran et al. (1994) developed a water-deficit index (WDI) that is capable of detecting water stress in full cover and partially vegetated fields using remotely sensed data. To accomplish this goal, authors utilized a vegetation index/temperature trapezoid to remove soil interference. Additional measurements required to calculate the WDI include red and infrared reflectance. Simulations and field trials suggested the WDI was capable of indicating relative field water deficit and field evapotranspiration rates.

A more recent evaluation of the WDI by Colaizzi et al. (2003b) compared the index to a soil water-deficit index (SWDI), calculated from soil water measurements. Results indicated coefficients of determination between the two indices ranged from 0.84 to 0.87. According to the authors, failure of the relationships to be stronger was due to the instantaneous point nature associated with the WDI in comparison with the average day nature of the SWDI. Still, the authors highlighted the potential of the remotely sensed WDI to increase water-use efficiency by increasing producer knowledge of water-stressed areas that most likely would not be noted from visual observations.

Canopy Time Temperature Thresholds. The canopy time temperature threshold (TTT) process and device, patented by Upchurch et al. (1996), varies substantially from the CWSI. This method requires constant monitoring of canopy temperature to determine when thermal stress occurs. Stress units are accrued when the monitored canopy temperature rises above the established temperature threshold and humidity is considered to be nonrestrictive to plant cooling. According to Wanjura and Upchurch (1997) the threshold for cotton is 28°C. If cotton's canopy temperature remains below the threshold temperature or humidity is considered restrictive to plant cooling, stress units are not accrued. If the threshold is violated and the relative humidity is considered to be nonlimiting, stress units begin to accrue. These stress units are accrued until an accumulated unit threshold is met, at which point an irrigation event is made.

Wanjura et al. (2004) further evaluated this method in Lubbock, TX with the objective of more accurately defining the relationship of irrigation water quantities and cotton yields to differing time thresholds (TT). The authors defined TT as the irrigation trigger associated with accumulated stress time (ST) above a temperature threshold. Authors observed canopy temperature under well-watered and 50% of well-watered irrigation regimes. In this study, the TT of 330 min/d was established and maintained. Results indicated increases in average calculated daily ST were associated with decreases in lint yield, total applied water, and irrigation. Surprisingly, however, average daily ST was greater than the established TT. This divergence, which would theoretically equal zero, was suggested to be due to the fluctuating canopy temperature of well-watered cotton when the atmospheric environment was also fluctuating.

More recently, O'Shaughnessy and Evett (2010) attempted to schedule irrigation by using an automatic, canopy temperature time-threshold-based system in comparison with a manual system. Research was conducted under a center-pivot irrigation system in Bushland, Texas. Authors found inconsistent yield responses from the treatments, but noted increased irrigation water-use efficiency with the automatic irrigation treatments. Still, authors concluded further research was needed due to the limited scope of the trials and the variability associated with the Texas climate.

As defined, this approach is capable of quantifying length of deficit, timing of deficit, and frequency of deficit; however, no incorporation of the magnitude of the deficit is included. To best understand this error, it is useful to consider two stressed plants, one of which is growing at a soil water content just below a restrictive volume and one of which at a soil water content at or near permanent wilting point (PWP). Regardless of soil water content, the time temperature threshold at a given mid-afternoon point within the day will be the same. Although accrued stress units throughout the day theoretically will be greater for the plant that has no available water (increased time during the day at which the canopy temperature exceeds the threshold), it is logical to expect some increase in the relationship between accumulated stress units and yield to result from the incorporation of information on the magnitude of the deficit.

Humid Climates and Canopy Temperature. It is important to note that the CWSI was developed in the arid Southwest and Midwest regions of the U.S. and an important source of error described by Jackson et al. (1981) was rapidly changing cloud conditions. According to the authors, quality measurements were possible during clear or overcast conditions but serious errors were associated with periods of intermittently cloudy conditions. More recent work by Colaizzi et al. (2003a) also indicated difficulty relating the CWSI to soil water under conditions of low vapor pressure deficits. According to Idso et al. (1981), "defining stress in this fashion limits our ability to confidently quantify (the onset of crop water stress) under conditions of low vapor pressure deficit, where the entire range of foliage to air temperature variability approaches the degree of scatter inherent in the data."

Therefore, utilization of the CWSI in the humid Mid-South or Southeast poses many challenges, most of which stem from canopy temperature relationships to soil water in more meteorologically inconsistent locations. First, the recommended early-afternoon measurement times coincide with times of cloud formation, and variations in sensing time to calculate CWSI have been shown to influence CWSI values (Taghvaeian et al., 2012). Rainfall might or might not occur during these isolated thunderstorms, but as a response of the storm building, weather conditions across the region become inconsistent. These inconsistencies result in highly variable air temperature, wind, and humidity, all of which change atmospheric moisture demand and transpiration. As a result, accurate site characterization in humid regions could prove difficult by the single measurements of canopy temperature or meteorological parameters proposed for arid climates. Critiques of the CWSI have alluded to this issue (Colaizzi et al., 2012; Idso et al., 1981; Jackson, 1982).

In theory, the canopy TTT concept would be less susceptible to such errors because measurements are conducted continuously. Nonetheless, research examining the TTT also has shown mixed results. Bockhold et al. (2011) tested this method in Portageville, MO with well-watered, semi-stressed, and stressed crops of corn, cotton, and soybeans. The canopy TTT irrigation scheduling method failed to significantly increase yields or irrigation water-use efficiency for any of the examined crops. Furthermore, differences in cotton canopy temperature between the well-watered and semi-stressed treatments were frequently insignificant. Although some results indicate potential of canopy temperature to determine water-stressed conditions, the authors concluded these measurements have limitations and more research is necessary before these instruments can be effective, particularly in humid environments.

Soil Water and the SD Concept. All aforementioned indices rely on some measured or predicted parameter (most frequently canopy temperature) to provide insight into the depletion of available soil water and the SD parameter. Initial development of canopy temperature-based measurements relied heavily on handheld infrared thermometers or the use of thermal imaging to detect temperature differences. These methods allow canopy temperature readings to be taken over a large area at a fine scale with little difficulty. Still, plant-based sensing is associated with a number of practical difficulties, which have, to this point, prevented large commercial adoptions (Jones, 2004). Indirect soil water measurements, in contrast, are most commonly characterized by small fields of influence. For example, the neutron probe, considered to have one of the larger fields of influence, is sensitive to soil only within a 4- to 16-in radius (Muñoz-Carpena, 2004). As a result, a large number of measurements must be conducted at a high spatiotemporal frequency to characterize field-scale soil water over time. Consequently, soil water measurements in the past have been characterized as labor intensive and expensive, therefore more spatially coarse and less practical for field-scale drought characterization.

Recent advancements in electronics have resulted in a large increase in the number of commercially available soil water sensors, many of which vary substantially in cost and application (Chávez and Evett, 2012; Muñoz-Carpena, 2004; Robinson et al., 2008). Only a few of these sensors are inexpensive enough to be appropriate for large deployments necessary for spatially dense readings. Two sensor types that currently meet these criteria are granular matrix sensors and low-frequency, capacitance-based sensors. Granular matrix sensors have been available commercially for many years and use resistance between two electrodes to infer soil water potential. Low-frequency, capacitance-based sensors have been introduced commercially more recently. In contrast to the granular matrix sensors, the low-frequency, capacitance-based sensors rely on the dielectric characteristics of the sensing medium to infer volumetric water content (VWC).

Tensiometric Sensors. Sensors estimating soil matric potential include tensiometers, gypsum blocks, granular matrix sensors, heat dissipation sensors, and soil psychrometers (Muñoz-Carpena, 2004). The majority of these sensors estimate the amount of energy with which soil water is held by monitoring water movement through a porous material in contact with the soil. Granular matrix sensors are used widely for large deployments due to their low cost. These sensors typically are composed of two electrodes embedded into a cylindrical granular matrix, which is buried in the soil. The granular matrix equilibrates to soil water content by the transfer of water from the surrounding soil. Moisture in the sensor is measured by the change in resistance between the two embedded electrodes. Specifically, a decrease in resistance is associated with an increase in soil moisture. One of the most commonly used granular matrix sensors is the Watermark Model 200SS (Irrometer Company, Inc., Riverside, CA).

Although the reported sensitivity for the Watermark 200SS sensor ranges from 0 to 200 kPa, erratic measurements have been reported during prolonged drying cycles exceeding 90 kPa (Berrada et al., 2001). Increased variability was suggested by Berrada et al. (2001) to be due to reduced soil contact with the porous matrix. Subsequently, use of these sensors in swelling soils should be avoided (Muñoz-Carpena, 2004). More concerning for quantification of seasonal drought stress, however, is the reported failure of the sensor to respond to rapid changes in soil water (Berrada et al., 2001; Muñoz-Carpena, 2004). McCann et al. (1992) reported accurate measurements during standard drying periods that were followed by complete rewetting; however, poor results were noted under partial rewetting or rapid drying conditions. After a prolonged drying period, authors suggested measurements taken during the following drying cycle would be accurate only if soil water reached or exceeded field capacity, or a threshold of -10 kPa. Furthermore, McCann et al. (1992) concluded that many deep sensors could fail to meet this rewetting threshold and therefore these sensors could provide a limited amount of useful information for irrigation scheduling. These errors also were highlighted by Shock et al. (1998) while developing calibration equations for the Watermark 200, 200SS, and 200SSX. According to other research, a minimum of 24 h should be given after a rainfall or irrigation event to allow the sensor time to respond (Enciso et al., 2007). Although these issues are less of a concern in a well-managed irrigated cropping system (Berrada et al., 2001), the rewetting requirement and slow response time pose significant challenges for the objective of drought quantification or under low-frequency irrigation regimes.

Still, the low sensor cost has made these sensors appealing for the large deployments necessary for field soil water characterization. Fisher and Kebede (2010) utilized the Watermark 200SS sensor in an effort to build a low cost canopy, soil, and air temperature monitoring device for the Mid-South region of the U.S. The developed monitoring device was capable of measuring each of these aforementioned parameters for less than 85 USD. Measurements of soil water and soil, leaf, and air temperature made by this system were later shown to be capable of detecting genotypic differences in corn response to stress (Kebede et al., 2012).

Additionally, Vellidis et al. (2008) utilized a 12-node, wirelessly monitored system in a Georgia cotton field to monitor soil water and temperatures. Each node consisted of three Watermark sensors and a thermocouple. Slight modifications in the sensor array resulted in a system that could be deployed early during the growing season and remain reliable until harvest without adjustment. Results indicated deployments of 2 to 3 nodes allowed for sufficient characterization of each irrigation management zone. Authors concluded that this technology was capable of driving variable rate irrigations to fields containing multiple irrigation management zones, thereby efficiently supplying irrigation water to spatially variable water demand.

Volumetric Sensors. A large percentage of VWC sensors utilize dielectric permittivity characteristics to make inferences on soil water content of the tested medium. This dielectric measurement of soil water is based on the concept that air and solid mineral particles are characterized by small dielectric constants (3-5 for most mineral components of soils, 1 for air). These small, consistent readings greatly contrast the large dielectric constant of water (78.9 at 23°C). Therefore, shifts in composite dielectric readings are noted even during small shifts in VWC (Kizito et al., 2008).

Several equations, which range from simple to highly complex, have been proposed to calculate VWC from measured composite dielectrics (Alharthi and Lange, 1987). The most frequently used is an empirical equation outlined by Topp et al. (1980). Dielectric responses of soils, as defined by Topp et al. (1980) are a function of texture, structure, soluble salt concentration, temperature, density, measurement frequency, and water content. The influence of water content on the dielectric constant is so dominant, however, that often the response of the constant can be considered “almost independent” of the other parameters (Topp et al., 1980).

Time domain reflectometry (TDR), frequency domain reflectometry, water content reflectometry, capacitance techniques, amplitude domain reflectometry, and phase transmission techniques are all based on the composite dielectric properties of soil composite and frequently utilize some form of the Topp equation (Chávez and Evett, 2012; Muñoz-Carpena, 2004). These sensor types vary slightly in methodology but all characterize the water content of a limited soil area immediately adjacent to the sensor. Extrapolation from these small spheres of influence to the field-scale is often complicated due to the spatial variability of soil characteristics. One way to compensate for this variability is to increase the number of deployed sensors. Historically, large deployments have been impractical financially. Subsequently, sensor expense was the first listed equipment challenge in a review of large-scale soil moisture sensing approaches by Robinson et al. (2008).

Volumetric water content sensors utilizing low-frequency, capacitance-based techniques are less expensive than higher-frequency alternatives (Czarnomski et al., 2005; Kizito et al., 2008; Seyfried and Murdock, 2004). Due to their cost, these sensors are frequently utilized for continuous logging in large deployments. Capacitance sensors correlate to soil water by measuring the charge time of a ground electrode buried in the soil (Kizito et al., 2008). The medium immediately surrounding the positive and ground capacitors increases or decreases charge time and this charge time is exponentially more dependent upon soil water than other parameters. The resulting relationship between capacitance charge times and VWC is fairly strong.

One concern with relatively inexpensive capacitance sensors are their low frequency. Low-frequency sensors are more susceptible to the dielectric constants of soil texture, electrical conductivity (EC), and temperature; therefore shifts in readings are not as strongly associated with changes in VWC. Sensitivities to medium characteristics beyond VWC have been reported to increase below frequencies of 100 MHz (Chen and Or, 2006). Unfortunately, higher frequencies are directly related to greater cost of sensor production and most commercially produced, low cost, low-frequency, capacitance-based sensors are below the reported 100 MHz threshold.

In an attempt to define more thoroughly the sensitivity of a low-cost, low-frequency, capacitance-based sensor, Kizito et al. (2008) monitored the response of an ECH$_2$O-TE, 70 MHz Capacitance Sensor (Decagon Devices, Inc., Pullman, WA) to changes in frequency, temperature, and EC in a wide variety of soil types. Results suggested the sensor, when used in cooperation with a generic calibration curve, was capable of accurately determining VWC while being relatively insensitive to other dielectric influencing parameters. These authors also monitored changes in sensor sensitivity as frequency was altered. Substantial decreases in sensitivity to EC, temperature, and soil type were noted as frequency was increased from 10 to 70 MHz. Although sensitivities continued to decrease until 150 MHz, no substantial decreases were noted at frequencies higher than 150 MHz. Results are in agreement with other research by Bogena et al. (2007), who noted increases in temperature and EC sensitivity associated with a 5 MHz Decagon EC-20 sensor relative to a 70 MHz Decagon EC-5. Even so, a moderately strong temperature sensitivity of the Decagon 5TE sensor has been reported by Chávez and Evett (2012) in a study comparing five commercially produced soil water sensors.

A variety of studies have examined the use of the low-frequency, dielectric permittivity sensors in comparison to other, more costly dielectric permittivity sensors. Czarnomski et al. (2005) compared the use of a Decagon ECH$_2$O capacitance sensors, TDR sensors, and water content reflectometry sensors to determine VWCs of undisturbed, extracted soil profiles as well as mixed soil profiles. Authors noted all three sensors failed to reasonably determine VWC with the use of standard calibration equations; however, after soil-specific calibration equations were developed, relationships strengthened greatly. The only sensor significantly influenced by temperature was the ECH$_2$O; as reported VWC decreased linearly by 0.1% for every 1°C increase in temperature. Even so, the authors concluded after evaluating cost, accuracy, and precision that the capacitance soil water sensors were appropriate for studies requiring high frequency observations at multiple sites over time.

Similarly, Seyfried and Murdock (2004) compared the low-frequency, capacitance-based 50 MHz Hydra Probes (Stevens Water Monitoring Systems, Inc., Portland, OR) to TDR sensors in a variety of fluids, soils, temperatures, and ECs. One notable characteristic of the Hydra Probe is the unit’s ability to measure temperature and soil EC, making the unit comparable to the Decagon 5TE sensor. Authors concluded differences between the low-frequency, capacitance sensors and the TDR sensors were due to frequency differences. Still, Seyfried and Murdock (2004) reported both sensor-estimated VWCs to correlate well with actual VWC for most soils.

Because the energy with which the water is held does not directly indicate amount of water held at the sampling time, conversion from matric potential to VWC requires a texture-specific soil water release/retention curve. These curves and a program used to derive them have been described in detail by multiple authors (Fredlund and Xing, 1994; Saxton et al., 1986; Saxton and Rawls, 2006). Difficulties have been reported with this conversion as bulk density changes with inconsistent soil layers (Chávez and Evett, 2012), but strong coefficients of determination and low root mean square errors (RMSEs) are characteristic of some conversions of soil matric potential to VWC (Eldredge et al., 1993).

Comparisons Between Low-cost Sensor Systems. Direct comparisons of similar low-cost sensors have been conducted, but concrete conclusions have been difficult. Sui et al. (2012) compared Decagon EC-5 and 5TM capacitance (frequency domain sensors) to Watermark 200SS (granular matrix sensors) in a 10-ha cotton field in Stoneville, MS. Soil texture at this site ranged from a silt to a silt loam. Sensor nodes were deployed in 10 plots and each node monitored soil water at three depths (15, 30, 60 cm). Authors noted substantially more soil-water depletion at the 15- and 30-cm depths than at the 60-cm depth from planting until 60 d after planting (DAP). From 60 to 80 DAP, a substantial decline occurred in soil water at the 60-cm depth. Difficulty was noted in comparing the reported soil water potential from the 200SS and the reported VWC from the Decagon sensors. Qualitative comparisons were made by monitoring trends over time. Resulting graphs were interpreted as displaying consistent behaviors between sensors at similar depths. Authors concluded that both sensors were capable of monitoring soil water status throughout the growing season.

Similarly, Varble and Chávez (2011) compared Decagon 5TE sensors with Watermark 200SS sensors under laboratory and field conditions. Measurements were then compared to VWCs determined by gravimetric sampling. Authors suggested each sensor required a unique calibration for every soil type and location within a field. Although increasing soil EC in laboratory tests did not significantly influence 200SS readings, increasing soil EC did increase errors in 5TE reported VWCs. Authors concluded that field-based calibrations were more appropriate than laboratory-based calibrations, because laboratory conditions fail to represent specific, representative field operating conditions for each sensor.

In a more recent comparison of Decagon 10HS VWC sensors and Watermark 200SS sensors in varying soil textures and changing water contents, Raper et al. (2015) noted substantial noise in the data when the two different sensors were correlated. This error, according to the authors, was suspected to be caused partially by hysteresis of the tensiometric sensor following periods of prolonged drying. Raper et al. (2015) proposed that sensors such as the VWC 10HS might be more appropriate for deployments attempting to characterize soil water content where drought is likely.

Cotton, Water Use, and the CS Factor. The second major component of most water-deficit stress indices is some CS factor. As mentioned before, this is a species-specific component that serves as a method of decreasing or increasing index readings as a function of growth stage sensitivity to stress. To formulate a CS factor, some background on cotton's physiological sensitivity to drought stress and water use is necessary. Parameters that must be defined clearly include the stress threshold (the point at which drought-stress index units should begin to accrue), cotton growth stage susceptibility, water use, and root water extraction characteristics.

Plant Available Water and Cotton Stress. If an inexpensive VWC soil water sensor is used to calculate the SD parameter, the threshold at which stress units begin to accumulate must be defined. Plant available water (PAW), from a volumetric standpoint, is defined as follows:

$$\theta_{PAW} = \theta_{FC} - \theta_{PWP}$$

where: θ_{PAW} = Volumetric water content of plant available water (PAW),
θ_{FC} = Volumetric water content of field capacity (FC), and
θ_{PWP} = Volumetric water content of permanent wilting point (PWP)

In this calculation of θ_{PAW}, θ_{FC} represents the amount of water held after gravitational water has drained away and represents the upper threshold of PAW. The lower limit, or θ_{PWP}, varies by species and cultivar, and represents the VWC at which the plant can no longer extract any water. From a tensiometric definition, this point is generally assumed to occur at -1500 kPa (Tolk, 2003). Subsequently, θ_{PAW} varies with soil texture. As texture becomes finer, PAW increases to a maximum near a texture of silt loams and then decreases (Brady and Weil, 2002).

Many studies have described water-deficit stress in terms of PAW. Meyer and Green (1981) determined 50 and 30% of PAW were safe irrigation scheduling values for crops of wheat and soybeans, respectively, as these values were associated with the onset of stress. Al-Khafaf et al. (1978) monitored evapotranspiration of cotton in arid New Mexico and suggested a substantial decline occurred at 40% PAW. In contrast, research in Arizona examining soil depletion levels of 35, 50, 65, and 80%, found significant decreases in yield associated with each decrease in PAW (Husman et al., 1999). This research suggested yield-limiting water stress might occur at a PAW above 50%. Rosenthal et al. (1987) noted decreases in relative transpiration of cotton at 25% and decreases in relative leaf extension rate at 51% PAW. Similarly, Colazzi et al. (2003a) found cotton stress to be minute at levels of available soil water greater than 60%. These studies and others have led to the general recommendation of a 50% PAW for management allowable depletion (MAD) in cotton (Lieb and Fisher, 2012; Martin, 2001).

Cotton Susceptibility. The physiological and morphological response of cotton to water-deficit stress is complex and has been well described elsewhere (Ball et al., 1994; Loka et al., 2011; Pettigrew, 2004a, b). Ultimately, this stress results in decreased lint yield by decreasing fruiting body production and by increasing abortion of present fruiting bodies (Guinn and Mauney, 1984a, b; Orgaz et al., 1992). Increased boll numbers typically are associated with more bolls on higher nodes and more distal branch locations in comparison to drought-stressed plants (Pettigrew, 2004a). Water-deficit stress also has been noted to increase earliness (Orgaz et al., 1992). The broad physiological growth stage most sensitive to drought stress in determinant crops, after stand establishment, is commonly considered to be flowering (Stewart et al., 1975). Cotton, an indeterminate, also has been shown to be most sensitive during flowering and boll formation, although generally it is considered to be less susceptible to drought than many other row crops (Brouwer et al., 1989).

Guinn et al. (1981) examined the effects of irrigation initiation and stress timing on multiple growth parameters of Arizona cotton. These authors noted great yield reductions when irrigation initiation occurred after flowering, as this water deficit decreased the number of produced fruiting positions and increased earliness. However, notable yield reductions and increased earliness were not associated with irrigation initiation immediately prior to flowering. Authors concluded that the crop was less susceptible to water stress prior to flowering but that it became much more susceptible during the flowering period. Results from this study are in agreement with those of Grimes et al. (1978), who noted decreases in lint yield associated with exceptionally late or early irrigation initiations during the flowering period. Research by Teague et al. (1999) examined irrigation initiation beginning 1 wk prior to first flower, during first flower, and 1 wk after first flower. Significant decreases were noted in cotton yield response for each week delay in irrigation initiation, with the greatest yield associated with initiation beginning 1 wk prior to first flower. Similarly, Radin et al. (1992) examined furrow irrigation during flowering in comparison with season-long, surface drip irrigation and noted comparable WUE (ratio of seedcotton yield to applied irrigation water and precipitation) and yields between these two treatments.

In contrast, recent research by Teague et al. (2012) noted significant increases in yield when irrigation initiation occurred more than 30 d prior to flowering when compared to irrigation timing 4 d prior to flowering. Because this trial examined irrigation and fertilizer treatments, only two irrigation initiation treatments were included. Authors suggest pre-flower drought stress should be avoided to maximize yields and promote earliness of the crop. Although drought stress was imposed during a growth stage that has been concluded in other studies to be less sensitive to deficits, this study suggests that a severe yield penalty still can be observed from a deficit pre-flower (Teague et al., 2012).

Although flowering in cotton encompasses a considerable amount of time compared to determinant row crops, many studies determining the specific period during flowering of greatest sensitivity have been conducted. Research by Grimes et al. (1970) indicated stress during the middle (peak) flowering period resulted in the greatest yield reductions, as it caused both significant increases in square shedding prior to flowering and reduced boll retention. In contrast, early flowering stress (prior to peak) only significantly increased square shed and late stress (after peak) only significantly reduced flowering rates and boll retention. Authors also found strong relationships between boll number and pounds of lint per acre, suggesting differences in boll size and lint percentage were not substantial. The ability of the cotton plant to drop fruiting bodies, therefore, allows the plant to sufficiently support and maintain the retained bolls.

Cotton Water Use. Methods to determine evapotranspiration of a cropped surface have been defined thoroughly by Allen et al. (1998). Crop evapotranspiration (ET_c) is a function of the crop coefficient (K_c) multiplied by a reference evapotranspiration (ET_o). The K_c can be defined through a single parameter approach or a dual parameter approach. The differences here are on the quantification of soil evaporation. In the single parameter approach, deemed suitable for most irrigation needs, K_c equals the average system (soil + crop) evapotranspiration over a period of time. Increases in soil evaporation after rainfalls or irrigation events are not quantified directly, but averaged across the quantified period. In contrast, the dual parameter approach considers the K_c to equal the sum of a basal crop coefficient (K_{cb}) and soil evaporation (K_e). In this calculation, the K_{cb} refers to the ratio of ET_c to ET_o when adequate soil water is present to support transpiration but soil evaporation is essentially null. Unlike the single parameter approach, the dual parameter approach includes differences in ET relative to a damp soil surface following irrigation or rainfall. According to Allen et al. (1998), this method is most appropriate for soil water balance calculations, high frequency irrigations, or studies sensitive to day-to-day variations in ET_c. These authors also outlined specific K_c for multiple crops in both single and dual parameter methods, which vary by growth stage. During the initial stage, K_c is generally constant and small. As the crop begins to develop, K_c increases linearly until the mid-season plateau is reached. During the mid-season stage, the K_c represents the highest value of the growing season. Finally, the K_c declines linearly through the late-season growth stage.

Inferences on seasonal K_c frequently are determined by the use of weighing lysimeters. These typically are characterized by an inner field-buried container placed on a scale mounted in an outer field-buried container. Although numerous studies have been conducted to determine the K_c of field-grown cotton, few studies utilizing lysimeters have been conducted on modern cotton cultivars in the Mid-South and corresponding K_c have been reported. Fisher (2012) observed two weighing lysimeters over a 4-yr period in Stoneville, MS. Due to large differences in crop growth patterns during the observed years, Fisher reported difficulty in constructing an average K_c curve. Early season values varied from 0.2 to 0.6, whereas maximum values varied from 1.1 to 1.3. Research by Kumar (2011) in St. Joseph, LA observed two lysimeters during the 2010 growing season. The measured K_c graphed by DAP appeared to represent a quadratic relationship. Reported average K_c were 0.42, 0.89, and 1.41 for initial, developmental, and mid-season growth stages, respectively. Both of these studies indicated an initial low, increasing developmental, mid-season plateau, and end-of-season decline in K_c, which is in agreement with the standard K_c progression with growth stage outlined by Allen et al. (1998).

Cotton Water Use and Susceptibility to Stress. Although a partial objective of many water-deficit stress indices is irrigation scheduling, the CS factor differs (at least theoretically) from a crop coefficient because it does not describe water use. Still, the theoretical trend of CS conceptually mirrors the trend of a crop coefficient; water use early in the year is limited through the squaring phase, increases up to a maximum during boll fill, and then declines into maturity (Fisher, 2012; Kumar, 2011). According to research defining cotton's susceptibility to drought, pre-square, and early square are less susceptible, followed by an increase and ultimate peak in susceptibility during peak flower, which precedes a late-season decline in susceptibility (Grimes et al., 1970, 1978; Guinn et al., 1981). These trends suggest the crop susceptibility factor should follow a similar trend; however, the CS factor must be calibrated and validated against observed site-relative yields.

Cotton Root Growth. Cotton root growth has been studied by many scientists, but research that accurately mimics field conditions is difficult to conduct. Still, this information is critical to defining the effective rooting zone. Klepper et al. (1973) examined the rooting characteristics of two cotton plants in the Auburn rhizotron (Taylor, 1969); one of which underwent a drought stress beginning 68 DAP, and another that was well-watered. Several findings from this study are applicable for the development of a drought-stress index. First, roots reached the bottom of the rhizotron (180 cm) by the initiation of stress (68 d). Conditions in the uniform- textured rhizotron definitely will not characterize all profiles, but it is important to note the cotton plant's potential rooting depth. Furthermore, authors noted a decrease of root density at shallow depths and an increase at deeper depths 4 wk after the onset of stress. This pattern was assumed to be associated with death of upper roots and preferential growth into the more moist, lower-profile regions. Most notably for the development of a drought-stress index, research by Taylor and Klepper (1971) suggested roots at varying depths varied little in effectiveness of water extraction. Given no difference in root water extraction by depth, characterizing the area by which water can be extracted becomes a function of rooting depth and requires no weighting by depth.

DISCUSSION

The insight into drought stress provided by a properly developed index could increase WP on both irrigated and dryland acreages. Ultimately, a drought-stress index could be useful for producers in the Mid-South and southeastern regions of the U.S. who lack the available tools of drought avoidance or large, soil water holding capacities common in other cotton producing areas. As evident through this review, drought-stress indices have taken many different forms since Nix and Fitzpatrick (1969) first outlined the concept more than 45 yr ago. Performance of each index ultimately simplifies to the ability of each approach to quantify plant demand for water as a function of environmental demand, quantify the water supply, and determine the impact of a water deficit on yield as a function of time and severity of the stress. Embedded pitfalls in utilized measurements, failure of drought to be the most yield limiting factor, and lack of information on crop susceptibility have each posed issues in developing drought indices.

Water supply was determined initially by Hiler and Clark (1971) through use of a neutron probe and atmospheric evaporative demand by calculating evaporative demand. In the 30 yr following 1971, soil water measurements were largely replaced by other plant indicators of drought for the purpose of drought-stress quantification. As stated by Hiler and Clark (1971), "the plant integrates the demand and the supply; the leaf water potential is an indication of how the plant performs this integration. Thus, the leaf water potential would appear to be a good characterization of SD." Due to the small footprint of leaf water potential measurements and the substantial sampling time, canopy temperature quickly became the standard in most subsequent attempts at quantifying drought stress. Still, the concept that a plant parameter could integrate demand and supply proved to be accurate for many scientists in arid environments (Gardner et al., 1981; Idso et al., 1977; Jackson et al., 1981; Wanjura et al., 2004). Compared to soil water sensors, canopy temperature sensors can be moved from location to location easily and are much easier to install. As a result, a single canopy temperature sensor could be used to collect a large amount of data across a relatively large spatial scale, resulting in a low cost-per-data point. Soil water sensors, traditionally, have been expensive and relatively immobile with small spheres of influence, resulting in a high cost-per-data point.

For these reasons, canopy temperature approaches largely have outnumbered soil water sensing approaches to quantifying drought stress. Unfortunately, canopy temperature approaches have been difficult to adopt in the more humid Mid-South and southeastern regions as compared to the arid Mid-West and western regions of the U.S. Limited utility of canopy temperature approaches in humid regions is, in part, due to high humidity and cloud cover during the most important sensing windows. Because of these issues, many scientists within humid regions have focused their efforts on quantifying soil water (Fisher and Kebede, 2010; Kebede et al., 2012; Vellidis et al., 2008; Vories et al., 2004). Fortunately, recent advances in electronics have reduced drastically the cost of soil water sensors (Robinson et al., 2008). Although most soil water sensing devices are still characterized by a small sphere of influence, the low cost of many of these devices allows large deployments to be made and subsequently has reduced the cost-per-data point into a range acceptable for drought-stress indices. The original approach pursued by Hiler and Clark (1971) to calculate SDI is now far more plausible: soil water sensing could be used to infer supply and demand calculations and could be calculated from atmospheric parameters measured by in-field monitoring stations or nearby weather stations.

Of the many commercially produced soil water sensors currently available, the two most inexpensive devices that appear to best fit large deployments include low-frequency VWC sensors and granular matrix tensiometric sensors. Both of these sensor types could be used to collect temporally dense measurements across a growing season at multiple depths for a marginal cost. Still, as noted by McCann et al.

(1992), the inability of the tensiometric sensors to collect meaningful measurements during periods of prolonged droughts and the requirement of the soil to reach or exceed field capacity after a drying period might prevent these sensors from fitting well into a drought-stress approach, given prolonged periods of drought are likely. The low-frequency VWC sensors have not been reported to experience the same issues with prolonged drying periods and respond rapidly to rewetting events (Raper et al., 2015). Therefore, the use of low-frequency VWC sensors should be examined for their potential to provide insight into experienced drought at a given location.

Developing an initial, empirical cotton CS factor is a function of summarizing a vast amount of research on the topic that has been conducted during the past 45 yr. Generally, the accepted threshold for the onset of drought is assumed to be 50% PAW. Furthermore, cotton sensitivity to drought is relatively low early in the season through the squaring stage, increases to a peak during peak flower, and then declines through maturity. Finally, root water extraction efficiency varies little by depth and might simply be a function of effective rooting depth. Although it is likely that these baselines will have to be modified to maximize the utility of the CS factor, they should serve as a valid, research-based starting point.

CONCLUSION

This review has summarized previously developed crop drought-stress indices, examined the potential of soil moisture measurements to provide insight into cotton water status, and highlighted cotton-specific data to serve as a baseline in the construction of a drought-stress index capable of providing insight into cotton water status. Although specific equations, hardware, and subsequent measurements used to quantify drought stress experienced at a given location now greatly contrast those used by Nix and Fitzpatrick (1969) and Hiler and Clark (1971), the framework outlined by the stress index and SDI first proposed more than 45 yr ago remains relatively unchanged. From this review, it is clear that recent advancements in sensor technologies and more robust information on cotton susceptibility supports the development of a more-accurate, reliable drought stress index capable of providing insight into cotton varietal drought tolerance and driving cotton irrigations within and beyond the humid Mid-South and southeastern regions of the U.S.

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