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Regulated deficit irrigation in almonds: effects of variations in applied water and stress timing on yield and yield components

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Abstract The impacts of three different water stress-timing patterns for three levels of seasonal applied water on production were evaluated in mature almond trees [*Prunus dulcis* (Mill.) Webb cv. Nonpareil] grown under high-evaporative demand conditions in the southern San Joaquin Valley of California. The stress timing patterns involved biasing water deficits to the pre-harvest or post-harvest periods in addition to uniform deficit irrigation for the entire season, referred to as A–C patterns. The three levels of water availability were 55, 70, and 85% of potential seasonal evapotranspiration (ET_c) equivalent to 580, 720, and 860 mm of applied water per season, respectively. Treatments were imposed over four seasons. Predawn leaf water potential was used as the stress indicator and approached -4.0 MPa with the A pattern at the lowest applied water level and -3.5 MPa with the B pattern at the same irrigation level. For every level of applied water, kernel weight at harvest was significantly reduced in the A pattern relative to the B and C patterns. At harvest, the most severe reduction in kernel dry weight relative to the control (17%) occurred in 580A, while there were 11% reductions in 580B and 580C. At the 860 mm level, only the A pattern dry kernel weight was less than the control. Moreover, the A patterns for all irrigation levels had lower kernel percentages than for the B and C patterns, indicating the greater sensitivity of kernel growth relative to shell growth in the regulated deficit irrigation (RDI) scenarios that biased the stress toward pre-harvest. The B stress patterns had a strong negative impact on fruit load relative to the A patterns

at the 580 and 720 mm levels of applied water. No differences in crop load relative to the control were observed among the A and C regimes for all three levels of applied water. Nut load tended to increase during the experiment with 580A and 720A while it decreased with time with the B patterns for the same irrigation levels. We believe that the lower fruit loads involve stress during flower bud differentiation, which occurs mid-August–September in this cultivar and location, quite late in the season relative to other fruit and nut crops. The most successful stress timing pattern in terms of yield (the integrator of fruit size and load) was C, which avoided the large swings in tree stress observed with A and B. The onset of hull splitting was delayed by the severe pre-harvest stress in 580A while being accelerated by the milder stress of 720A. Spider mite levels were unaffected by the RDI. Canopy size was reduced with the A patterns at all irrigation levels. This occurred without any concomitant reduction in fruit load, resulting in higher fruiting densities (305 and 283 nuts/m² of orchard floor shaded area in 580A and 720A, respectively, vs. 214 nuts/m² in the control). Coupling the higher fruiting densities and smaller canopy sizes with higher tree planting densities offers growers the possibility of increasing yields while consuming less water. Maintaining more compact canopies with RDI rather than pruning would also lessen the amount of wood requiring disposal, thereby moderating air quality degradation resulting from burning. It must be emphasized that the scenario we outline—increasing kernel yields while using less water due to stress-related higher fruiting densities—requires that the smaller canopies be maintained by RDI, not pruning.

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Introduction

Almonds are California's largest tree nut crop in total dollar value (Almond Board of CA 2002) and land area, with an excess of 200,000 bearing ha

(USDA-NASS 2004). Almonds rank as the top dollar value U.S. horticultural export crop, nearly all of which comes from production in California. Potential almond orchard water use is 960–1070 mm (2.06–2.30 billion m³) in the primary growing areas of the state (Snyder and Pruitt 1989a, b). As its population grows and environmental concerns increase, California is likely to be 2.46 billion m³ short of water for a normal rainfall year annually in the immediate future (State of California 1998). Water currently used in agriculture is being considered as a possible source by the municipal sector for bridging this gap in supply versus demand. Moreover, the costs of developing new water resources will likely make additional supplies unaffordable to most almond growers. Regulated deficit irrigation (RDI) strategies that reduce consumptive use are being considered as alternatives to traditional irrigation scheduling approaches that fully meet the water requirements of the trees. While RDI can reduce consumptive use, possible negative impacts on productivity must be addressed.

Although almond trees are considered drought tolerant (Feres and Goldhamer 1990; Hutmacher et al. 1994; Torrecillas et al. 1996), there is no doubt that irrigation is critical in producing high yields of top quality nuts (Castel and Feres 1982; Prichard et al. 1993; Nanos et al. 2002). Water stress can negatively affect both the primary yield components in almond, kernel size (Girona et al. 1993) and fruit load (Goldhamer and Smith 1995; Goldhamer and Viveros 2000; Esparza et al. 2001). The effects of water stress on kernel size depend primarily on the magnitude of pre-harvest stress. However, not all studies report kernel size reductions; Torrecillas et al. (1989), Teviotdale et al. (2001), and Shackel (2002) found that mild to moderate water stress after the onset of hull split had little or no impact on individual kernel dry weight. Fruit load in a given year is reduced by water stress during and immediately after the harvest of the previous year (Goldhamer and Viveros 2000; Esparza et al. 2001). While the former group theorized that this resulted from stress during the reproductive bud differentiation period negatively impacting flower quality, and ultimately fruit set as with apricot (Uriu 1964), the latter researchers suggested that reduced vegetative growth leading to fewer fruiting positions was the mechanism involved. Not all impacts of deficit irrigation in almond are negative. Teviotdale et al. (2001) reported that mild to moderate water stress imposed just after the onset of hull split can significantly reduce hull rot, a fungal disease associated with spur die back. On the other hand, Youngman and Barnes (1986) found that water stress can increase spider mite populations in almond trees.

For growers interested in reducing irrigation inputs or forced to go for deficit irrigation simply because of water scarcity, the question is how to allocate a limited water resource. While the studies identified to date quantified effects of stress timing on production, none evaluated different stress timing strategies for applying given

amounts of seasonally available water. In other words, the water application pattern that results in the most successful production for a given fraction of the seasonal potential water requirements has not been studied. In the study reported here, we tested three RDI patterns, stress biased toward pre-harvest, post-harvest, and a sustained deficit irrigation, all of which applied the same total amount of water for the season for three levels of water availability—55, 70, and 85% of potential seasonal evapotranspiration (ET_c). Emphasis was placed on determining RDI impacts not only on water use, kernel development, and fruit load but also on other factors that determine grower profitability, including harvestability, insect damage, and nut processing qualities.

Materials and methods

This work took place in a commercial almond [*Prunus dulcis* (Mill.) Webb] orchard of 18-year-old cv. 'Nonpareil' and 'Carmel' trees (7.62×7.62 m² spacing) located in northern Kern County, California that had been fully irrigated throughout its history. The soil was a sandy loam (Typic Xeric Torriorthents) with a root zone depth of about 1 m. Only the Nonpareil trees were monitored in this study. The experiment was carried out between 1992 and 1996. From October 1 to September 30, total rainfall for 1992–1996 was 196, 143, 292, and 143 mm, respectively, which fell almost entirely during the winter months.

The orchard was divided into six blocks, each of which contained ten plots. Thus, we had six replicates for each of our ten irrigation regimes (nine RDI regimes and a fully irrigated control). The plots were eight trees long and four rows wide. The middle two rows were Nonpareil and the interior 12 trees of these rows were monitored in this study.

The RDI regimes were designed to apply three different seasonal irrigation amounts (levels), each applied with three different stress timing patterns, hereafter referred to as A–C. The three irrigation levels were projected to be 55, 70, and 85% of applied water required to meet potential seasonal ET_c, which averaged 1073 mm for 1993–1996. The A stress pattern biased the stress to the pre-harvest period, reserving a relatively large percentage of water for post-harvest irrigation. The B pattern did the opposite, biasing the stress to the post-harvest period (applying most water pre-harvest), while the C pattern imposed sustained deficit irrigation by applying water at a given percentage of full ET_c over the entire season. Due to discrete differences in emitter discharge and operating pressures used in the experimental irrigation system design as outlined below, we were unable to apply exactly the same amount of water for the different stress patterns within each level. The A regime always had the least (3–7% less than the mean applied to each irrigation level) while C received the most (4–5% more than the mean applied to each level; Table 1).

Table 1 Regulated deficit irrigation (RDI) treatments and mean applied water for 1993–1995; the three years of the study when both pre-harvest and post-harvest irrigation was relevant

	Percent of Control								
	580A	580B	580C	720A	720B	720C	860A	860B	860C
March 1–15	100	100	55	100	100	70	100	100	85
March 16–31	100	100	55	100	100	70	100	100	85
April 1–15	100	100	55	100	100	70	100	100	85
April 16–30	50	50	55	100	100	70	100	100	85
May 1–15	50	50	55	50	100	70	100	100	85
May 16–31	50	50	55	50	100	70	100	100	85
June 1–15	50	50	55	50	50	70	50	100	85
June 16–30	50	50	55	50	50	70	50	100	85
July 1–15	0	50	55	50	50	70	50	50	85
July 16–31	50	50	55	50	50	70	100	100	85
August 1–15	50	100	55	100	100	70	100	100	85
Harvest									
August 16–31	100	100	55	100	100	70	100	100	85
September 1–15	100	50	55	100	100	70	100	100	85
September 16–30	100	0	55	100	50	70	100	100	85
October 1–15	50	0	55	100	0	70	100	0	85
October 16–31	0	0	55	50	0	70	100	0	85
November 1–15	0	0	55	0	0	70	100	0	85
Mean applied water									
Pre-harvest (mm)	376	457	475	483	546	588	599	707	694
Post-harvest (mm)	191	123	135	212	155	174	201	182	198
Total (mm)	567	580	610	695	702	762	800	888	892
Pre-harvest (% total)	66.3	78.8	77.8	69.5	77.9	77.2	74.8	79.6	77.8
Post-harvest (% total)	33.7	21.2	22.2	30.5	22.1	22.8	25.2	20.4	22.2

The grower/cooperator used microsprinkler irrigation with one, 41.6 l h⁻¹, circular, 3.5 m diameter spray pattern sprinkler located in the row midway between trees. We maintained this system but added additional irrigation laterals to apply our RDI regimes. The deficit irrigation in our system was accomplished by using different combinations of pressure regulators and microsprinkler sizes. Each lateral was equipped with a pressure regulator to insure a high-distribution uniformity of applied water across the experimental area. The grower/cooperator was responsible for irrigation scheduling, which occurred two to three times per week and generally for 24 h periods. Irrigation scheduling utilized estimated orchard ET_c based on published crop coefficients (K_c; Snyder and Pruitt 1989a) and reference evapotranspiration (ET_o; Snyder and Pruitt 1989b) obtained from a California Irrigation Management Information System (CIMIS) weather station located about 15 km from the experimental site.

Fertilizer applications were injected monthly in the irrigation system during the season. The applications were completed within 12 h and during this period, we switched all irrigation laterals to the grower/cooperator's system, thus insuring that all trees received the same amounts of fertilizer.

Predawn leaf water potential (Ψ_{pd}) was measured generally weekly during the irrigation season from 1993 to 1996 using a pressure chamber (Model 3005; Soil Moisture Equipment Co., Santa Barbara, CA, USA). Measurements were taken in a single replication on single leaves on each of three trees per plot in all ten

irrigation regimes. Leaves were placed in the chamber within seconds of excision and precautions recommended by Hsiao (1990) were taken to prevent leaf water loss during measurement.

Beginning in mid-March in 1995 and 1996, fruit samples (four nuts on each of six trees per plot) were randomly collected weekly until harvest. These nuts were dissected into kernels, hulls, and shells and dry weights were determined.

On single days in April–June 1993, the number of spider mites (Acari: Tetranychidae) on ten leaves on each of the 12 monitored trees per plot were counted.

At harvest (usually the second week of August), the 12 monitored trees per replicate plot were shaken mechanically by commercial equipment and the collected nuts were field-dried for about 8 days. The nuts were collected with a commercial pick-up machine and a wagon equipped with load cells was used to determine gross yields. A 2 kg nut sample was collected from each plot. Hull split of each nut in this sample was characterized as full split (more than 50% of the suture line separated), partial split (less than 50% of the suture line separated), or “hull tight” (no evidence of hull split). The kernels were separated from the shells and hulls to determine the kernel percentages of the gross yields. Nut loads were determined by multiplying the gross plot yields by the percentage of kernels in the corresponding 2 kg sample.

To evaluate the effects of the RDI on nut processing, a large (450 kg) sample of each RDI treatment was collected from each of three replications. These samples were transported to a commercial almond hulling

facility where they were individually tracked through the hulling process. We quantified the percentages of the delivered nuts that left the huller as in-shell nuts and kernels, which occurs when the machine removes both the hull and shell. Samples (2 kg) of both in-shell and loose kernels were collected from each replicate and transported to an almond processing facility where they were commercially analyzed for quality. After shaking, the nuts that remained in the trees (“stick tights”) were counted on each of the 12 monitored trees per plot. Stick tights are an issue for the almond industry because they can house Naval Orange Worms over the winter. Thus, they must be manually removed with poles, which is expensive. Scaffold growth was determined on each of the 12 monitored trees per plot by taking the difference in the diameter of a primary scaffold about 1 m above the crotch of the tree from early 1993 to late 1996.

Canopy cover was assessed in early September 1996, using a 1 m light bar (Sunfleck PAR Ceptometer, Model SF-80, Decagon Devices Inc., Pullman, WA, USA). Approximately 240 measurements per tree were taken from 1200 to 1400 h in a grid that encompassed the entire ground area allocated for each tree on each of four trees per plot and the mean sunfleck value determined. The percentage of area shaded by the canopy was calculated as $100 \times (1 - \text{mean sunfleck value/above canopy radiation})$.

Results

Applied water and distribution of stress

Actual applied water for the three RDI treatment levels approximated design objectives of the experiment. For stress patterns A–C, the most severe deficit treatment applied 53–57% (567–610 mm) of potential ET_c from mid-March to early November, the moderate treatment applied 65–71% (695–762 mm), and the mild treatment applied 75–83% (800–892 mm). The control treatment applied an average of 976 mm from 1993 to 1995. When averaged over the three irrigation levels, stress pattern A allocated 70.2% of seasonal applied water to the pre-harvest period compared with 78.8 and 77.6% applied for patterns B and C, respectively (Table 1). There was remarkably little variation in calculated ET_c from year to year. Cumulative seasonal ET_c (1993–1995) varied by less than 2% (Fig. 1a) while cumulative applied water in the control varied by 7% (Fig. 1b), which was primarily due to relatively large differences that occurred near the end of the season.

Predawn leaf water potential

The complete Ψ_{pd} data set is presented in Fig. 2 to allow the reader to directly relate differences in kernel development and fruit load to the timing and magnitude of stress in the various RDI regimes.

Differences in applied water were directly reflected by tree water stress levels. Stress patterns A–C affected the time-course development of tree water deficits with the exception of early in the season. From mid-April to mid-June, Ψ_{pd} ranged from 0.03 to 0.07 MPa for all irrigation regimes (Fig. 2). Thereafter, Ψ_{pd} declined through mid-July in all the RDI regimes. The sharpest decline occurred in 580A, which reached a value of almost -4.0 MPa in mid-July 1993. On the other hand, the pre-harvest declines in Ψ_{pd} for the B and C patterns at the 580 mm level were much less dramatic with mid-July values ranging from only -1.0 to -2.0 MPa (Fig. 2).

In all RDI regimes, significant stress developed prior to harvest but its magnitude depended on both the treatment level of applied water and the stress pattern (Fig. 2). Pre-harvest control Ψ_{pd} generally ranged from -0.4 to -0.8 MPa except for the mid-August harvest when it fell to about -2.0 MPa due to the cessation of watering for 10–12 days to allow for tree shaking, orchard floor nut drying, and nut pickup. In comparison, Ψ_{pd} at harvest for the A pattern regimes declined to between -3.5 and -4.0 MPa (Fig. 2a, d, g). For the B and C pattern regimes, Ψ_{pd} reached -2.5 to -3.5 MPa just prior to harvest (Fig. 2b, c, e, f, h, i). Following harvest in the A pattern treatments for all irrigation levels, Ψ_{pd} recovered to about -0.5 MPa with the exception of 1994 when a system breakdown interrupted irrigation and caused a mid-September Ψ_{pd} drop in all treatments with the notable exception of 580A (Fig. 2a), which had partially defoliated by this time. For the B stress patterns, Ψ_{pd} recovered temporarily to values similar to the A patterns but then declined again in response to less applied water. In 580B, Ψ_{pd} reached -3.5 MPa in early October during the last 2 years of the experiment (Fig. 2b). The same stress pattern resulted in higher Ψ_{pd} values in 720B and 860B that did not exceed -1.5 MPa at the end of the season (Fig. 2e, h). The post-harvest Ψ_{pd} values for the C pattern generally ranged between the A and B patterns (Fig. 2c, f, i).

Fruit dry matter accumulation

The evolution of 1996 dry matter accumulation in the nut components is presented in Fig. 3 for all nine RDI regimes and the control. The data for 1995 (not shown) were very similar. Kernel growth started in mid-March and grew very slowly until mid-May, when the growth rate accelerated until mid-July (1 month before harvest) when the kernels achieved near full size. Kernel growth was reduced beginning in late June in the A stress pattern at the 580 and 720 mm levels while it was much less affected by water deficits in the B and C regimes (Fig. 3a, c). At the 860 mm level, there was little difference in kernel growth with time between the stress patterns (Fig. 3e). The A pattern pre-harvest water deficits had much more impact on the growth of the hull and shell than on the kernel (Fig. 3b, d). The hull and shell dry matter accumulation rate peaked in mid-May

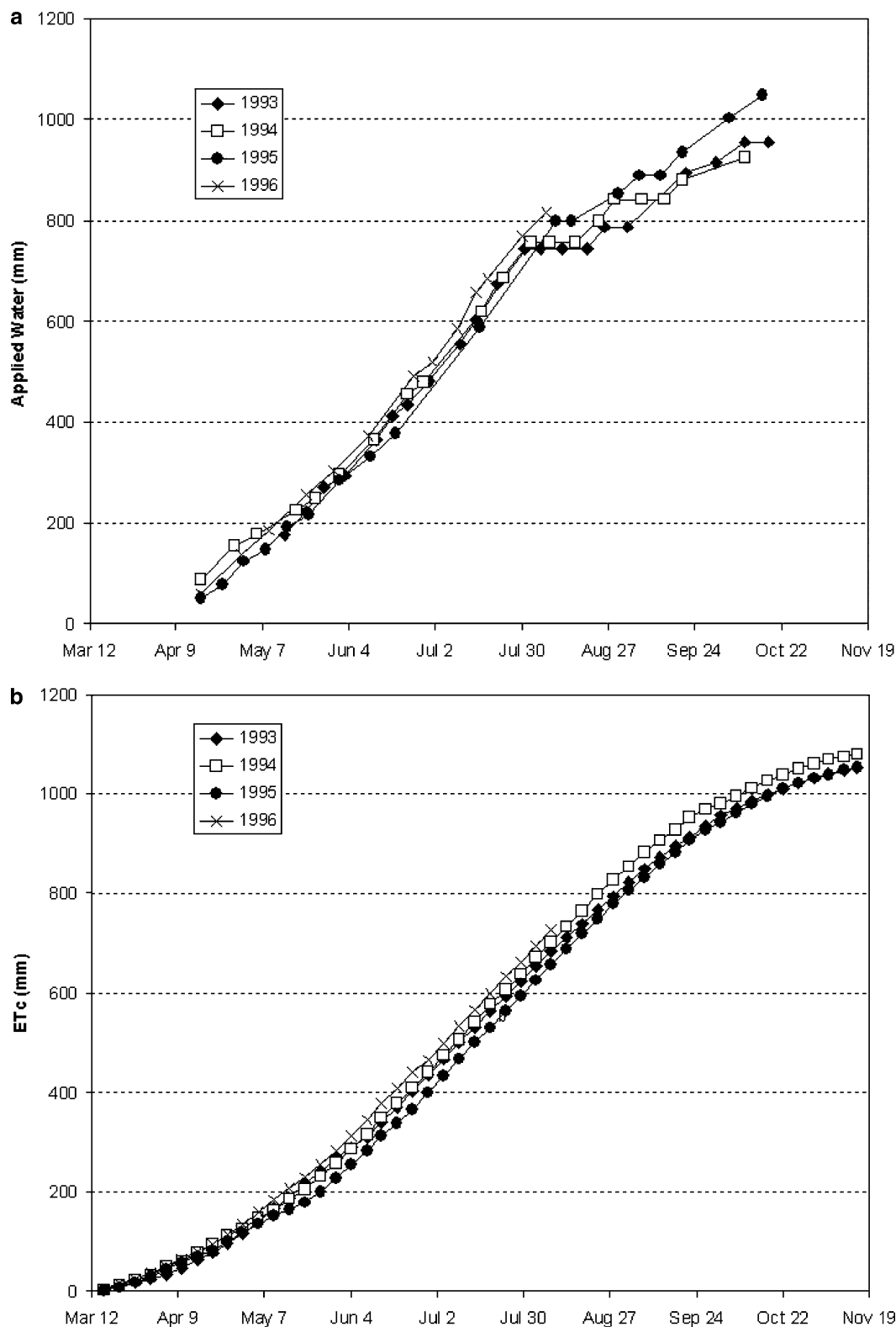


Fig. 1 For each year of the study, **a** applied water, and **b** estimated evapotranspiration (ET_c)

and then generally continued at a slower rate through harvest (Fig. 3b, d, f). Hull and shell growth were reduced in 580A and 720A earlier in the season and to a

greater degree than kernel growth. In 580A, the growth of the hull plus shell stopped around mid-June (Fig. 3b) while it continued, albeit at a reduced rate, in 720A

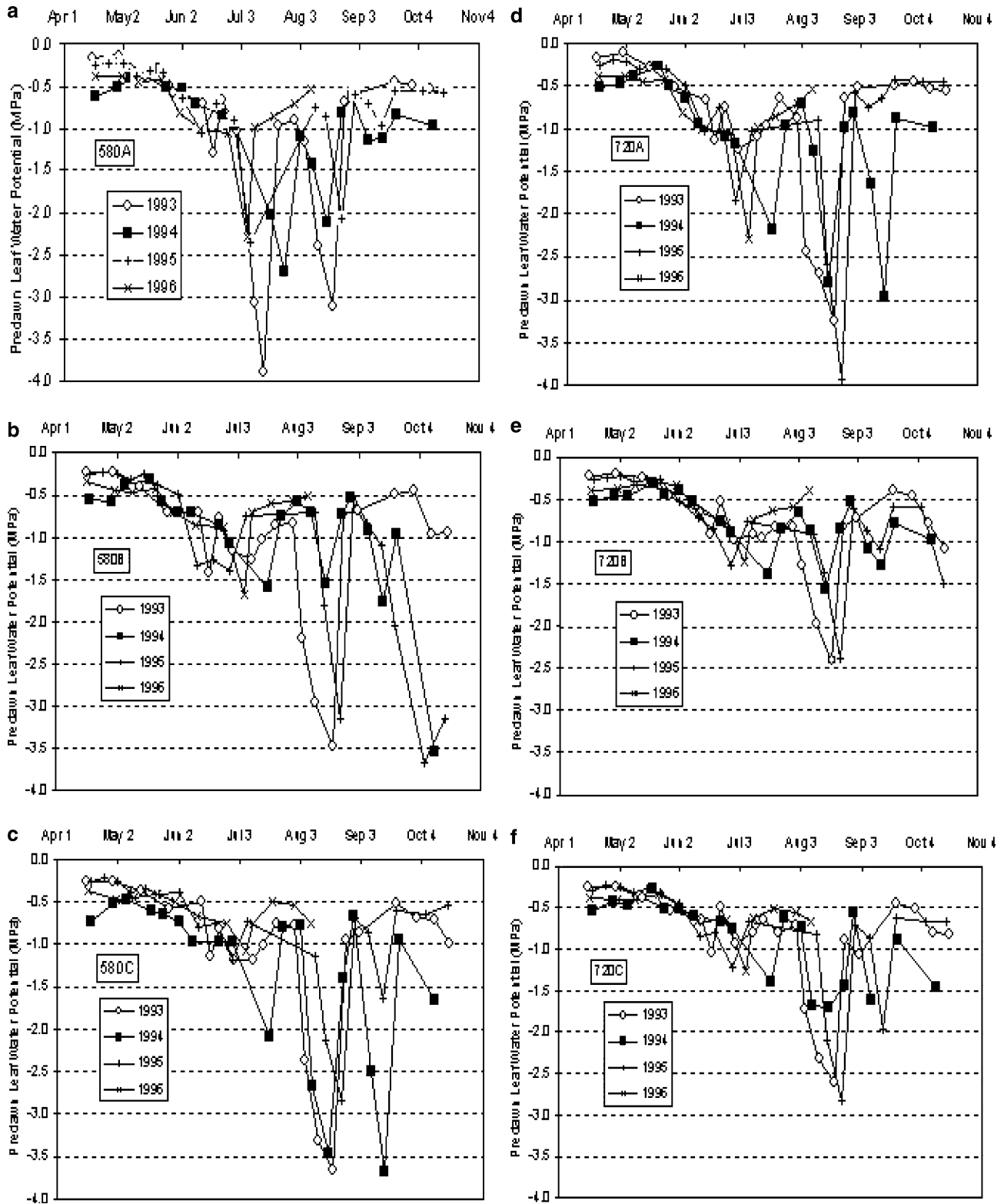


Fig. 2 Predawn leaf water potential for each irrigation regime and year of the study

relative to the equivalent B and C stress patterns (Fig. 3d). There were no differences in either kernel or hull plus shell growth between the B and C patterns, even at the 580 mm level (Fig. 3a, c, e).

Yield and yield components

Kernel yields were affected by both the level of applied water and the stress timing patterns. At the 580 mm

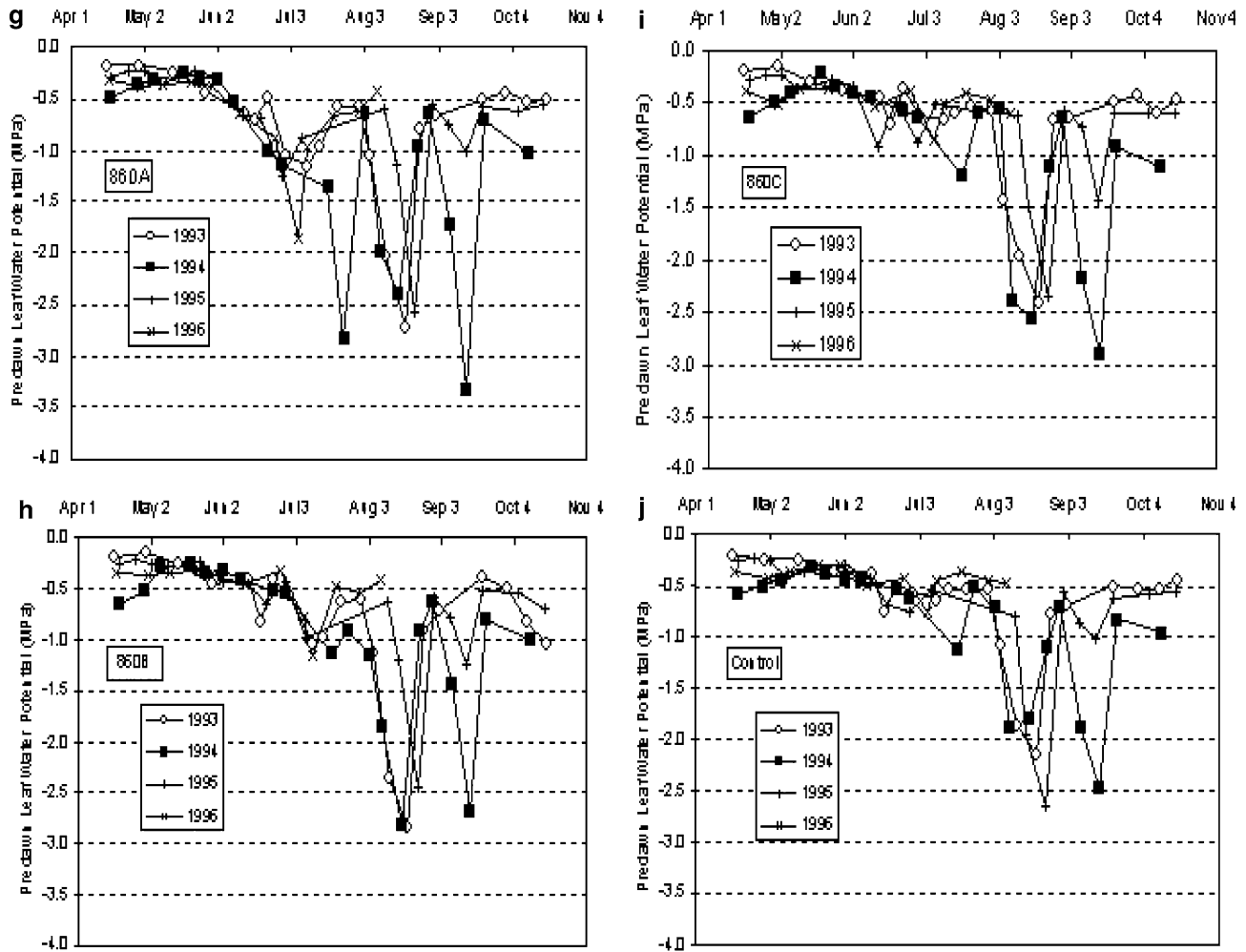


Fig. 2 (Contd.)

level, kernel yield (dry weight) for the 4 years of the study averaged 1754, 1480, and 1827 kg ha⁻¹ for the A–C patterns, respectively; all significantly lower than the control yield of 2099 kg ha⁻¹ (Table 2). Yields of 720A (1849 kg ha⁻¹) and 720B (1757 kg ha⁻¹) were also significantly less than the control while the yield of 860A (1839 kg ha⁻¹) was the only one of the three timing patterns at that applied water level that was significantly lower than the control. As for the impact of the stress patterns, yields of 580B were significantly lower than those of both 580A and 580C (Table 2). A similar response occurred at the 720 mm level but was not statistically significant. The yield response of the A regime was insensitive to the level of applied water; the yields at the 580, 720, and 860 mm levels did not differ significantly, albeit all being significantly lower than the control (Table 2). With the C pattern, only the 580 mm level was significantly lower than the control. Irrigation water productivity (IWP) differed considerably among treatments, exhibiting a decreasing trend as applied water increased (Table 2). The highest IWP occurred in 580A (0.311 kg m⁻³) and the lowest in the control

(0.216 kg m⁻³). All stress timing patterns had significantly higher IWP at the 580 and 720 mm levels than the control as opposed to none at the 860 mm level.

The yield response was directly tied to the reaction of the two yield components of almond production (nut load and nut size) to the levels of applied water and to the stress patterns. For every level of applied water, kernel weight was significantly reduced in the A pattern relative to the B and C patterns. Kernel weights of the 580 and 720 mm applied water levels were significantly less than that of the control regardless of the timing pattern, whereas it did not differ from the control in the 860B and 860C treatments. Kernel weight was significantly lower in the A than in the B and C patterns for all timing patterns. Moreover, the A patterns for all irrigation levels had lower fractions of dry matter in the nut allocated to the kernel than in the B and C patterns, indicating the greater sensitivity of kernel growth relative to shell growth in the RDI scenarios that biased the stress period to pre-harvest (Table 2).

The B stress patterns had a strong negative impact on fruit load relative to the A patterns at the 580 and

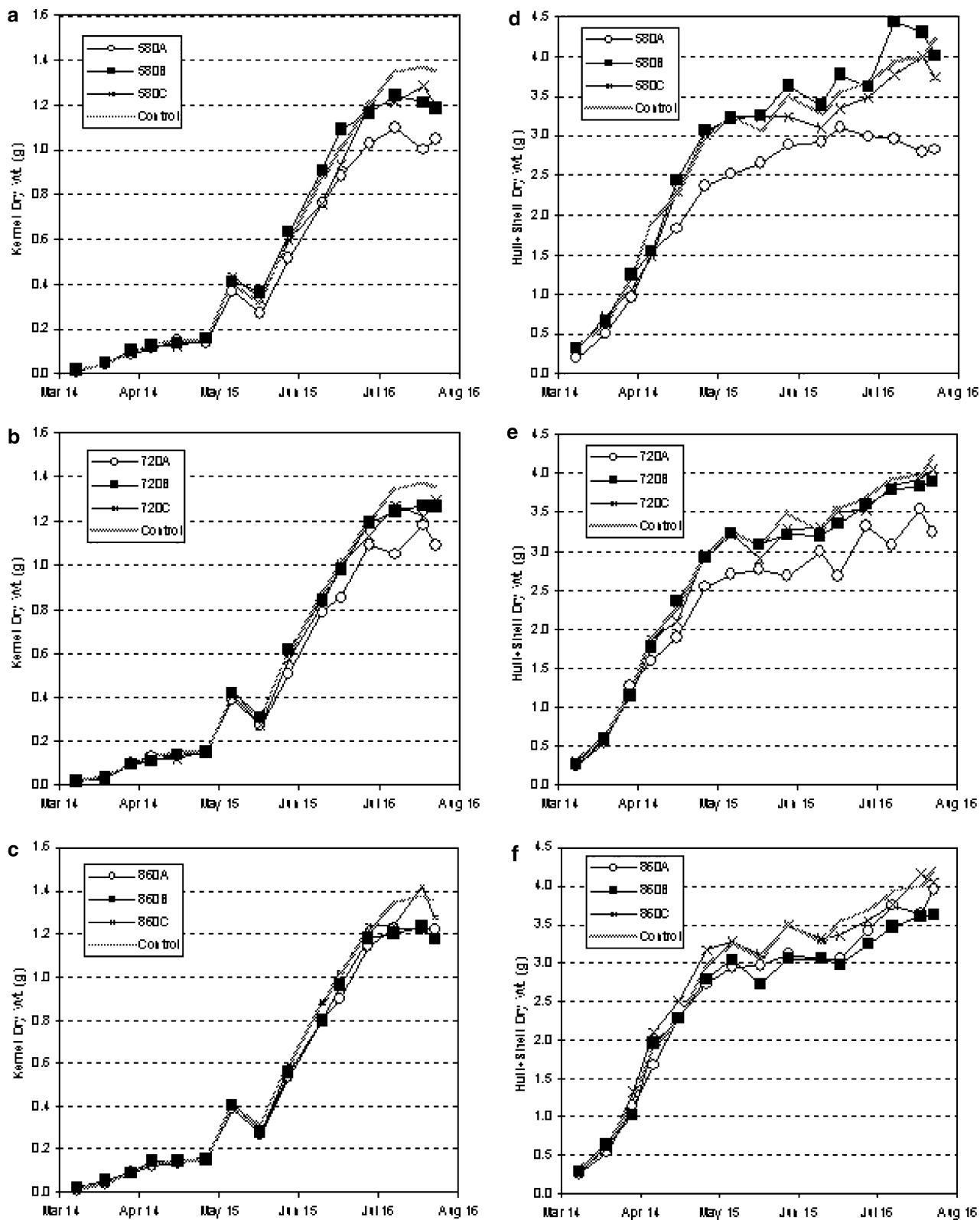


Fig. 3 Dry matter accumulation in the kernels and hulls plus shells for each RDI regime. Control values are shown for comparison

720 mm levels of applied water (Table 2). At the 860 mm level, there was no significant reduction of crop load due to a bias toward post-harvest stress. No

differences in crop load were observed among the A and C regimes for all three levels of applied water relative to the control.

Table 2 Yield, yield components, tree growth, canopy size, and fruiting density

Irrigation regime	Kernel weight (g/kernel)	Kernel/kernel + shell (%)	Fruit load (No./tree)	Kernel yield (kg ha ⁻¹)	Irrigation water productivity (kg m ⁻³)	Scaffold X.S. Area growth (cm ²)	Shaded area ^a (m ² /tree)	Fruiting density (nuts m ⁻²)
580A	1.08 a*	0.662 abc	9550 bc	1754 b	0.311 a	36.9 ab	26.5 a	305 d
580B	1.16 b	0.672 bcd	7590 a	1480 a	0.256 b	34.7 ab	27.8 ab	192 a
580C	1.16 b	0.667 abc	9300 bc	1827 bc	0.301 a	32.7 a	32.0 bcd	227 abc
720A	1.09 a	0.655 a	9910 c	1849 bc	0.267 b	39.4 ab	31.0 abc	283 cd
720B	1.20 bc	0.662 abc	8630 ab	1757 b	0.251 bc	43.4 abc	30.7 abc	225 ab
720C	1.22 cd	0.670 bc	9130 bc	1911 bcd	0.252 bcd	41.4 ab	30.6 abc	250 bcd
860A	1.17 b	0.659 ab	9260 bc	1839 bc	0.231 cde	46.7 bcd	30.5 abc	262 bcd
860B	1.26 de	0.675 cd	9060 bc	1951 bcd	0.221 e	54.4 cd	31.9 abcd	249 bcd
860C	1.28 e	0.675 cd	9130 bc	2008 cd	0.226 de	55.0 cd	34.8 cd	230 abc
Control	1.30 e	0.684 d	9400 bc	2099 d	0.216 e	59.1 d	36.6 d	214 ab

Values are means from 1993 to 1996 inclusive unless otherwise noted

*Values not followed by the *same letter* are significantly different using Fisher's least significant difference method; $P=0.05$

^a Based on September 6 1996 light interception measurements

The carry-over effects of water deficits from year to year on kernel weight and fruit load relative to the control are shown in Fig. 4. In 580A and 720A, nut load tended to increase with time while kernel weight remained uniformly below control values (Fig. 4a, d). In contrast, 580B nut load declined with time (Fig. 4b) and a similar, albeit more modest, response was observed in 720B (Fig. 4e). With the C patterns, there were fluctuating nut loads and to a lesser extent, kernel weights, at the 580 mm level, whereas these primary yield components were remarkably stable at the 720 and 860 mm levels.

Vegetative growth and fruiting density

The cumulative effects of reduced water application were evidenced by significant changes in vegetative growth parameters (Table 2). Scaffold growth did not differ among stress patterns in any of the three irrigation levels. At the 580 and 720 mm levels, scaffold growth over the four experimental years averaged 34.8 and 41.4 cm², respectively, across all timing patterns compared with 59.1 cm² for the control. The 860 mm irrigation did not result in reduced scaffold growth regardless of the stress timing pattern (Table 2). While tree canopy size at the end of this 4-year study was also proportional to the applied water level, there were some differences among stress patterns. Canopy shading of the orchard floor with the A stress pattern was 26.5, 31.0, and 30.5 m² for the 580, 720, and 860 mm levels of applied water, respectively—all significantly smaller than the 36.6 m² canopy in the control. The B pattern also generally had reduced canopy size relative to the control for all irrigation levels while the C pattern generally had the least impact on canopy size. At the 580 and 720 mm levels of applied water, it is important to note that the smaller tree canopies with the A pattern occurred without any impact on fruit load, resulting in a significantly higher fruiting density (305 and 283 nuts m⁻², respectively) for these treatments relative to the

control (214 nuts m⁻²). The fruiting densities of B and C patterns did not differ from the control in all other RDI regimes. However, there were large differences within given irrigation levels. For example, 580B had a fruiting density 37% lower than 580A.

Hull splitting, harvestability, and mite pressure

Several features related to the harvest process and factors that influence crop marketability are shown in Table 3. These include hull split at harvest, hull split measured during the season, stick tights (nuts that remain in the tree after mechanical shaking), and mite levels in the tree during the season. At harvest, 580A was the only RDI scenario that had a significantly lower percentage of full hull split nuts than the control (95.8% vs. 98.4%, respectively). On the other hand, the same A pattern but with 720 and 860 mm of applied water resulted in a significantly higher percentage of full hull split nuts at harvest relative to the control (99.5 and 99.6% for the RDI regimes, respectively). Not surprisingly, 580A had a higher percentage of hull tight nuts (adhering hulls) at harvest but 720A and 860A both had significantly lower hull tights than the control.

Data taken on July 12, 1996 show how stress timing could either accelerate or delay the onset of hull split. At the 580 mm level of applied water, 9.7 and 98.6% of the nuts had fully split hulls in the A and B patterns, respectively. At the same time, 70.9% of the control nuts had fully split hulls. The lowest level of applied water (580 mm) significantly reduced the number of stick tight nuts, averaging 1.2% of the tree nut load for the three different stress timing regimes compared with 2.55% for the control. In fact, there was a 64% reduction in stick tights with 580A relative to the control. None of the RDI regimes caused an increase in stick tights. During a representative period of the season (April–June 1993), no significant differences were observed in spider mite populations among all ten irrigation regimes (Table 3).

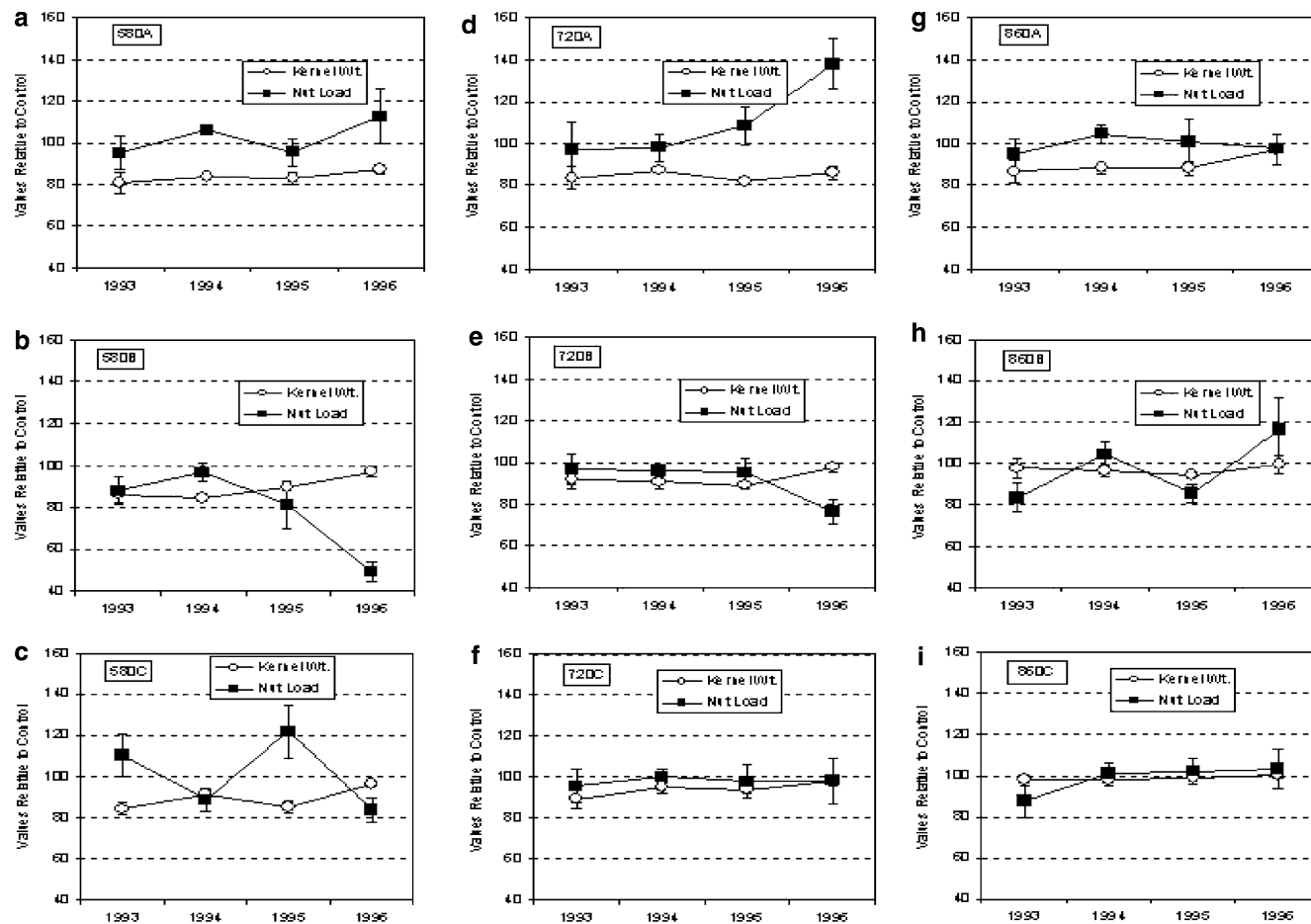


Fig. 4 Kernel weight and fruit load expressed relative to the control for each RDI regime and year of the study

In 1994, a commercial assessment of the hulling properties of harvested nuts was conducted at a commercial hulling facility (huller) to quantify the impacts of RDI on different measures of kernel quality and thus, farm profits (Table 4). There were only minor impacts

on huller turnout on in-shell nuts (percent of delivered nuts that were successfully hulled). However, the turnout of kernels at the huller (inadvertent removal of shells by the hulling equipment) was significantly lower in 580A, 580B, and 720A relative to the control. As found

Table 3 Hull split, sticktight, and mite data

Irrigation regime	Full hull split nuts (% by No.)	Partial hull split nuts (% by No.)	Hull tight nuts (% by No.)	Mid-July ^a full hull split (% by No.)	Sticktight ^b (% fruit load)	Mites ^c (No./leaf)
580A	95.8 a*	2.06 a	2.15 d	9.7 a	0.91 a	0.115
580B	99.3 cd	0.15 b	0.51 ab	98.6 e	1.28 ab	0.085
580C	99.5 cd	0.15 b	0.38 a	95.8 e	1.42 ab	0.152
720A	99.5 cd	0.12 b	0.39 a	93.1 e	1.72 abc	0.120
720B	99.2 bcd	0.15 b	0.63 abc	86.1 de	1.64 abc	0.162
720C	99.3 cd	0.14 b	0.54 abc	87.0 de	2.12 bcd	0.103
860A	99.6 d	0.07 b	0.36 a	80.6 cde	2.81 d	0.055
860B	99.3 bcd	0.11 b	0.60 abc	47.2 b	2.51 cd	0.203
860C	98.6 bc	0.51 b	0.85 bc	61.1 bc	2.77 d	0.082
Control	98.4 b	0.68 b	0.93 c	70.9 cd	2.55 cd	0.237 NSD ^d

Values are means from 1993 to 1996 inclusive unless otherwise noted

*Values not followed by the same letter are significantly different using Fisher's least significant difference method; $P=0.05$

^a July 12, 1996

^b Nuts remaining in tree after shaking; 1993, 1995 only

^c Sum of monthly measurements; April–June 1993

^d No statistically significant differences

Table 4 Selected commercial hulling and shelling data; 1994 only

Irrigation regime	Huller turnout in-shell nuts (% delivered wt.)	Huller turnout kernels (% delivered wt.)	Huller ratio kernel/ in-shell nuts	In-shell nut hull tights (% by wt.)	In-shell nut kernels (% by wt.)	In-shell nut NOW kernels (% by wt.)	In-shell nut chipped and broken kernels (% by wt.)	Loose damaged kernels (% by wt.)
580A	29.7 b*	5.54 a	18.6 a	22.1 a	67.7 a	0.133	0.000 a	4.46 ab
580B	26.5 ab	4.97 a	18.8 ab	2.9 b	69.4 bc	0.110	0.585 b	2.65 a
580C	27.1 ab	6.24 ab	23.2 abc	3.1 b	70.4 cd	0.133	0.133 a	3.70 a
720A	27.3 ab	5.44 a	19.9 ab	2.3 b	69.0 b	0.093	0.233 a	5.48 ab
720B	29.0 b	6.68 ab	23.1 abc	4.4 b	68.5 ab	0.123	0.063 a	3.09 a
720C	27.0 ab	6.01 ab	22.2 abc	2.5 b	70.3 cd	0.097	0.100 a	5.00 ab
860A	25.8 a	6.18 ab	24.1 abc	3.0 b	69.0 ab	0.037	0.113 a	1.82 a
860B	25.0 a	7.41 b	30.5 c	4.4 b	70.5 cd	0.100	0.043 a	5.58 ab
860C	27.3 ab	7.57 b	27.8 bc	4.0 b	70.5 cd	0.067	0.017 a	4.62 ab
Control	27.3 ab	7.57 b	28.2 bc	5.2 b	71.0 d	0.083 NSD ^a	0.240 a	8.46 b

Values not followed by the *same letter* are significantly different using Fisher's least significant difference method; $P=0.05$

^a No statistically significant differences

earlier in our harvest analysis of hull splitting, 580A hull tights were significantly higher than all the other irrigation treatments. The kernel percentage of the in-shell nuts was significantly smaller than the control in all the A patterns regardless of the level of applied water and in the B patterns of the 580 and 720 mm levels. None of the C pattern in-shell kernel percentages differed from the control. In only one case (580B) was in-shell kernel damage due to chipping and breaking at the processor greater than the control. In contrary, loose kernel damage after commercial processing was significantly lower than the control in all RDI regimes (Table 4). Commercial analysis revealed no differences in NOW damage of the processed kernels.

Discussion

Applied water levels covered a range from 53 to 83% of the crop water requirements that averaged 1073 mm for the study period. Given the combination of low soil water storage capacity, which we estimate at no more than 110 mm, and high evaporative demand, the contribution of stored soil water and minimal rainfall during the irrigation season was insufficient to meet the full potential ET_c requirements of even the 860 mm treatment level, as evidenced by modestly lower Ψ_{pd} relative to the control at certain times of the season for all stress patterns (Fig. 2g–j). No attempt was made to estimate actual ET_c using a soil water balance approach given the spatial variability of root distribution, soil moisture extraction, and water application patterns of the microsprinklers.

While kernel yields were generally lower when seasonal applied water was reduced, the overall impact on yield in many of the RDI regimes was modest. A 45% reduction of applied water relative to potential ET_c in 580C effected a yield reduction of only 13%. In 720C, 860B, and 860C, yield was not significantly different from the control despite reductions of applied water that ranged from 17 to 29% of potential ET_c . This deviation

from the classical 1:1 functional relationship between crop production and water use is consistent with the findings in almond of Prichard et al. (1993), Girona et al. (1993), Goldhamer and Smith (1995), and Goldhamer and Viveros (2000). The limited yield decline coupled with the appreciable reduction in applied water combined to generate substantial increases in IWP for the RDI regimes relative to the control. As found in the olive (Moriani et al 2003), the first increment of applied water in this experiment produced the greatest yield increase. Thus, the IWP at the 580 mm level was the highest followed by the 720 and 860 mm levels and the control (Table 2).

While some of the RDI regimes showed an insensitivity of yield to reduced water use, the fact that others had more marked responses illustrates the importance of water application patterns on production. In patterns A and B, relatively small differences in the proportion of the total amounts applied pre- and post-harvest had large impacts on production. Post-harvest water deficits in the B patterns of the 580 and 720 mm levels impacted most negatively on crop load (Table 2) while the pre-harvest stress of pattern A reduced kernel weight more than B and C for all three irrigation levels. In contrast, 860B, which had an average of 182 mm of post-harvest applied water against 123 and 155 for 580B and 720B, respectively, did not have reduced nut loads relative to the control (Table 2). This shows how small amounts of water applied at stress-sensitive periods can ameliorate negative impacts.

It appears that even mild water deficits before harvest, such as those imposed by 860A where July Ψ_{pd} was about 0.5 MPa lower than the control (Fig. 2g), have a negative impact on kernel weight and thus, production. It must be noted that smaller kernels not only reduce yields for a given fruit load but processors pay less for smaller fruit; each of five or so kernel size categories is worth about 5% less than the next largest size. Other trends in Fig. 4 can be explained by the often-observed compensation between fruit size and fruit load (Ferreles and Goldhamer 1990).

We believe that the lower fruit loads observed with the B stress patterns at the 580 and 720 mm irrigation levels involve the well-documented late flower bud differentiation in almond relative to other fruit and nut crops (Tufts and Morrow 1925; Lamp et al. 2001). With apricot, which also has relatively late floral bud differentiation, Uriu (1964) found that post-harvest water deficits reduced the following season's fruit load, which he attributed to flower bud-related stress. With cv. Nonpareil, the bulk of floral differentiation occurs post-harvest, especially in the southern part of the San Joaquin Valley and Lamp et al. (2001) suggest that avoidance of Nonpareil post-harvest water stress during critical stages of flower development is essential in order to avoid reduction in the following year's crop. This observation is supported by the work of Goldhamer and Viveros (2000) who found that post-harvest Ψ_{pd} values in the -2.5 to -3.5 MPa range significantly reduced fruit set. On the other hand, Esparza et al. (2001) proposed that reduced fruit loads following water stress during and immediately after harvest was due to fewer fruiting positions resulting from reduced vegetative growth. These researchers reported midday stem water potential (Ψ_{ms}) that reached a minimum of -2.6 MPa during the harvest stress period. Work in the same orchard (Klein et al. 2001) found a strong correlation between Ψ_{pd} and Ψ_{ms} and using that relationship results in an equivalent Ψ_{pd} of -1.2 MPa. It should be noted that Ψ_{pd} in 580B was about -3.5 MPa for two of the three experimental years while 720B ranged from -1.0 to -1.5 MPa. Thus, there may be a threshold value of tree stress (-1.5 MPa for Ψ_{pd} and -2.8 MPa for Ψ_{ms}) during the floral bud differentiation period that should not be exceeded to avoid fruit set problems, and thus, fruit load reductions.

The carry-over effects of stress on the yield components suggest that the negative impact of post-harvest stress is amplified as time goes on (Fig. 4). The other interesting response is the increase in fruit loads with time in treatments 580A and 720A; an apparent beneficial long-term adjustment of those treatments to periodic pre-harvest stress. The dramatic increase in fruiting density observed in 580A and to a lesser extent, 720A (Table 2), somewhat offsets the lower kernel sizes in these RDI regimes. Coupling the higher fruiting densities with the smaller canopy sizes in these treatments offers growers the possibility of exploiting these observations to possibly increase yields while consuming less water. This would be accomplished by planting to a higher tree density enabled by the smaller, RDI- rather than pruning-controlled, tree canopies thus potentially producing more, albeit smaller, nuts per ha. For example, if kernel size and value was cumulatively reduced by 15% due to the pre-harvest stress but planting density was increased by 20%, not only kernel yield but also grower revenue would be increased.

In addition to exploiting the higher fruiting densities observed in 580A and 720A toward greater crop yields, the reduced vegetative growth and smaller tree canopies

of these treatments suggest that the amount of pruning would be less. This would reduce the amount of pruned wood and help alleviate air quality degradation resulting from the current disposal practice of burning. This change in pruning practice is supported by research that suggests that traditional pruning can be reduced without negative effects on sustained almond orchard productivity (Castro and Jimenez 2002; Edstrom and Krueger 2000). As suggested by Jerie et al. (1989), maintaining compact canopies required for high-density orchard using RDI is preferable to pruning since the latter actually stimulates vegetative growth.

Accelerated hull splitting resulting from pre-harvest stress could allow the kernels to dry earlier and/or more completely on the tree rather than on the ground. This could result in either an earlier harvest or reduction of the time required for drying on the orchard floor. That would lessen the possibility of fruit contamination from soil-borne bacteria such as salmonella, ant damage (Zalom and Bentley 1985), and result in a more timely completion of all harvesting operations, minimizing the irrigation cessation time during the stress-sensitive period at and immediately following harvest (Esparza et al. 2001).

Among the three stress patterns for a given level of applied water tested in this study, the uniform/sustained strategy C was most effective in terms of crop yields (Table 2). With the 580 and 720 mm irrigation levels, pattern C had the highest yields of the three stress patterns evaluated, even though differences between patterns were not statistically significant. At the 720 mm level, the C pattern was the only regime that did not differ from the control (Table 2). There may be several reasons for the advantage of the C pattern. One is that it avoids severe stress during both pre- and post-harvest relative to the A and B patterns (Fig. 2). Avoidance of severe stress in almonds seems highly desirable for a crop where nut size is determined before harvest and nut load is determined after harvest. The slower development of stress in pattern C may maximize tree adaptation to water deficits, known in almond to include stomatal and osmotic adjustment and hastened leaf senescence (Castel and Fereres 1982). Nevertheless, it cannot be ruled out that the small differences in applied water in favor of C relative to the other stress patterns in each irrigation level may have also had a positive impact on yield. Also, the 100% ET_c irrigation rates in the A and B patterns early in the season (Table 1) may have resulted in some deep percolation. Thus, the effective applied water that went into tree transpiration may have been higher for the C pattern than for A and B, although this is not evident in the Ψ_{pd} data (Fig. 2).

The low buffering capacity of the soil caused sharp declines in Ψ_{pd} in very short time periods (Fig. 2). Values approached -4.0 MPa in many RDI regimes numerous times during the experiment. Even in the control, Ψ_{pd} reached -2.5 MPa when watering was interrupted for harvest operations (Fig. 2j). In general, the time-course development of Ψ_{pd} matched applied

water and helps explain the impact of stress on the yield components. For example, the low nut load values of 580B may be associated with the very low Ψ_{pd} (-3.5 MPa) that occurred in the fall of 1994 and 1995 in 580B but not in 580A and C (Fig. 2a–c). The stress that 580A and 720A underwent prior to harvest was well quantified by the Ψ_{pd} values (Fig. 2a,d) relative to the values experienced by the equivalent B and C regimes at that time. Interestingly, Ψ_{pd} in 860A was much more negative prior to harvest (1994; Fig. 2g) than in the 860B and C only in one year (Fig. 2h,i). That was sufficient to reduce kernel weight significantly in that 860A regime and it is consistent with the relatively high sensitivity of kernel size to pre-harvest stress (Girona et al. 1993; Goldhamer and Smith 1995; Goldhamer and Viveros 2000).

Many of the RDI regimes, especially those with the A and B stress patterns, reduced canopy size (Table 2). The sensitivity of vegetative growth to water deficits is well known (Hsiao 1973; Urui et al. 1970). The increase in fruiting density that pre-harvest stress induced in A was not found in the other B and C regimes, and points to a shift in harvest index, commonly observed in some herbaceous crops in response to water deficits, e.g., in cotton (Orgaz et al. 1992). The time-course fruit development monitored in 1996 was affected by the stress patterns and to a lesser extent, the irrigation levels. In 580 and 720A, the dry matter accumulation in the hull plus shell slowed down very early relative to all other stress patterns (Fig. 3b, d). However, the reduction in kernel growth occurred later and was less pronounced indicating that accumulation of dry matter in the kernel took precedence over the growth of the other nut components. The lack of kernel damage during commercial nut processing (mechanical hulling and shelling) as a result of any of the RDI regimes relative to the control removes this as a concern for possible grower adoption. Since water stress has been reported to increase spider mite levels in almond trees (Youngman and Barnes 1986), the fact that this did not occur in our study may be due, in part, to the effective standard pesticide program used by the grower/cooperator.

From a practical perspective, almond growers with limited water supplies must balance potential yield reductions due to pre-harvest stress impacts that reduce kernel size and post-harvest stress that lowers fruit load in the following season. For all irrigation levels tested in this study, the best yields were achieved when water application occurred at a uniform rate relative to potential ET_c over the entire season (stress pattern C). However, the important finding that relatively high pre-harvest stress (A patterns) can increase fruiting density and reduce tree canopy size holds promise for their exploitation in orchards planted to higher tree densities. We believe that these changes in water management and horticultural practices could lead to higher fruit yields while reducing the consumptive use of water, with the added benefit of reduced pruning.

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