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EVALUATION OF PHYSIOLOGICAL RESPONSES OF MODERN VERSUS OBSOLETE COTTON CULTIVARS UNDER WATER-DEFICIT STRESS FOR EXPLAINING YIELD VARIABILITY

R.S. Brown, D.M. Oosterhuis, A. Bibi, M. Arevalo, and D.L. Coker
University of Arkansas
Fayetteville, AR

Abstract

Year-to-year variability in yield is a major concern in U.S. cotton production. It is speculated that the reason for this variability in yield is a combination of adverse environmental conditions, particularly during boll development, coupled with changes in breeding objectives over the past few decades. Field studies were conducted in 2001 and 2002 in northeast Arkansas and in northeast and northwest Arkansas in 2003 to investigate physiological responses of modern versus obsolete cultivars under water-deficit stress to help explain yield development and variability in cotton. Treatments consisted of four modern and four obsolete cultivars subjected to both well-watered and water-deficit conditions. The cultivars evaluated were ST 474, DP NuCotn33B, SG 747, Acala Maxxa (modern) and ST213, DP 16, Rex, Acala SJ2 (obsolete). Results from 2001 and 2002 indicated no differences between obsolete and modern cultivars or differences between water treatments for altering physiological responses or yield development. However, the 2001 and 2002 seasons received above average rainfall making conditions to test the research problem in the field difficult. The 2003 season experienced a brief period of water-stress at the northwest Arkansas test location allowing for an assessment of the physiological responses of modern versus obsolete cultivars to that stress. A few physiological measurements such as leaf protein and leaf membrane integrity indicated that obsolete cultivars were better adapted to the brief water-stress than the modern cultivars, however the differences were not significant. We believe that if the water-stress would have lasted one to two weeks longer into boll development more physiological differences between modern and obsolete cultivars would have arisen. Also, differences would have been observed at harvest with lint yields being higher for obsolete cultivars under water-stress conditions. Future research will continue in growth chamber environments in which the amount of water-stress, duration of water-stress and timing of water-stress can be controlled. We anticipate that this information along with information already collected should help to explain why modern cultivars have increased potential for such variable yields from year-to-year.

Introduction

Cotton yields in Arkansas as well as much of the U.S. increased steadily during the 1980's, but in the 1990's there has been a leveling off and lately a decrease in yields (Meredith, 1998; Lewis and Sasser, 1999). Of more concern, however, is the extreme year-to-year variability. The U.S. Cotton industry has faced difficult times in recent years due to problems with year-to-year variability in yields. According to Helms (2000), there is clearly a significant problem with the lack of uniformity in current yields. In Arkansas, three out of five seasons from 1995 to 1999 were extremely disappointing with unusually low yields (Oosterhuis, 1999). The 1998 and 1999 crop yields were the poorest in recent history and much of this was related to extreme weather conditions and less on insect pressure. Generally, each year the cotton crop appears to have good potential at mid-season, but this potential is not always achieved at harvest due to combinations of moisture stress and high temperatures during the critical first three to five weeks of flowering and boll development. Besides environmental conditions, changes in breeding objectives over the past few decades may also be an underlying reason for yield variability. It is hypothesized, that increased yield variability may be the result of differential partitioning of carbohydrate and energy pools between fiber and seed of modern and obsolete cultivars as a result of environmental stress during early boll development. To test this research hypothesis the following research objectives were initiated. The first objective was to evaluate lint yield and boll and yield components of modern versus obsolete cultivars under well-watered and water-deficit conditions. The second objective was to study physiological and biochemical parameters of modern and obsolete cultivars in order to better understand boll development and yield as affected by environmental stresses. An improved understanding of physiological differences between modern and obsolete cultivars under water-deficit stress should help to clarify yield development and potentially answer yield variability issues.

Materials and Methods

Field studies were designed in northeast and northwest Arkansas in 2003 to test the impact that contrasting environmental conditions coupled with genotypic differences had on partitioning in field grown cotton. The study contained two factors which were water and cultivar. Water was the whole plot factor and consisted of either well-watered or water-deficit conditions. The sub-plot factor was cultivar and consisted of eight cultivars (four modern and four obsolete). The modern cotton (*Gossypium hirsutum L.*) cultivars were ST 474, SG 747, DP 33B, and Acala Maxxa and the obsolete cultivars included ST 213, DP 16, REX, and Acala SJ2. Each of these eight cultivars was subjected to both water treatments and replicated six times. Numerous in-season physiological and end-of-season agronomic measurements were evaluated to help explain yield variability. Physiological measurements included leaf fluorescence measured with a fluorometer, canopy temperature measured with a handheld infrared thermometer, chlorophyll content taken with a Minolta SPAD meter, specific leaf weight (SLW) or leaf thickness, leaf adenosine triphosphate (ATP) measured with an ATP lumitran, leaf total soluble protein utilizing the Bradford method through colorimetric procedures, leaf membrane integrity measured with a seed analyzer, leaf wax concentrations, and leaf antioxidant enzyme concentrations. End-of-season measurements included lint yields, yield and boll components, gin turnout, and fiber quality. Boll components consisted of average boll weight, seed weight, fiber per seed, and seeds per boll. Yield components consisted of bolls per acre and seeds per acre.

Results and Discussion

The 2003 season was the third year for the project investigating the yield and physiology of modern versus obsolete cultivars under water-deficit conditions. Unfortunately, the 2001 and 2002 seasons resulted in above average rainfall during the growing season. As a result we were unable to impose moderate water stress conditions during boll development to properly evaluate physiological differences between modern and obsolete cultivars in response to water stress as a means of explaining yield differences and arising yield variability questions. Fortunately, in 2003 we were able to obtain an appreciable water-deficit stress at the Fayetteville, Arkansas location. This paper will include the physiological results from the Fayetteville location in 2003 and yield and yield component results from both the Clarkedale and Fayetteville locations collected in 2003. Results will be presented as the average of the four obsolete and the average of the four modern cultivars and presented as modern versus obsolete cultivars under each water level.

Lint Yields

In 2003, modern cultivars had higher lint yields than the obsolete cultivars at both test locations under both well-watered and water-deficit conditions (Figure 1). At the Fayetteville test site this increase in lint yield by the modern cultivars was significant ($P \leq 0.05$). Our hypothesis was that obsolete cultivars would yield higher than modern cultivars under a significant stress event, such as water-deficit stress, due to improved partitioning of carbohydrates between fiber and seed. However, the modern cultivars yielded higher than obsolete cultivars even under water-deficit conditions. An explanation for this might be that the stress did not last long enough during boll development and compensation occurred giving the modern cultivars the advantage to yield higher since modern cultivars contain more seeds per acre which give rise to more fiber/acre since modern cultivars have equal or more fiber/seed (Tables 1 & 2) than obsolete cultivars.

Yield and Yield Components (Boll Dynamics)

Boll and yield component data from Clarkedale (Table 1) and Fayetteville (Table 2) showed similar results when comparing modern cultivars to the obsolete. At Clarkedale, obsolete cultivars had significantly ($P \leq 0.05$) larger bolls and greater seed weight than the modern cultivars at both water levels (Table 1). However, the modern cultivars had significantly ($P \leq 0.05$) more bolls and seeds per acre than the obsolete cultivars (Table 1). There were no significant differences between modern and obsolete cultivars for producing fiber/seed. This indicates that the improved yields by the modern cultivars (Figure 1) was the result of more bolls and more seeds per acre with fiber per seed being near equal between modern and obsolete cultivars. There were no significant trends in relation to seeds/boll between modern and obsolete cultivars (Table 1). However, the obsolete cultivars had numerically more seeds/boll than the modern cultivars, which was not expected and difficult to explain. Boll and yield component data from the Fayetteville test site (Table 2) showed the same trend as Clarkedale with increased boll weight and seed weight with obsolete cultivars and more bolls and seeds per acre with modern cultivars. However, the only significant differences were detected under the water-deficit conditions and not under well-watered environments.

Gin Turnout

Results from gin turnout were very similar between test locations. At both test locations gin turnout was significantly ($P \leq 0.05$) higher for modern cultivars compared to the obsolete (Figure 2). This was expected since breeders have generally breed for higher gin turnouts in recent years. However, there was no significant interaction between cultivar and water.

Fiber Quality

Seedcotton samples collected from the Clarkedale location were ginned at the University of Arkansas and lint subsamples were sent to the Cotton Fiber Laboratory at Louisiana State University for analysis of fiber length, length uniformity, elongation, strength and micronaire. Results indicated no differences between modern and obsolete cultivars under well-watered or water-deficit conditions for any measured parameters with the exception of fiber length. Fiber length was significantly ($P \leq 0.05$) increased under water-deficit conditions by the obsolete cultivars (Table 3). Also, there was a significant increase in elongation and a significant decrease in micronaire under well-watered conditions as opposed to water-stress conditions when averaged over cultivars (Table 3).

Leaf Fluorescence

There were no statistical differences ($P \leq 0.05$) between modern and obsolete cultivars for increasing leaf fluorescence at either water level measured three weeks after first flower during peak water-stress (Figure 3). Leaf fluorescence was significantly higher ($P \leq 0.05$) under well-watered conditions compared to water-deficit conditions when averaged over cultivars (Figure 3).

Canopy Temperature

There were no statistical differences ($P \leq 0.05$) in measured canopy temperature between modern and obsolete cultivars under either water level (Figure 4). However, when averaged over modern and obsolete cultivars the well-watered plants had significantly cooler leaves than the water-deficit plants (Figure 4). This measurement helps to show the degree of stress that the water-deficit plants were experiencing regardless of any interactions that took place between contrasting cultivars.

Specific Leaf Weight (SLW) and Chlorophyll Content

There were no differences between modern and obsolete cultivars for changing specific leaf weight (an indication of leaf thickness) or chlorophyll content at either water level in 2003 (Figure 5). However, there was a significant increase ($P \leq 0.05$) in leaf chlorophyll and specific leaf weight (SLW) under water-deficit conditions compared to well-watered conditions (Figure 5). Under water-deficit stress conditions a leaf will typically be smaller and thicker indicating plant stress and will have a higher SLW value (more weight per unit area). The increase in leaf chlorophyll observed under water-deficit conditions is probably due to the stacking of chloroplasts in the leaf since the leaf was thicker. This may be a negative aspect of using a Minolta SPAD meter in the field as a means of assessing nutritional demand, in which chlorophyll content is misinterpreted under moderate to severe plant stress.

Leaf ATP Concentrations and Leaf Soluble Protein

ATP concentrations and total soluble protein levels of cotton leaves were measured to determine any differences in plant energy dynamics. There were no significant differences in measured ATP or protein concentrations at the water or cultivar level (Figure 6). However, modern cultivars had numerically higher ATP and protein concentrations under each water level compared to the obsolete cultivars (Figure 6). It was also noticed that protein concentrations were higher under well-watered conditions, but ATP concentrations were lower under well-watered conditions. An explanation for this might be that under well-watered conditions the cotton plant is better suited for making protein than water-stressed plants, however this manufacturing of protein cost the plant more energy (ATP).

Leaf Wax Concentrations and Leaf Membrane Integrity

There were no significant differences between modern and obsolete cultivars at either water level for altering leaf wax concentrations or leaf membrane leakage (a measure of leaf integrity). However, membrane leakage was significantly greater ($p \leq 0.05$) in water-stressed leaf samples compared to well-watered leaf samples (Figure 7). Leaf membrane leakage appears to be an excellent technique for quantifying water stress. This measurement also supported our hypothesis of improved stress resistance of obsolete cultivars under stress environments by showing a numerical decrease in membrane leakage of obsolete cultivars compared to modern cultivars. This difference was not observed under an adequate moisture environment.

Antioxidant Enzyme Concentrations of Leaves

All living organisms produce reactive oxygen species such as superoxide, hydrogen peroxide and hydroxyl radicals as part of normal metabolism particularly under stressful environments. To prevent excessive cellular oxidation from the production of these reactive oxygen metabolites, plants have adapted strategies such as the antioxidant defense system to detoxify or remove these harmful oxygen radicals. To better quantify the stress levels of obsolete versus modern varieties under water-deficit stress, the antioxidant enzymes catalase, peroxidase, ascorbate peroxidase, and glutathione reductase were measured from sampled leaf tissue. Results showed no significant differences between modern and obsolete cultivars, at either water level, for altering the activity of antioxidant enzymes (Table 4). Furthermore, there were no clear and explainable trends of enzyme activity between cultivars. The activity of antioxidant enzymes in response to water-deficit stress needs to be further investigated to determine (a) the time sequence at which each enzyme is being activated relative to the stress, and (b) how the activity of one enzyme reacts to the activity of another enzyme. It is believed that when one enzyme is activated another enzyme may be silenced. We anticipate that further investigation of antioxidant enzymes during stressful environments will help to explain current yield variability issues.

References

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Oosterhuis, D.M. 1999. Yield responses to environmental extremes in cotton. *In*. D.M. Oosterhuis (ed.) 1999. Proc. Cotton Res. Meetings and Research Summaries, Univ. of AR, Ark. Agri. Exp. Sta. Special Report 193:30-38.

Table 1. Boll and yield components of modern versus obsolete cultivars under well-watered and water-deficit conditions at Clarkedale, Arkansas in 2003.

Treatment	Boll Weight	Bolls/acre	Seeds/acre	Fiber/Seed	Seed Weight	Seeds/Boll
	g/boll	#/acre	#/acre	mg	g/100 seed	#/boll
Modern--Water	4.00	79,000[x]	2,162,000[x]	57.7	9.22	27.1
Obsolete--Water	4.59[x]	57,000	1,649,000	57.8	10.40[x]	28.9[x]
Modern--Dryland	4.24	96,000[x]	2,721,000[x]	62.5	9.28	28.1
Obsolete-Dryland	4.68[x]	78,000	2,235,000	61.3	10.37[x]	28.9

[x] Significant at P≤0.05 for the paired treatments.

Table 2. Boll and yield components of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003

Treatment	Boll Weight	Bolls/acre	Seeds/acre	Fiber/Seed	Seed Weight	Seeds/Boll
	g/boll	#/acre	#/acre	mg	g/100 seed	#/boll
Modern--Water	3.72	312,000	8,373,000	55.1	8.55	27.1
Obsolete--Water	3.72	281,000	7,584,000	51.0	8.88	27.0
Modern--Dryland	3.77	285,000[x]	7,718,000[x]	56.0	8.57	27.0
Obsolete-Dryland	4.16[x]	235,000	6,527,000	57.0	9.46[x]	27.7

[x] Significant at P≤0.05 for the paired treatments.

Table 3. Fiber quality components of modern versus obsolete cultivars under well-watered and water-deficit conditions at Clarkedale, Arkansas in 2003

Treatment	Fiber Quality				
	Length	Uniformity	Elongation	Strength	Micronaire
	inches	%	inches	g/tex	unitless
Modern--Water	1.17	84.3	9.29	30.3	3.6
Obsolete--Water	1.18	84.5	8.99	29.9	3.6
Modern--Dryland	1.16	84.4	8.98	31.0	3.9
Obsolete-Dryland	1.18[x]	84.2	8.78	30.5	3.8

[x] Significant at P≤0.05 for the paired treatments.

Table 4. Leaf antioxidant enzyme concentrations of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003.

Treatment	Antioxidant Enzymes			
	Catalase	Peroxidase	Ascorbate	Glutathione
	mM/g fresh wt	mM/g fresh wt	mM/g fresh wt	nM/ g fresh wt
Modern--Water	1121	2.99	0.012	329
Obsolete--Water	1002	2.93	0.012	338
Modern--Dryland	1012	2.99	0.014	316
Obsolete-Dryland	1061	3.22	0.015	310

Non-significant at p≤0.05 for the paired treatments.

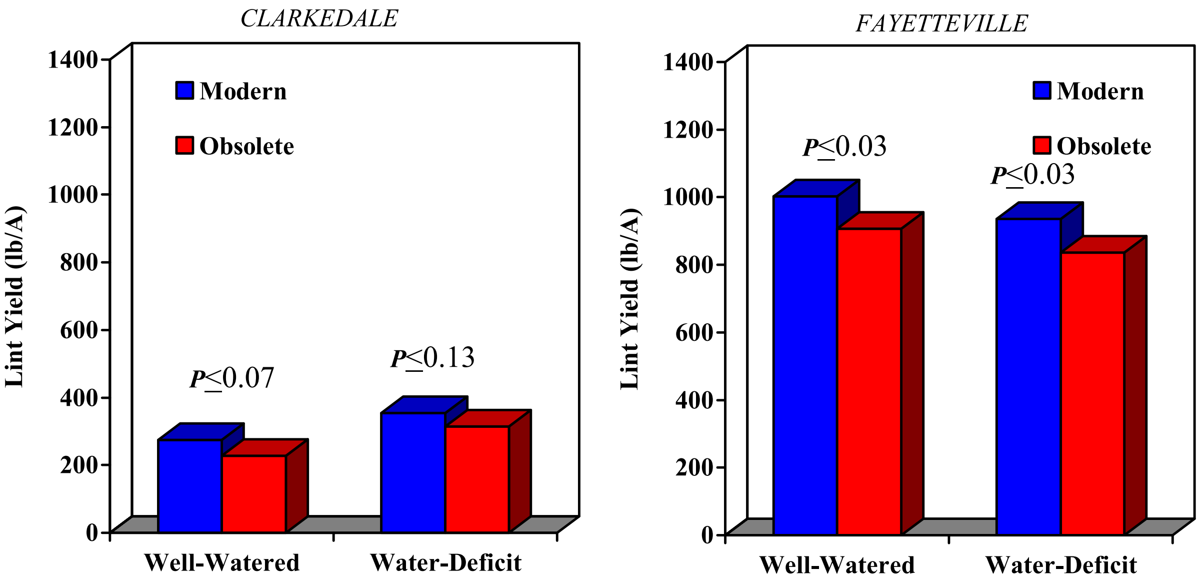

Figure 1. Lint yields of modern versus obsolete cultivars under well-watered and water-deficit conditions at Clarkedale and Fayetteville, Arkansas in 2003.

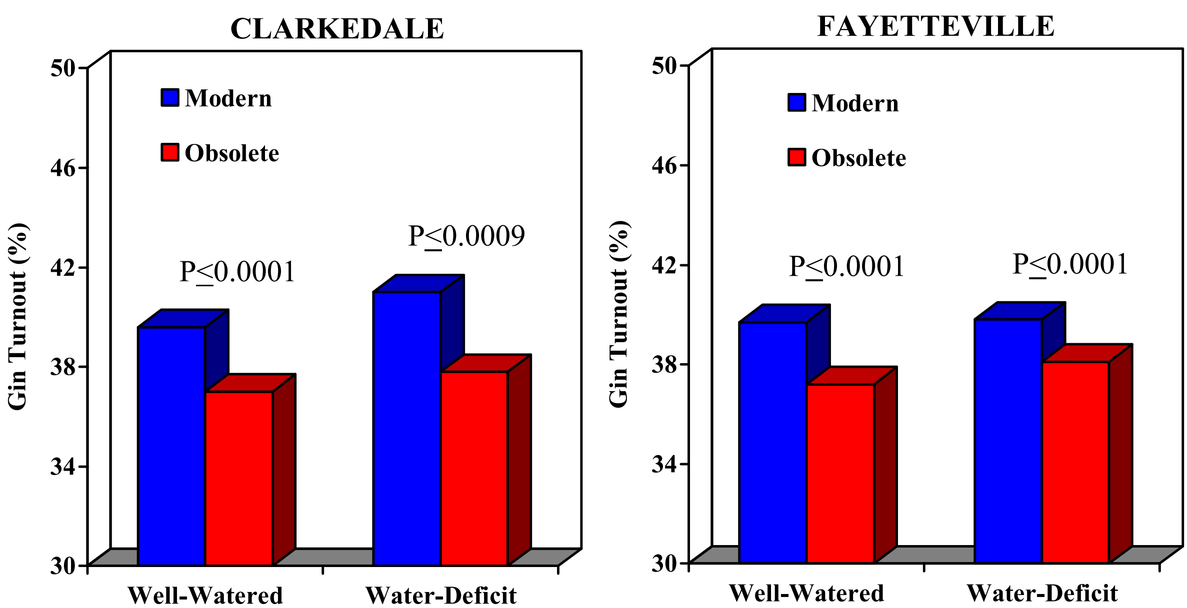

Figure 2. Gin turnout of modern versus obsolete cultivars under well-watered and water-deficit conditions at Clarkedale and Fayetteville, Arkansas locations in 2003.

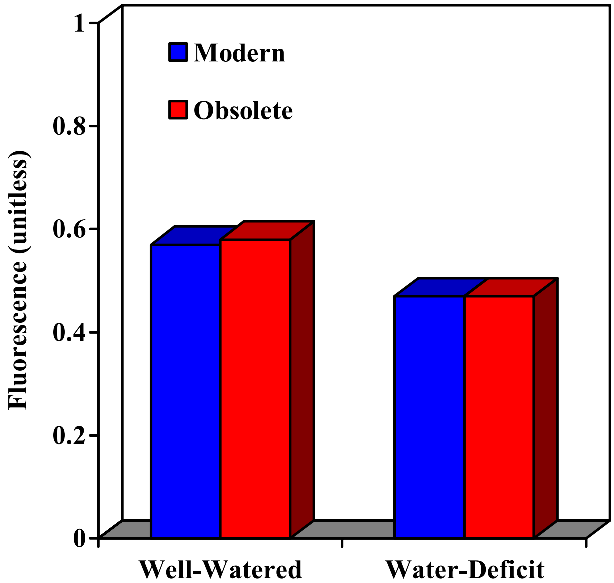

Figure 3. Leaf fluorescence of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003. No significant differences existed between treatments at P≤ 0.05.

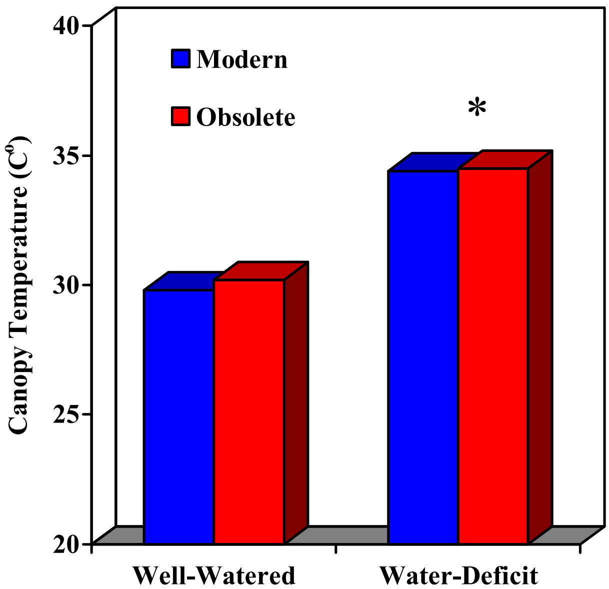

Figure 4. Canopy temperature of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003. *Indicates a significant (P≤0.05) difference at the water level averaged over cultivars.

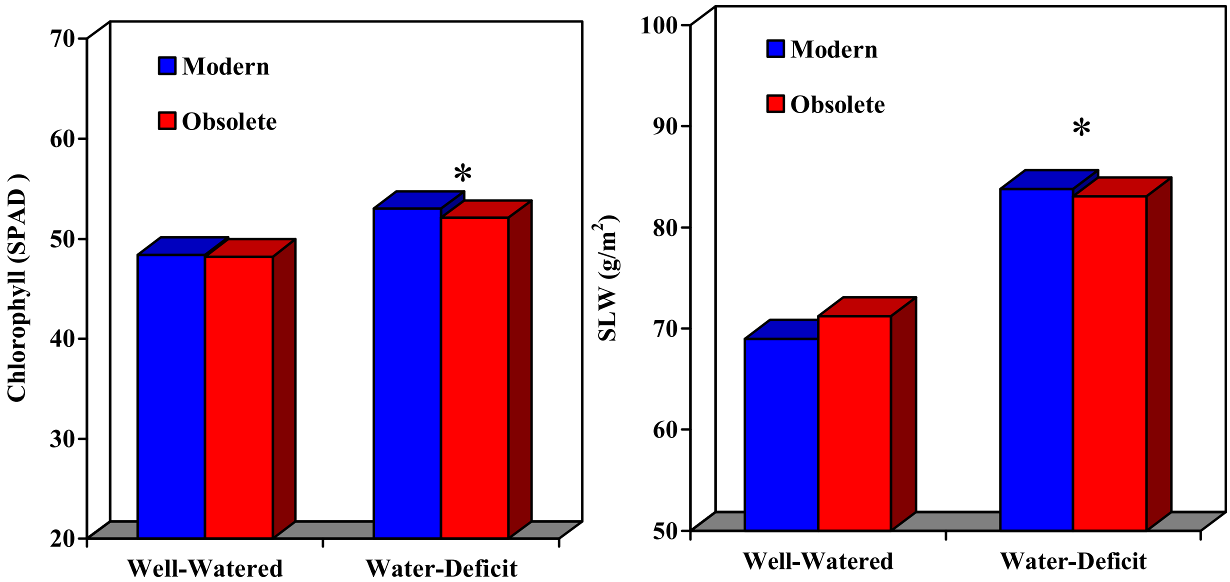

Figure 5. Leaf chlorophyll and specific leaf weight (SLW) of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003. *Indicates a significant ($P \leq 0.05$) difference at the water level averaged over cultivars.

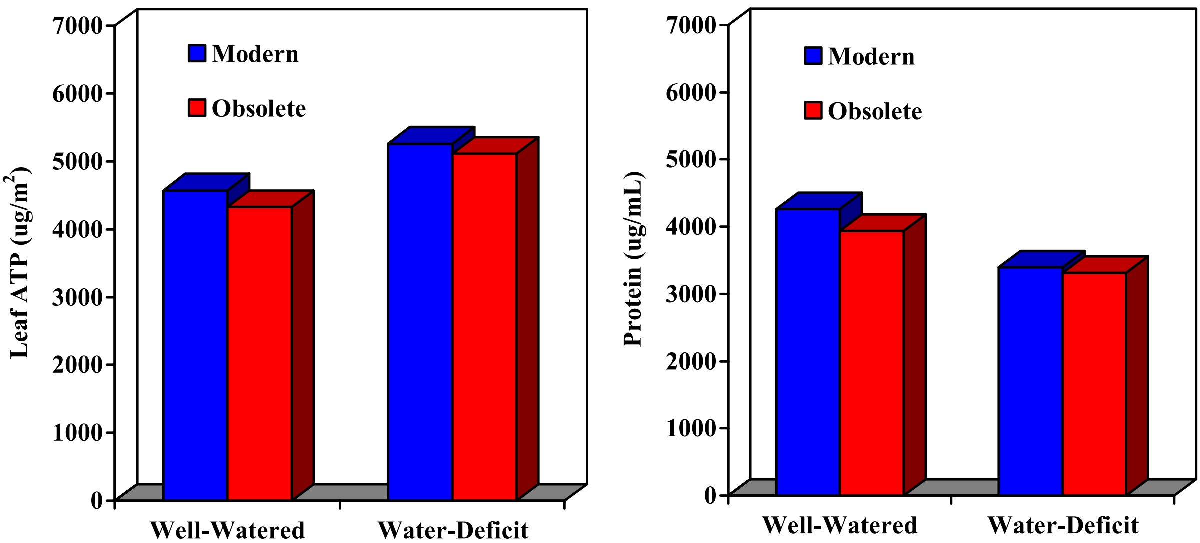

Figure 6. Leaf ATP and leaf total soluble protein of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, AR in 2003. No significant differences existed between treatments at $P \leq 0.05$.

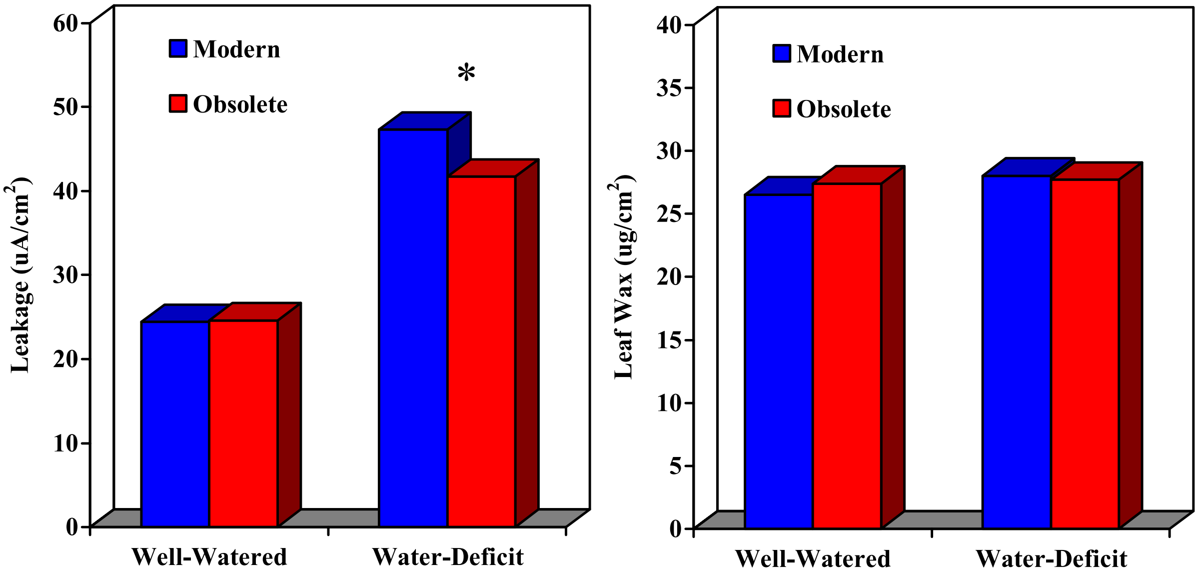

Figure 7. Leaf membrane leakage and leaf wax concentration of modern versus obsolete cultivars under well-watered and water-deficit conditions at Fayetteville, Arkansas in 2003. *Indicates a significant P≤0.05 difference at the water level averaged over cultivars.

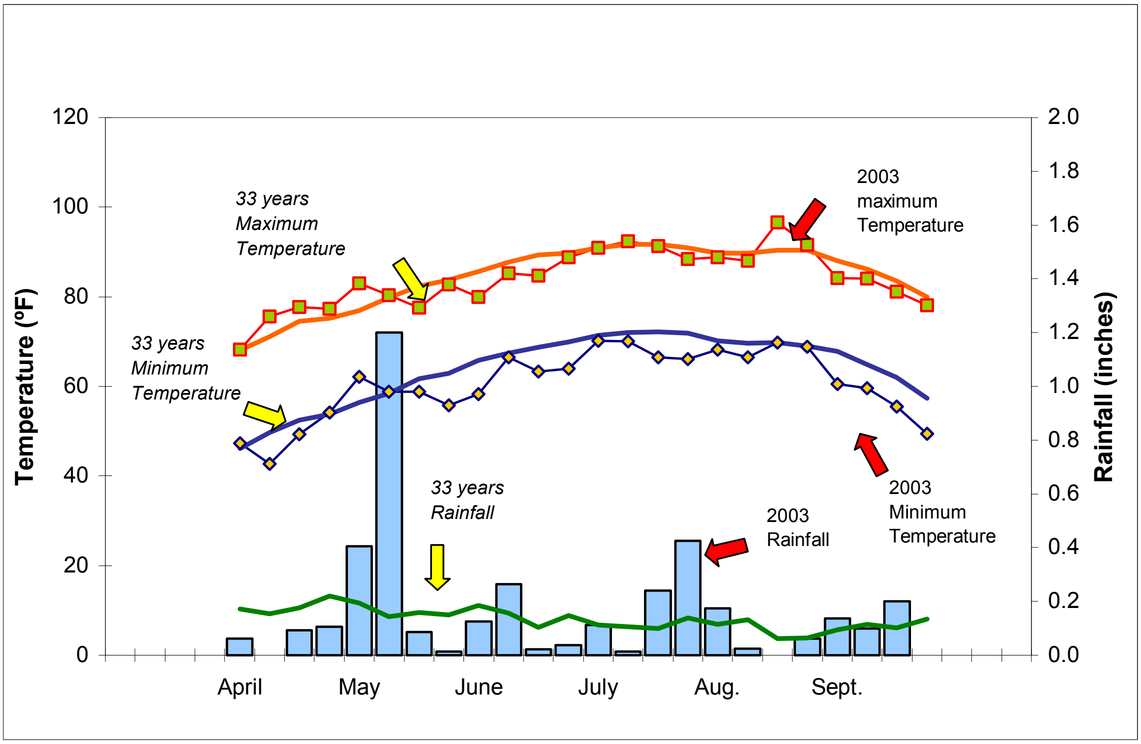

Figure 8. Weekly maximum and minimum temperatures and rainfall at Clarkdale, Arkansas in 2003 compared with a 33 year long-term average at that location.

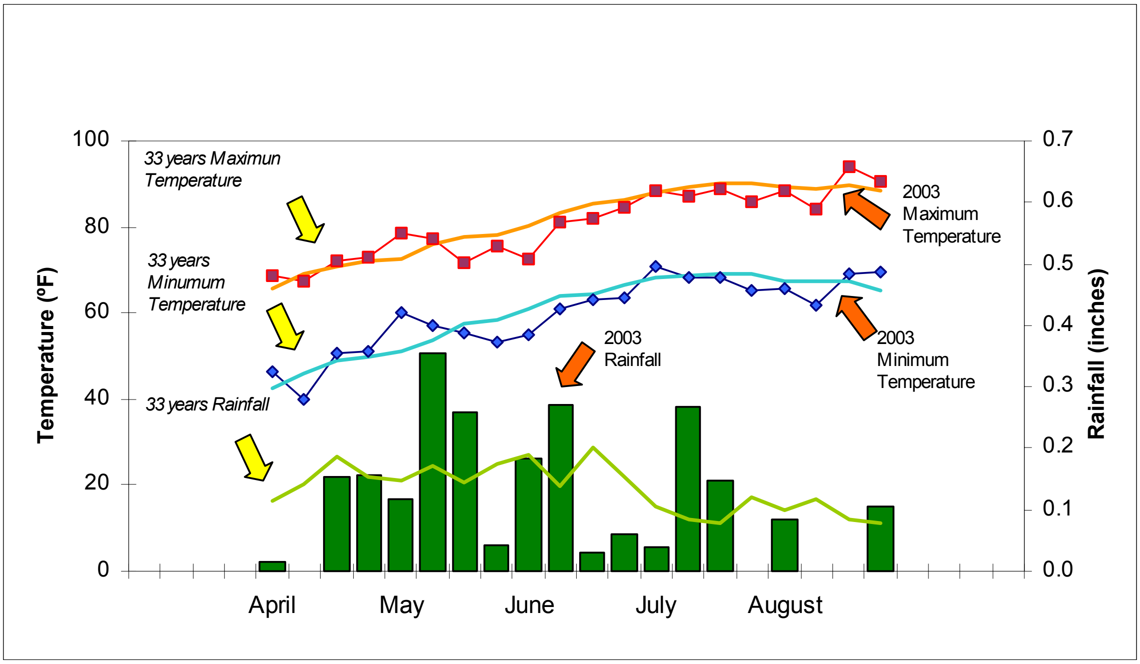

Figure 9. Weekly maximum and minimum temperatures and rainfall at Fayetteville, Arkansas in 2003 compared with a 33 year long-term average at that location.