Deficit Irrigation in Prunes: Maintaining Productivity with Less Water

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Prune (*Prunus ×domestica* L.) trees are believed to be relatively tolerant of water stress, and since the fruit are dried, a low fresh to dry weight ratio ("drying ratio") of the fruit at harvest will reduce energy requirements for drying, and improve economic returns to the grower. In previous research we found that, under some orchard conditions, irrigation deprivation was associated with a number of economically beneficial effects, including a lower drying ratio of the fruit, and increased return bloom and final marketable crop yield. Analysis of these results was complicated by alternate bearing, and by the fact that tree water stress could differ substantially within the same irrigation regime, depending on soil conditions. After accounting for these factors, our analysis indicated that economic yield could be maintained or increased by managing trees at a moderate level of water stress. An experiment was established to determine whether midday stem water potential (Ψ_{stem}) could be used to guide irrigation and to achieve a target level of water stress during the growing season. In addition, we wished to assess whether allowing a moderate level of water stress would result in any economic benefit to prune production. Managing prune trees at a moderate level of water stress (Ψ_{stem} reaching about -1.5 MPa by the end of the season) over 3 years saved an average of 40% of the irrigation water normally applied. Modest increases in return bloom, and an improved (lower) fruit drying ratio occurred in moderately water-stressed trees, although overall yield was not changed. The substantial savings in water, without reducing yield, should represent a net economic benefit to growers, depending on the price they pay for water.

MANAGEMENT OF DEFICIT IRRIGATION

Even though water stress is generally associated with an overall reduction in plant productivity (Bradford and Hsiao, 1982), previous work on water deprivation in prune (Hendrickson and Vehemeyer, 1934; Lampinen et al., 1995) has shown that fruit production is relatively tolerant of water-limited conditions. Prunes are typically grown for use as a dried product, and a beneficial reduction in fruit water content could partially offset the negative effects of water stress on processes such as photosynthesis and growth. Apparent enhancement of spring bloom, which favors fruit production, has also been associated with water stress the previous season (Lampinen et al., 1995).

Many current irrigation recommendations for deciduous fruit trees are based on an evaporative-demand driven model of water requirements (e.g., Ferreres and Goldhamer, 1990). Such recommendations are based on the assumption that water stress should be avoided, and that sufficient irrigation should be applied to satisfy the maximum water requirements under the given environmental conditions. In prune (Lampinen et al., 1995) and other tree crops (Shackel et al., 1997), we have found that the same quantity of irrigation, particularly at a deficit level, can result in very different levels of tree stress, depending on soil depth and, possibly, additional factors related to root-health. Hence, in order to reliably manage deficit irrigation strategies such as Regulated Deficit Irrigation (RDI, Chalmers et al.,

1986) under different soil conditions, a plant-based measure of stress, such as midday stem water potential (Ψ_{stem} , Shackel et al., 1997), may have to be used as an irrigation guide. For prune, McCutchan and Shackel (1992) proposed that a fully irrigated baseline (reference) value of Ψ_{stem} could be calculated for any given value of midday air vapor pressure deficit (VPD). Based on a large-scale survey of prune orchards in California, Shackel et al. (1997) concluded that this baseline value is applicable to a wide variety of soil and irrigation conditions. This paper presents some of the results of a 3-year irrigation study, in which midday Ψ_{stem} was used to manage deficit irrigation treatments in prune.

MEASUREMENT OF MIDDAY STEM WATER POTENTIAL

The method used for the measurement of Ψ_{stem} was described by McCutchan and Shackel (1992). Briefly, an interior canopy leaf, attached near the trunk or main scaffold, is enclosed in a foil-covered, black polyethylene envelope to stop leaf transpiration. After ≈ 2 h, the Ψ of this nontranspiring leaf is assumed to be well-equilibrated with the stem at the point of attachment, and hence the Ψ of this leaf, which can be easily measured with a pressure chamber, is referred to as Ψ_{stem} . Water-filled xylem has a high hydraulic conductivity, and Ψ_{stem} measured close to the trunk or main scaffolds is quite uniform, so that typically a single leaf per tree is an adequate sample. In view of the strong correlation between this measure of water stress and water stress responses at the whole tree level, such as reduced vegetative and fruit growth (Shackel et al., 1997), we believe that it represents a reasonable measure of the water status of the tree as a whole.

EXPERIMENTAL DESIGN

Three irrigation treatments were applied to prune trees in a commercial orchard in Butte County, Calif., from 1994 to 1996. The orchard was drip-irrigated, on a Gridley clay loam soil, and the trees, which were ≈ 18 years of age in 1994, were planted at a 5.5×5.5 -m spacing on 'Mariana 2624' rootstock. A randomized complete-block design of three irrigation treatments and five blocks was utilized, and the center four trees in a 16-tree (4×4) plot were used for experimental measurements. The irrigation regimes (treatments) were modified as needed to attempt to achieve three contrasting target levels of stress, as measured by midday Ψ_{stem} : > -1.0 MPa throughout the entire growing season (wet treatment); a decline to about -1.5 MPa by harvest (medium treatment); and a decline to about -2.0 MPa by harvest (dry treatment). Because this experiment was performed within a commercial orchard, the recommended amounts of irrigation were communicated to the grower, who managed the irrigation system for the orchard as a whole. Differential irrigation treatments were achieved by altering the number and size of drip emitters in each treatment plot, and the actual amounts of water applied were determined using water meters. Recommended irrigation amounts were based in part on local conditions of reference crop evapotranspiration obtained from a nearby California Irrigation Management and Information Systems (CIMIS) weather station (Gridley, Calif.), and the measured midday Ψ_{stem} was compared with the respective target value for each irrigation treatment. Orchard water use was also calculated using the published values of crop coefficient for a mature, clean-cultivated deciduous orchard in California's central valley (California Dept. of Water Resources, 1986).

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FRUIT EVALUATION

Each experimental tree was shaker-harvested, and the total fruit fresh weight was measured using a harvester-mounted load cell. For each tree a sample of ≈ 1 to 1.5 kg of fruit was taken as the fruit exited the harvester, and dried to $\approx 18\%$ moisture at a commercial dryer. The fruit in the sample were counted, evaluated for various quality characters and weighed. Fruit drying ratio was calculated by dividing sample fresh weight by sample dry weight, and, together with the number of fruit in the sample, was used to convert fresh yield into dry yield and to determine the numbers of fruits harvested. Yields and numbers of fruits were expressed per unit land area.

RESULTS AND CONCLUSIONS

The commencement of irrigation depended on the pattern and amount of winter rains each year, but was usually in late April or early May. For the purposes of illustration, the seasonal patterns of estimated crop water demand, water applied and Ψ_{stem} for each treatment are presented as monthly means over all 3 years (Fig. 1). Prior to irrigation, midday Ψ_{stem} was essentially identical in all treatments and equivalent to the predicted fully irrigated Ψ_{stem} (Fig. 1B). Once irrigation treatments began and water was withheld from some plants (Fig. 1A), clear treatment differences in midday Ψ_{stem} became apparent (Fig. 1B). The trees in the medium and dry treatments exhibited midday Ψ_{stem} close to the respective target values of -1.5 and -2.0 MPa by harvest, but the trees in the wet treatment were somewhat below the target of -1.0 MPa throughout the season (Fig. 1B), and substantially below the predicted fully irrigated values of McCutchan and Shackel

Fig. 1. Monthly means of: (A) cumulative crop water demand and water applied in three irrigation treatments (wet, medium, dry), and (B) midday reference Ψ_{stem} for fully irrigated trees, as calculated from VPD, and as measured for the trees under the three irrigation treatments imposed from 1994 to 1996.

Table 1. Three-year means of fruit yield and drying ratio^a and of irrigation water applied to trees under three contrasting irrigation regimes in a commercial prune orchard at Gridley, Calif.

Irrigation treatment	Fruit yield (t·ha ⁻¹)		Drying ratio	Water applied (mm)
	Fresh	Dry		
Wet	40.6	13.7	2.97	737
Medium	39.2	13.7	2.87*	449
Dry	36.3*	13.0	2.80*	309
LSD _{0.05}	4.00	1.2	0.07	---

^aFresh wt/dry weight.

*Significantly different from the wet treatment by Dunnett's test, $P \leq 0.05$.

(1992). This was due to the generally low level of water applied by the grower in the orchard as a whole through the month of June (Fig. 1A), but did not preclude valid treatment comparisons. Substantial savings in irrigation water were achieved by withholding water from the medium and dry treatments (Fig. 1A).

Previous reports (Lampinen et al., 1995) have indicated that mild water stress reduces prune tree vegetative growth and increases return bloom, leading to somewhat higher overall fruit production, but the average yields of dry fruit over the 3 years of this study did not differ significantly among treatments (Table 1). There was a progressive reduction in fresh fruit yield in the medium and dry as compared with the wet treatment, and the effect was significant for the dry treatment (Table 1). Dry fruit yield was slightly lower in the dry treatment than in the control, but drying ratio was significantly lower in both the medium and the dry treatment than in the control (Table 1), as also reported by Lampinen et al. (1995). Irrigation was reduced 40% and 58%, respectively, in the medium and dry treatments (Table 1). These results indicate that a substantial savings in irrigation water can be realized with a minimal impact on dry fruit production in prune. One factor, however, that can complicate the interpretation of treatment mean yields, even for a 3-year average, is the possibility that irrigation treatments might influence the pattern of alternate bearing, as reported by Lampinen et al. (1995). The trees in this study exhibited alternate bearing, with 1994 and 1996 being high crop years (15 – 18 dry t·ha⁻¹) and 1995 a low crop year (6 – 7 dry t·ha⁻¹). An analysis similar to that used by Lampinen et al. (1995), however, indicated that the yield corresponding to a stable fruit load did not differ among treatments (Fig. 2). For this analysis we have expressed fruit load as numbers of fruit per unit land area, because we have previously reported a close relation between this parameter and average size of dry fruit (Lampinen et al., 1995), which are the two most important economic factors in prune production. The fruit load that does not affect the next year's crop ($Y = 0$, Fig. 2), represents the crop that could theoretically be maintained from year to year without exhibiting alternation. Even though the points in this figure are not evenly distributed over the range of possible fruit loads, and also exhibit some deviation from the regression line, a linear approximation should be reasonable for the purposes of treatment comparisons. Lampinen et al. (1995) found that this theoretically stable cropping level was slightly increased by imposing an irrigation deficit, but this was not the case in the present study.

As mentioned above, for each year the commencement of irrigation depended on the amount and distribution of winter rains. In all years

Fig. 2. Individual tree yield expressed as number of fruit per ha in any given year (X-axis) and the subsequent change in the number of fruit the following year (Y-axis). Separate symbols and linear regressions are shown for each irrigation treatment, but the regression lines are essentially identical, and the overall regression was $Y = 2.03 - 1.37 \cdot X$ (r -square = 0.92^{***}). The X-coordinate where the regression lines cross $Y = 0$ indicates the fruit load required in any current year for no change in the subsequent year (i.e., no alternation).

winter rainfall was sufficient to consider the soil fully wet at the time of bloom, and so for each year, beginning with bloom date, an irrigation deficit was calculated as:

$$\text{Estimated irrigation deficit} = \text{rainfall} + \text{irrigation water applied} - \text{orchard water use} \quad [1]$$

This deficit represents the amount of stored soil water that would be required if the crop continued to use water at the full evapotranspiration rate. In a similar manner, a water potential deficit was calculated as:

$$\text{Water potential deficit} = \text{fully irrigated (reference)} \Psi_{\text{stem}} - \text{observed } \Psi_{\text{stem}} \quad [2]$$

where the fully irrigated (reference) Ψ_{stem} corresponds to that expected under nonlimiting soil water conditions under any given midday condition of vapor pressure deficit (VPD) as reported by McCutchan and Shackel (1992). There was a very clear positive relation between the deficit in irrigation and the deficit in water potential for all treatments, years and dates of measurement (Fig. 3). Even though there is substantial scatter, the relationship is generally linear; for a water potential deficit of 0, the regression line can be extrapolated to an irrigation deficit of 0. This is consistent with the fact that the fully irrigated Ψ_{stem} values of McCutchan and Shackel (1992) were measured under field capacity conditions, and indicates that even small amounts of soil water depletion may be associated with systematic reductions in Ψ_{stem} . Modern concepts of soil available water have stressed that the availability of water to plants is a dynamic process (Ahuja and Neilsen, 1990), affected both by soil water status and by evaporative demand. This contrasts with earlier concepts that considered water to be more or less equally available between field capacity and what was considered an "allowable depletion." Fig. 3 shows that, for our experimental site, a simple linear combination of an estimated irrigation deficit effect and the effects of evaporative demand (VPD) can account for the effect of irrigation on plant water status.

If irrigation water can be conserved by imposing mild water deficits on prune trees, then it is of interest to determine how irrigation should be managed to achieve a given target level of midday Ψ_{stem} , given year-to-year differences in rainfall and evaporative demand. In this study, frequent measurements of Ψ_{stem} were used to adjust irrigation practices, and even though substantially reducing this frequency under typical orchard production conditions may be possible, the economics of monitoring versus other methods of water management are important considerations. Since we have previously determined the relation of fully irrigated midday Ψ_{stem} to midday VPD in prune (McCutchan and Shackel, 1992), and in this study have empirically determined the relation between a Ψ_{stem} deficit and an irrigation deficit (Fig. 3), we can now determine how much irrigation should be necessary to achieve any given target value of midday Ψ_{stem} for any yearly pattern of rainfall and midday VPD. Daily values of midday

Fig. 3. The relation between treatment average water potential deficit (Eq. [1]) and the estimated irrigation deficit (Eq. [2]) for all years and sampling dates of the irrigation study. Vertical lines are treatment means $\pm$ 2SE for each measurement date, the solid line is the linear regression through all individual data points ($Y = 0.00226X - 0.026$, $r^2 = 0.52^{***}$) and the dashed lines indicate the estimated irrigation deficit for a water potential deficit of 0 (X-intercept of the linear regression)

VPD in 1995 were used to generate the seasonal pattern of fully irrigated midday Ψ_{stem} , and three arbitrary seasonal targets were proposed for the purpose of illustration (Fig. 4A). In a few cases the proposed target values were above the fully irrigated value, but were considered equivalent to the latter for the purposes of this analysis. Based on the linear relation shown in Fig. 3, a value of irrigation deficit corresponding to each target was then calculated (Fig. 4B). Under fully irrigated conditions, this corresponds to no irrigation deficit throughout the season. The quantity of water required for each of these deficits was then calculated (Fig. 4C), based on real-time values of reference crop evapotranspiration (ET_0) and published values of crop coefficients (K_c , California Dept. of Water Resources). As expected, this analysis shows that, compared with a fully irrigated condition, progressively more tree water stress will occur as irrigation is delayed and less water is applied (Fig. 4 A and C). In addition however, Fig. 4 indicates that application of water at a relatively constant fraction of crop water requirements (Fig. 4C) may not result in a constant level of plant water stress, but rather an increasing level of stress as the season progresses (Fig. 4A). The seasonal patterns in the amount of water necessary to achieve different target levels of tree water stress were very similar in different years (Fig. 5A–C). Some differences between years were apparent in the time irrigation was commenced for a given target stress; for instance, for the moderate/severe stress target, irrigation would have been started in mid-May in 1994, late May in 1995, and late April in 1996. There were also some year-to-year differences in the quantity of water applied for a given target stress, even when this was expressed as a percentage of the fully irrigated treatment. The mild/moderate stress corresponded to application of 60% to 70% full

Fig. 4. (A) Modeled values of midday Ψ_{stem} for fully irrigated prune trees (solid lines) in 1995 (Gridley, Calif.) and hypothetical target values (dashed lines) under contrasting irrigation regimes; (B) irrigation deficit; and (C) the water required to achieve the targets proposed in (A).

Fig. 5. Modeled values of the irrigation required to achieve target levels of midday Ψ_{stem} for the 1994–96 (A–C) growing seasons.

irrigation, and the moderate/severe stress to 40% to 50% full irrigation, depending on the year (Fig. 5).

Overall, the modeled effects of irrigation on midday Ψ_{stem} in prune (Figs. 4 and 5) indicate that, under the conditions of this study, a relatively wide range of irrigation amounts may not result in severe tree water stress, and hence the limited sensitivity of dry fruit yield to irrigation is not surprising (Table 1). These modeled results underscore the need for a plant-based measurement as part of irrigation management, particularly irrigation management that seeks to reduce the amount of applied water for economic, environmental, or other reasons.

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