

## Effects of irrigation deprivation during the harvest period on yield determinants in mature almond trees

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**Summary** Effects of irrigation deprivation during the harvest period on yield determinants in mature almond (*Prunus dulcis* (Mill.) D.A. Webb cv. Nonpareil) trees were investigated during a 3-year field experiment. Return bloom and fruit set were measured on 2185 individually tagged spurs. Water stress resulting from irrigation deprivation during the harvest period, which purportedly coincides with the time of flower initiation, had no effect on the percentage of spurs that flowered or set fruit during subsequent years. Although water stress had no apparent effect on spur mortality, 66% of the tagged spurs died within 3 years. In addition, many spurs were vegetative by the third year, indicating the importance of spur renewal for sustained fruit production. Reductions in nut yield were evident after two successive years of irrigation deprivation during the harvest period. Regression analysis indicated a loss in yield of 7.7 kg tree<sup>-1</sup> in response to each 1 MPa decrease in stem water potential below -1.2 MPa during the previous seasons. The number of fruiting positions per tree (estimated indirectly for whole trees based on weight of current-year shoots > 5 cm in length) was negatively associated with water stress. Yield reduction in response to water stress during harvest appears to be a compound, multiyear effect, associated with reduced annual growth and renewal of fruiting positions.

*Keywords:* crop yield, fruit set, *Prunus dulcis*, water stress.

### Introduction

Commercial harvesting in almond (*Prunus dulcis* (Mill.) D.A. Webb cv. Nonpareil) orchards in California is a highly mechanized, multistep process usually occurring during August and September. Irrigation is intentionally cut off prior to harvest, to prevent trunk damage during the mechanical shaking operation (Fridley et al. 1970). Because of the harvest operations and the interplanting of pollenizers that mature later than cv. Nonpareil, resumption of irrigation after the harvest period is often delayed and consequently results in tree water stress (Klein et al. 2001), especially in large orchards growing under conditions of high summer evaporative demand, such as in the southern San Joaquin Valley, CA. Irrigation deprivation peri-

ods of 35 days, and even longer, are common and frequently result in premature defoliation as well as tree water stress.

Timing, magnitude and duration of water stress, as well as species, influence tree responses to water stress (Brown 1953, Chalmers et al. 1981, 1986, Lampinen et al. 1995). Although almond is considered a drought-tolerant crop, almond production can be severely limited under either dry-land farming or continuous, seasonal, severe water stress, especially if trees are young and the stress persists (Castel and Fereres 1982, Torrecillas et al. 1989, Girona et al. 1993, Hutmacher et al. 1994).

Almond yield is a function of the number of nuts per spur or shoot, determined by flowering, pollination and fruit set; the number of fruiting positions, determined by growth and mortality of spurs and shoots; and nut weight (Kester et al. 1996). Reductions in flowering, fruit set, and ultimately yield, have been associated with water deprivation during previous post-harvest periods in almond trees growing in shallow soils (Goldhamer and Shackel 1990). Almond productivity may also be vulnerable to water stress during the harvest period, because flower initiation (for the subsequent crop year) also occurs during late August–early September (Tufts and Morrow 1925, Brooks 1940).

It is important to consider long-term effects of water stress for spur-bearing species such as almond, because spurs formed in one year produce fruit during the following years. Kester et al. (1996) proposed that water stress reduces vegetative growth and therefore potential fruiting positions, which determine future cropping potential. Recently, Klein et al. (2001) reported that irrigation deprivation during the harvest period results in significant tree water stress (midday stem water potentials typically between -1.8 and 2.7 MPa) with associated reductions in leaf CO<sub>2</sub> assimilation, leaf stomatal conductance and canopy light interception. However, the impacts of irrigation deprivation during harvest on the factors and components that determine subsequent and future cropping of mature almond trees have not been evaluated.

Our objective was to determine the yield and bearing characteristics of mature almond trees subjected to water stress during the harvest period. Specifically, we examined the link-

age between fruit yield and water stress during the harvest period and how yield is affected by the multiyear dynamics of vegetative growth and spur longevity.

## Materials and methods

### Experimental site

The experimental site has been described in detail by [Klein et al. \(2001\)](#). Briefly, an irrigation experiment was initiated in 1995 in an almond (*P. dulcis* cv. Nonpareil grafted on *P. persica* L. Batsch cv. Nemaguard rootstock) orchard in the arid San Joaquin Valley at the Paramount Farming Company, Shafter, CA (35°N, 117°E). Mean annual precipitation at the site is 162 mm, confined to winter months. The normal yearly evapotranspiration ( $ET_0$ ) for grass at the location is 1110 mm for March–October. The experiment was carried out in a 7-year-old (in 1995), high-yielding orchard, planted at a spacing of 6.4 × 7.9 m in a quincunx design with rows oriented north–south and irrigated by microjets. The canopy was fully developed when the experiment started, intercepting 73% of daily radiation, measured before harvest in 1995. The orchard comprised rows of *P. dulcis* cv. Nonpareil (50%) planted alternately with pollenizer rows of cv. Monterey (25%) and cv. Price (25%). All measurements were made on cv. Nonpareil trees. Treatments were applied in a complete randomized block design with four replicates, each replicate representing a 17-tree row.

### Irrigation treatments

The irrigation treatments were applied during the almond harvest period of three consecutive years (1995–1997). Three treatments were evaluated: (1) FI = full irrigation (based on full crop evapotranspiration demand); (b) MS = moderate stress; and (3) SS = severe stress. Because the trees withstood stress better than expected during the first year, a second, more severe stress treatment (SS2) was included in 1996 and 1997. The irrigation treatments were applied during August 1–September 4, August 6–September 22 and July 31–September 23, respectively, for 1995, 1996 and 1997. The irrigation cut-off period (days), number of irrigations withheld, and  $ET_0$  (mm) during these periods were: 18, 2, and 118 (MS, 1995); 35, 5, and 219 (SS, 1995), 18, 1, and 119 (MS, 1996); 47, 6, and 271 (SS, 1996); 20, 1, and 123 (MM, 1997); and 53, 5, and 283 (SS, 1997). Water was applied every 3–7 days in the FI treatment. The irrigation schedule has been described in detail by [Klein et al. \(2001\)](#).

### Water stress measurements

Midday stem water potential ( $\Psi_{ms}$ ), which was measured with a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA), was used to relate water stress to individual tree yields (cf. [McCutchan and Shackel 1992](#)). Because  $\Psi_{ms}$  tended to decline gradually as the period of irrigation deprivation increased (cf. [Klein et al. 2001](#)), we used the lowest mean values of  $\Psi_{ms}$  per harvest period as an indicator of the relative severity of water stress experienced by individual trees.

### Yield determinants

Monitored yield determinants included flowering, fruit set, and mortality of individually tagged spurs. On July 27, 1995, 15–20 individual successive spurs along each of eight branches (four branches per tree) per irrigation replicate (total of 2185 spurs) were selected. On each branch, every fifth spur was tagged to facilitate record keeping. Tagged spurs were distributed evenly among the irrigation treatments. Fruiting status and number of fruits per spur were recorded in 1995, before the initiation of the irrigation treatments. Flower counts on individually tagged spurs were made a few days before bloom in February of 1996, 1997 and 1998. Final fruit set was recorded after fruitlet drop each year during the first week of May (Kester and Griggs 1959).

### Yield

Within each replicate (17 trees per row), individual tree yields were determined for four trees during 1996 and 1997. Row yields were also monitored for these years. Yield data collected in 1995 served as reference data, because they reflected growing conditions before the application of the differential irrigation treatments during harvest. Whole fruits (including kernel, shell and hull) were considered for yield calculations.

### Fruiting positions

Based on information obtained as the experiment progressed, we hypothesized that the quantity of fruiting positions played a major role in the observed yield reductions caused by water stress. Because individual tree yield data were available, we attempted to quantify potential water stress effects on whole trees. Current-year stem dry weights of comparable FI and SS trees were obtained by analyzing three whole trees per irrigation treatment in December 1997. All current-year shoots longer than 5 cm (including watersprouts) were harvested. (Current-year shoots longer than 20 cm or with diameters larger than 1 cm were referred to as watersprouts.) Because trees had been subjected to three seasons of harvest-period stress (1995–1997) prior to excavation, these measurements reflected the cumulative effects of the treatments on above-ground annual vegetative growth.

### Individual fruit and spur growth

Both individual fruit and vegetative spur growth were monitored on eight trees in each of the FI and SS treatments, as well as on eight additional FI trees that were almost completely de-blossomed at the beginning of the 1997 growing season (24 trees total). Trees subjected to flower thinning were selected for uniformity in bud break.

Within each tree, four healthy branches (microsites) were randomly chosen from the periphery of the outer canopy to monitor fruit growth. At least six fruits per tree were sampled on February 10, 17 and 21, March 28, May 3, June 6 and August 6. Samples were put in an ice chest, taken to the laboratory and dried at 65 °C. Growth of newly developing vegetative spurs was monitored by the same procedure as for fruits, except that no samples were taken after May 3.

### Statistical analysis

Analysis of variance and regression as well as *t*-tests were carried out with the SAS statistical software package (SAS Institute, Inc., Cary, NC).

## Results

### Irrigation deprivation/water stress and yield

Irrigation deprivation affected row yields in 1997, 2 years after the first stress was imposed (Figure 1). A similar pattern was observed in 1996, but the effect was not statistically significant. The yield differences were more evident when each year's yield was subtracted from that of the 1995 reference year.

A plot of mean minimum midday stem water potentials ( $\Psi_{ms}$ ) of individual trees in 1995 against yield of the same trees in 1996 and 1997 (Figure 2) indicated that individual tree yields were correlated with the maximum water stress experienced during the previous years. Although there was a tendency toward a negative association between minimum  $\Psi_{ms}$  in 1995 and yield in 1996, the  $r^2$  value (0.18) in 1996 was low. The  $r^2$  value (0.38) and the slope of the regression curve in-

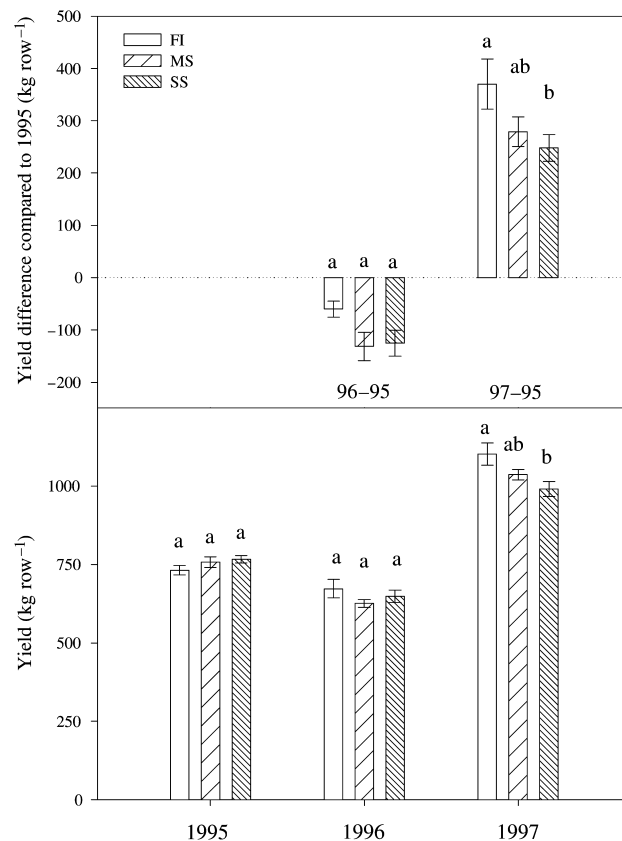


Figure 1. Effect of water stress on row (17 trees) yield of cv. Nonpareil almond trees. Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard errors of the mean. Different letters indicate statistical difference according to the Tukey procedure ( $P < 0.05$ ).

creased when minimum  $\Psi_{ms}$  in 1995 was related to 1997 yield, indicating that the effects of water stress persisted for 2 years. When the combined mean minimum  $\Psi_{ms}$  for individual trees in 1995 and 1996 was plotted against mean tree yields for 1997, the  $r^2$  value was 0.35 (data not shown), indicating a reduction in mean yield of 7.7 kg tree<sup>-1</sup> during 1997 for each 1 MPa decrease in minimum  $\Psi_{ms}$  below -1.2 MPa measured during 1995–1996.

### Water stress and flowering, fruit set and spur shoot mortality

The distribution of the tagged spurs carrying different numbers of fruit were comparable among treatments in the initial reference year (1995) before treatments began (Figure 3a). Irrigation deprivation had no consistent effect on the number of flowers or fruits on the remaining viable spurs during the following 3 years (Figures 3 and 4). The frequencies of flowers and fruits per spur were also relatively constant during the 3-year study.

Spur mortality was unaffected by irrigation deprivation during the 3 years following spur tagging (Figure 5). However, 66.1% of the 2185 spurs tagged in July 1995 had died by May 1998, with most mortality occurring in 1997. In addition to spur mortality, many of the surviving spurs were vegetative (Figure 6). In 1996, 44.5% of the tagged spurs had flowers, whereas only 21.3% flowered in 1998. After 3 years, only 10% of the original spur population bore fruit. The decrease in spur fruitfulness was attributable mainly to spur mortality.

### Water stress and individual fruit and spur growth

Fruit growth on FI trees with more than 50% of their crop load

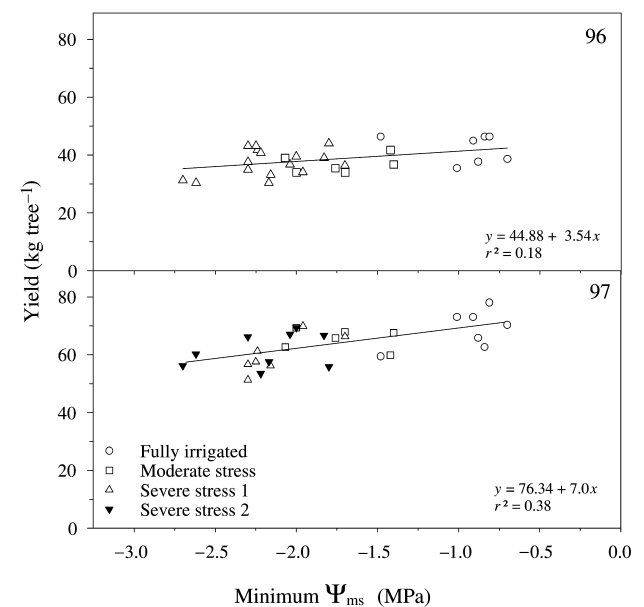


Figure 2. Relationship between the lowest 1995 seasonal stem midday water potential ( $\Psi_{ms}$ ) and individual tree yields in response to differential irrigation during the harvest period in 1996 and 1997. Differential irrigations began during the summer of 1995 and were repeated during the 1996 and 1997 summers.

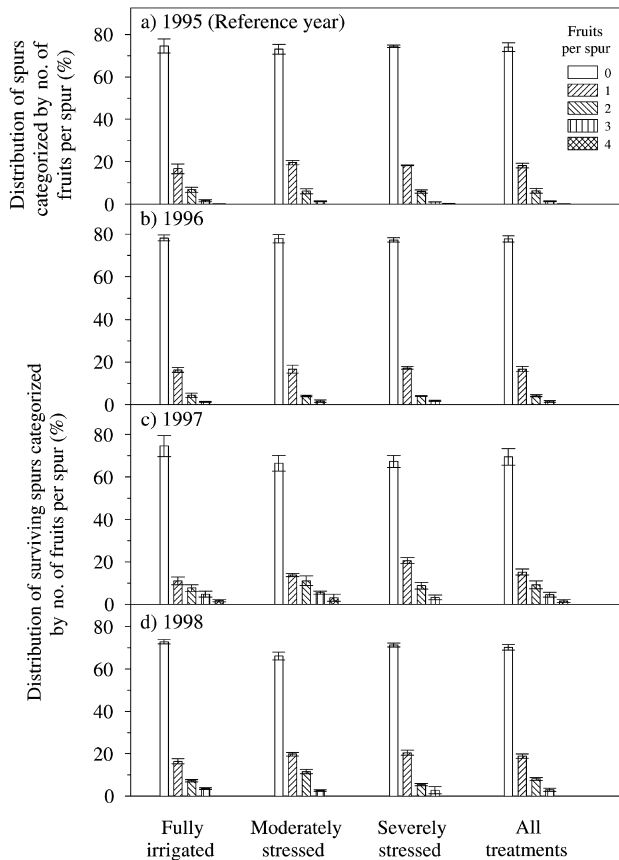


Figure 3. Effect of water stress during the harvest period on fruiting of cv. Nonpareil almond spurs classified according to fruit load over the period 1996–1998, compared with the 1995 reference year (before treatments started). Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard error of the mean.

removed was substantially greater than on unthinned FI or SS trees during 1997 (Figure 7). There was no significant difference in fruit growth between unthinned FI and SS trees. The growth of new developing vegetative spurs on FI and SS trees was similar, although there was a tendency toward greater spur dry weight in FI trees compared with SS trees on the last measurement date (Figure 7), but this tendency was not statistically significant.

#### Water stress and whole-tree stem growth

Water stress had a negative effect on whole-tree annual stem dry weight after three successive seasons of irrigation deprivation (Figure 8). This was true both for stem dry weight and for dry weights of short and long stems (watersprouts) separately.

#### Discussion

Almond nut yields were reduced in trees subjected to 2 years of successive irrigation deprivation during the harvest period. The lack of a significant yield reduction in 1996 in response to irrigation deprivation during the 1995 harvest period (Tufts

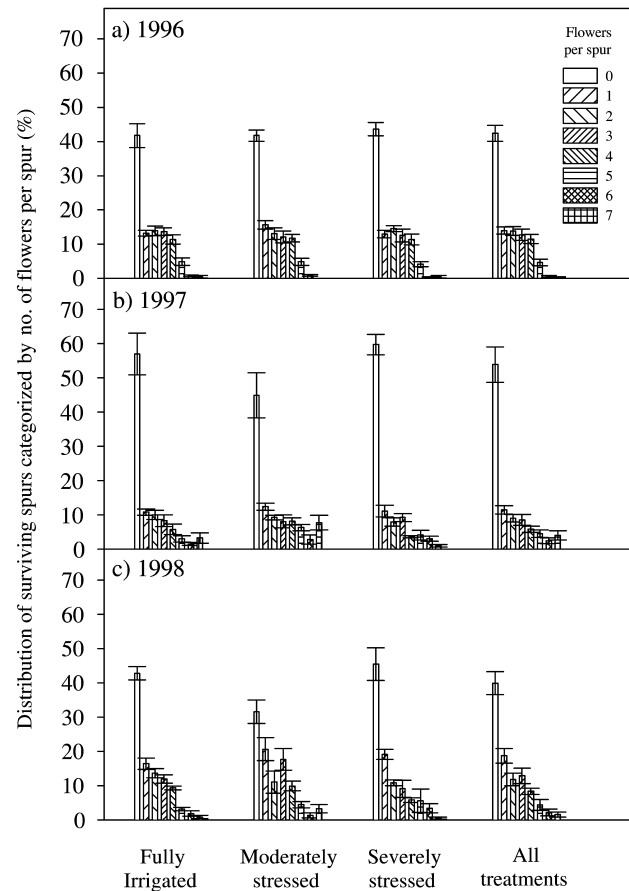


Figure 4. Effect of water stress during the harvest period on fruiting of cv. Nonpareil almond spurs classified according to flower load over the period 1996–1998, compared with the 1995 reference year (before treatments started). Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard errors of the mean.

and Morrow 1925, Brooks 1940) suggests that the water stress imposed was not severe enough to inhibit flowering directly. In addition to reductions in row yields in response to irrigation deprivation (Figure 1), we found a negative linear association between the minimum seasonal water status ( $\Psi_{ms}$ ) and individual tree yield in subsequent years (Figure 2). This finding indicates that substantial yield loss ( $7.7 \text{ kg tree}^{-1}$ ) occurred for each 1 MPa decrease in  $\Psi_{ms}$  below the minimum values measured in FI trees ( $-1.2 \text{ MPa}$ ) during the previous seasons. Nevertheless, effects of water stress on the yield components of experimental units smaller than whole trees could not be detected. In contrast, severely restricted irrigation of apricot (*Prunus armeniaca* L.) trees, which stunted tree growth, reduced differentiation and development of flower buds and consequently yield (Brown 1953). This discrepancy can be explained on the basis that, in our almond study, stress occurred relatively late in the growing season, long after completion of the vegetative growth cycle.

Although irrigation deprivation results in less carbon gain as a result of decreased leaf photosynthesis and partial defolia-

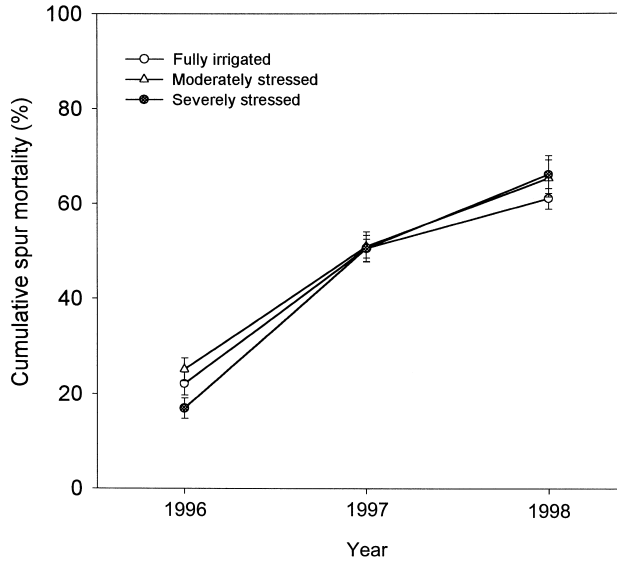


Figure 5. Effect of water stress during the harvest periods (1995–97) on cumulative mortality of cv. Nonpareil almond spurs (1996–98). Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard errors of the mean.

tion (Klein et al. 2001), the stress was not severe enough to affect flowering and fruiting directly. Because irrigation deprivation was temporary and irrigation was resumed before dormancy, it appears that floral initiation was completed, even though it was arrested during the period that irrigation was withheld (G. Esparza, unpublished data).

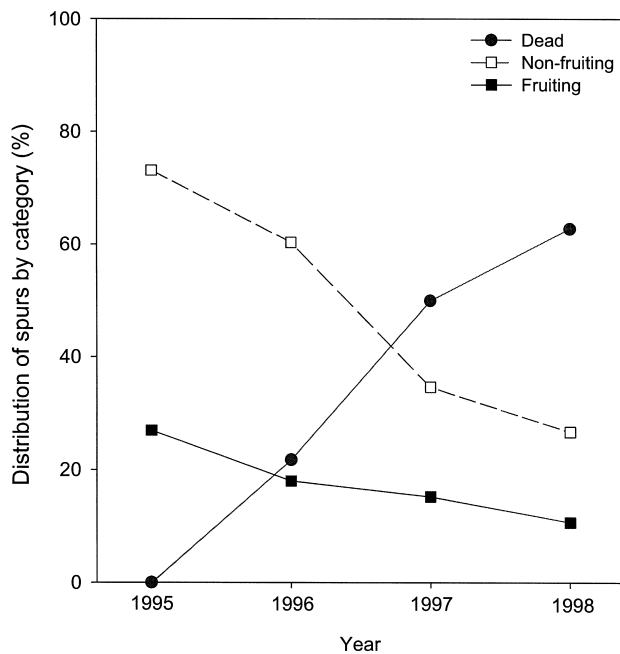


Figure 6. Distribution of dead, flowering and fruiting cv. Nonpareil almond spurs during 1996–1998. Spurs were monitored throughout the period after selection of each viable spur in 1995.

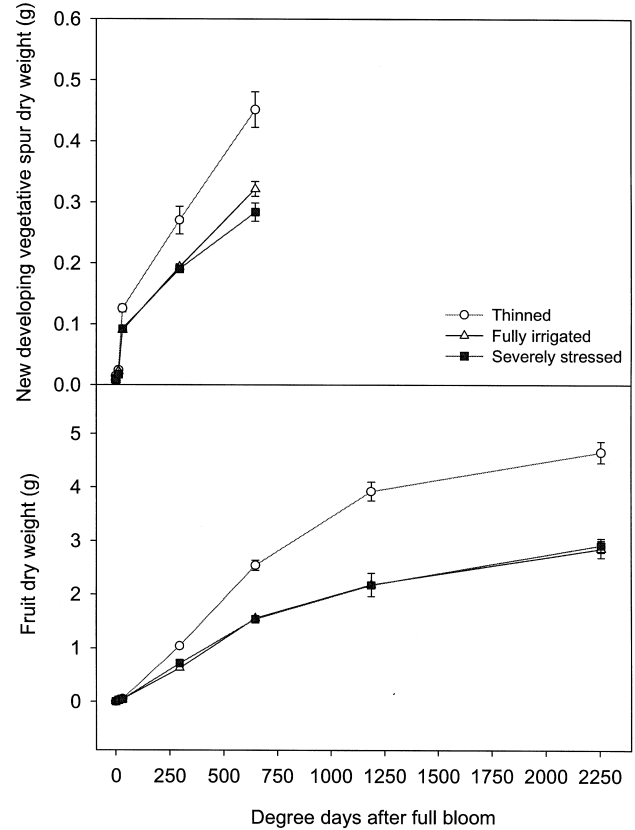


Figure 7. Effects of water stress during the harvest period and flower thinning (1997) on vegetative spur and fruit growth of cv. Nonpareil almond trees during the 1997 growing season. Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard errors of the mean. Full bloom occurred on February 24.

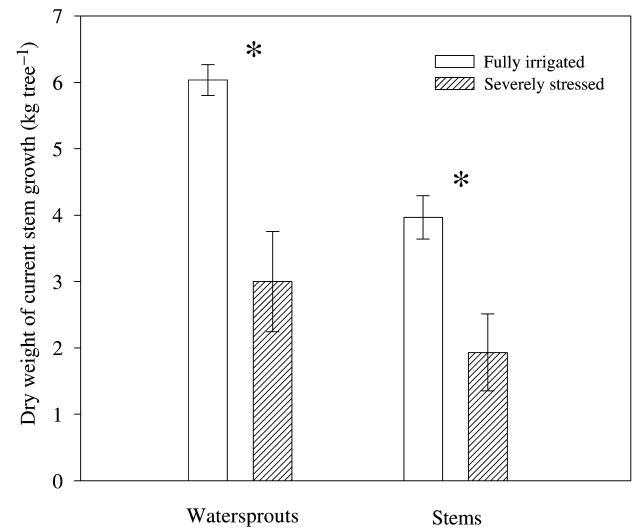


Figure 8. Effects of water stress on tree stem and sprout growth (kg<sub>dw</sub> tree<sup>-1</sup>) of cv. Nonpareil almond trees. Irrigation treatments began during the summer of 1995 and were repeated during the 1996 and 1997 summers. Bars represent the standard errors of the mean of three entire trees. Asterisks represent statistical differences according to the *t*-test ( $P < 0.05$ ).



Irrigation deprivation also had no effect on spur mortality (Figure 5); however, the finding that more than 60% of the tagged spurs died in all treatments indicates the importance of fruiting wood renewal in the almond orchard studied.

Because irrigation was withheld during the summer when both spurs and fruits had already completed their growth (Kester et al. 1996, Esparza et al. 1997), a stress effect was not expected in the same year that the stress was imposed. However, we predicted that irrigation deprivation would reduce the amount of reserves accumulated at the end of the season and thus affect yield determinants in subsequent years as a result of decreases in growth and development of fruiting positions. In apple (*Malus × domestica* (Borkh.)), spur fruitfulness is associated with spur vigor; regular bearing is related to the ability of a cultivar to produce lateral vegetative growth on the spur simultaneously with fruit growth (Heinicke 1917, Roberts 1921). As in apple, growth and vigor of almond spurs occurs at the beginning of the season when there is strong competition for tree reserves (Heinicke 1917, Grossman and DeJong 1995, Esparza et al. 1997). Bearing capacity (i.e., the renewal of fruiting positions, measured indirectly at the whole-tree level by analyzing stem growth) was reduced in SS trees (Figure 8), and developing vegetative spurs also showed a similar tendency (Figure 7); however, nut weight was unaffected by irrigation deprivation imposed during the harvest period of the previous summer. Our data are consistent with the concept that reduced almond yields 2 years after imposition of irrigation deprivation during the harvest period are a result of a compound, multiyear effect on bearing capacity.

Long-term studies of water deprivation of almond trees have associated yield reductions with reduced canopy development or total growth (less fruitwood) (Castel and Fereres 1982, Torrecillas et al. 1989, Girona et al. 1993, Hutmacher et al. 1994, Shackel et al. 1998). These studies, however, involved immature trees, and stress was imposed at different times than those in our study. Interestingly, our results corroborate these studies in implicating renewal of fruiting position as a major determinant of yield.

In almond trees, carbohydrate reserves limit early spring growth, as indicated by the increased fruit and spur growth after severe fruit thinning (Figure 7). Although carbohydrate limitation was evident in FI trees, it was probably more severe in MS and SS trees, because irrigation deprivation reduces carbohydrate accumulation (Klein et al. 2001). Although leaf function of MS trees recovered fully after the resumption of irrigation, recovery was only partial in SS trees (Klein et al. 2001), suggesting that decreased photosynthesis would result in a carbohydrate shortage in these trees in the following spring. Early defoliation, which presumably also reduces carbohydrate accumulation, has been shown to delay flowering and reduce shoot elongation in the following year in peach (*Prunus persica*) (Couvillon and Lloyd 1978) and reduce nut size and yield of pecan (*Carya illinoensis* (Wangenh.) C. Koch) in the year of treatment as well as fruit set, yield and shoot growth the following year (Worley 1971). In almond, flowering, fruit set and fruit size did not change in response to

early defoliation, but both shoot and spur (stem) growth were affected. Almond harvest is earlier than pecan harvest, allowing some carbohydrate accumulation if defoliation is not complete. In addition, almonds are commercially harvested before full maturation of the kernel to avoid navel orangeworm (*Amyelois transitella* (Walker)) damage (Rice et al. 1996). Early defoliation, therefore, is probably more detrimental for almond than for pecan. It appears that flowering, fruiting, and early fruit growth in almond are strong sinks and have priority over stem growth for carbohydrates in the spring.

Reduced shoot growth in SS trees was evident at the end of the third treatment season (Figure 8). Shoot and spur growth—and consequently the formation of future growing positions—occur early in the season, when there is strong competition for tree reserves (Roberts 1921, Kozłowski 1992, Grossman and DeJong 1995, Esparza et al. 1997). Strong competition was evident when we manipulated fruit loads. Thus, flower thinning minimized competition for reserves and resulted in enhanced fruit and spur growth (Figure 7). Although we did not measure fruiting spur renewal directly, we suggest that the reductions in annual growth of stems and watersprouts reflect reductions in canopy renewal and are probably associated with long-term spur production and renewal of bearing capacity. Almond bears a significant proportion of fruit laterally on stems produced during the previous season as well as on spurs. It is possible that the yield differences in response to the treatments were the result of differences in the crop component that was produced on these stems. Alternatively, because we studied trees that have been manipulated to stimulate some watersprout growth each year to provide new bearing sites in subsequent years, it is possible that some of the yield reductions were associated with reductions in this canopy renewal process.

We conclude that water stress did not influence flowering and fruit set on established spurs, nor did it accentuate spur mortality, which was over 60% during the 3-year experimental period. Nevertheless, two successive cycles of harvest-period irrigation deprivation resulted in yield reductions that were associated with reduced shoot growth in SS trees. We conclude that water stress impacts shoot and stem growth, both of which are necessary for renewal of fruiting positions. Irrigation deprivation resulted in yield reductions of 7.7 kg tree<sup>-1</sup> during 1997 per each 1 MPa decrease below the minimum  $\Psi_{ms}$  (-1.2 MPa) measured in FI trees during 1995–96.

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