Tree Physiology 28, 1255–1261

Responses of apple fruit size to tree water status and crop load

A. NAOR,[1,2] S. NASCHITZ,[1] M. PERES[3] and Y. GAL[3]

[1] *Golan Research Institute, P.O. Box 97, Kazrin 12900, Israel*

[2] *Corresponding author (amosnaor@research.haifa.ac.il)*

[3] *Extension Service, Ministry of Agriculture and Rural Development, Kiryat Shmona 12100, Israel*

Received January 31, 2008; accepted March 31 2008; published online June 2, 2008

Summary The combined effects of irrigation rate and crop load on apple yield and fruit size were examined in two commercial apple orchards (cv. Golden Delicious) in a semi-arid zone. The irrigation rates applied were 1, 3 and 7 mm day^{-1}, and the two fruit thinning treatments involved adjusting crop load to 100 and 300 fruits per tree at Ortal and 50 and 150 fruits per tree at Matityahu. Unthinned trees served as the control. The fruit from each tree was picked separately, and fruit size distribution was determined with a commercial grading machine. Midday stem water potentials varied from –0.9 to –2.8 MPa, crop load varied from 80,000 to 1,900,000 fruit ha^{-1} and crop yield varied from 10 to 144 Mg ha^{-1}. Midday stem water potential decreased with increasing crop load in all irrigation treatments at Matityahu, but only in the 1 mm day^{-1} treatment at Ortal. The extent of the lowering of midday stem water potential by crop load decreased with increasing soil water availability. At both orchards, a similar response of total crop yield to crop load on a per hectare basis was observed. Mean fruit mass and relative yield of fruit > 70 mm in diameter increased with midday stem water potential, with the low crop loads having similar but steeper slopes than the high crop load. The responses of mean fruit mass and relative yield of fruit > 70 mm in diameter to midday stem water potential were similar at both orchards, perhaps indicating that thresholds for irrigation scheduling are transferable to other orchards within a region. Factors that may limit the transferability of these thresholds are discussed.

Keywords: irrigation, Malus domestica, stem water potential, water stress indicators.

Introduction

Dryland orchards can survive and be productive in temperate zones without irrigation, whereas the survival of deciduous orchards in semi-arid zones depends on the availability of water for irrigation throughout most of the growing season. Worldwide, the amount of fresh water available for agricultural use is decreasing, so there is a need to increase water-use efficiency. This goal may be achieved either by improving genetic performance and horticultural practices, or by improving irrigation scheduling.

Modern irrigation scheduling of deciduous orchards is based on sets of crop coefficients derived from reference crop evapotranspiration (Allen et al. 1998). However, published crop coefficients may require adjustment to suit actual conditions because water use in commercial orchards varies with numerous combinations of many factors. These factors include cultivar (Robinson and Lakso 1991), rootstock (Robinson and Lakso 1991, Wünsche et al. 1995, Giuliani et al. 1998), training system (Palmer 1993) and row spacing, which affects light interception on a per hectare basis, the number of fruit per tree and potential fruit size that, in turn, determine the crop demand for assimilates. In addition, application efficiency in commercial orchards is always lower than 1 and there is no straightforward procedure to make site-specific estimates of it. The diversity in the above mentioned factors among plots within an orchard creates considerable uncertainty about optimal irrigation scheduling. Growers may overcome most of the uncertainty in irrigation scheduling by using assessments of tree or soil water status to adjust the irrigation rate once it exceeds a certain threshold. However, adjusting irrigation rate based on water stress assessment is not straightforward.

Soil water stress indicators have been proposed as a basis for evaluating the ability of the soil to meet the peak demand for water by the tree. Determination of soil water stress is not an easy task because it involves the integration of soil water characteristics and hydraulic properties in conjunction with the distribution of roots (sinks) and evaporative demand. Moreover, soil water content is not uniform, even within the root zone of a single tree. Soil water stress indicators were reported to have greater variability than maximum daily trunk shrinkage and midday stem water potential (Naor et al. 1995, 1999, 2000, Goldhamer and Fereres 2001, Intrigliolo and Castel 2004, Naor et al. 2006) because the tree responds to the mean soil water availability. Thus, measuring tree water status avoids the need to deal with the variability within the root zone (Naor 2006). Both midday stem water potential and maximum daily trunk shrinkage, the most popular proposed plant water stress indicators, provide an indication of peak water stress but their correlation with integrated daily canopy conductance and assimilation rate may vary with climatic conditions and crop load, and may change during the growing season (e.g., Lakso 1979, Möller et al. 2007) because of osmotic adjustment.

Recent studies indicate that midday stem water potential is a relevant and reliable water stress indicator in fruit trees, but its use is labor intensive and measurements are limited to about 2 h around midday (see review, Naor 2006). Daily trunk shrinkage, on the other hand, is highly responsive to water availability (Goldhamer et al. 1999, 2000, Goldhamer and Fereres 2001, Fereres and Goldhamer 2003, Naor and Cohen 2003, Intrigliolo and Castel 2004), easy to use and yields an analog output. However, maximum daily trunk shrinkage is more dependent on evaporative demand than midday stem water potential. Setting thresholds of maximum daily trunk shrinkage for irrigation scheduling is problematic; however, calibration of maximum daily trunk shrinkage against midday stem water potential may provide thresholds for the use of maximum daily trunk shrinkage for irrigation scheduling (Naor 2006).

Setting thresholds of midday stem water potential for irrigation scheduling is empirical and the question of the scale and conditions at which thresholds are transferable among orchards has not been examined. The objectives of our study were (1) to determine the responses of crop yield and fruit size of apples to combined manipulations of irrigation and crop load at two distant commercial orchards, and (2) to examine the possibility of transferring thresholds of midday stem water potential among apple orchards within a region.

Materials and methods

Experimental site

Two experiments were conducted in the northern part of Israel during the growing season of 2006, one in the Golan Heights (Ortal) and the other in the upper Galilee (Matityahu experimental station). Both orchards are situated in a semi-arid zone where no precipitation occurs during the summer. Reference crop evapotranspiration was calculated from weather station data located at 4000 m and 250 m from the experimental sites at Ortal and Matityahu, respectively. Mean midsummer evapotranspiration was 6.9 and 6.6 mm day^{-1} at Ortal and Matityahu, respectively. Precipitation in the 2005–2006 winter was 860 and 545 mm at Ortal and Matityahu, respectively.

Experimental orchard

Plant materials were 15-year-old ‘Smoothie’ (a ‘Golden delicious’ strain) apples (*Malus* × *domestica* Borkh.) on the local Hashabi rootstock at Ortal and 10-year-old ‘Golden delicious’ on M9 rootstock at Matityahu. Planting density was 4.5 × 2.5 m and 3.5 × 1.5 m at Ortal and Matityahu, respectively with a north–south row orientation in both orchards. To minimize water percolation below the root zone, the irrigation system consisted of three laterals of 1.6 l h^{-1} drippers spaced 0.5 m apart, providing irrigation rates of 1.6 and 2.1 mm h^{-1} at Ortal and Matityahu, respectively. The daily irrigation amounts were delivered in 1-mm pulses.

Treatments

Two factors were examined, irrigation rate and crop load. The trees were not irrigated during the cell division stage (up to the beginning of June) and three irrigation rates were applied thereafter, 1, 3 and 7 mm day^{-1}. At the start of irrigation treatments, the trees were hand thinned to three crop loads ~100, ~300 fruit per tree and unthinned control at Ortal and ~50, ~100 fruit per tree and unthinned control at Matityahu.

The experimental design was a split plot with irrigation as the main plot and crop load as the sub-plot. Each main plot comprised six measurement trees (two for each crop load) that were surrounded by border trees and rows. Treatments at each orchard were replicated three times.

Measurements

Midday stem water potential was measured with a pressure chamber (Ari-Mad, Kfar Charuv, Israel or PMS, Corvallis OR) on shaded leaves from the inner part of the canopy that were inserted (while intact) into a plastic bag covered by aluminum foil for 90 min before measurements were taken. Measurements were made weekly in the medium crop load treatments and every 2 weeks in the low and high (unthinned) crop loads. Six leaves were measured for each irrigation × crop load combination. Additional midday stem water potential measurements were made on July 31 at Ortal on six trees of each irrigation × crop load combination (total of 54 trees). Two leaves were measured on each tree. Two pressure chambers were used simultaneously to shorten the measurement period. Measurements started at noon and were completed within 90 min.

Harvest

The fruits were picked on September 6, 2006 at Ortal and on September 13, 2006 at Matityahu. The fruit from each tree was picked separately and fruit size distribution was determined with a commercial sorting machine (Greefa, Tricht, Netherlands).

Results

Irrigation coefficients varied among treatments (Figure 1).

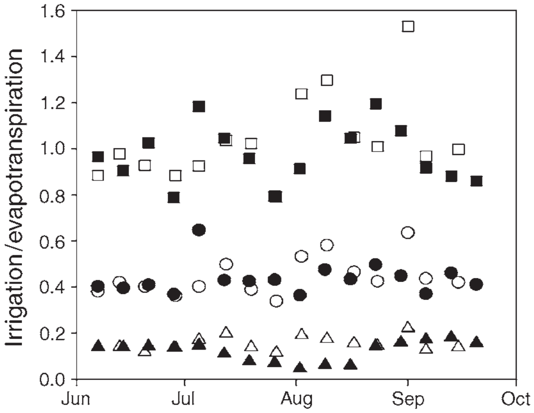

Figure 1. Weekly means of daily irrigation rates (fraction of evapotranspiration) at Ortal (filled symbols) and Matityahu (open symbols) in 2006 in the three irrigation regimes: 1 mm day^{-1} (▲, △); 3 mm day^{-1} (●, ○); and 7 mm day^{-1} (■, □).

Mean coefficients were 0.15, 0.43 and 1.0 in the 1, 3 and 7 mm day^{-1} treatments, respectively, at Ortal and 0.15, 0.45 and 0.98 in the 1, 3 and 7 mm day^{-1} treatments, respectively, at Matityahu. Cumulative irrigation rates up to harvest were similar at both orchards, with 101, 285 and 665 mm applied in the 1, 3 and 7 mm day^{-1} treatments, respectively, at Ortal and the corresponding values at Matityahu were 80, 292 and 661 mm.

At both orchards, midday stem water potential decreased with decreasing irrigation rate (Figure 2). Midday stem water potential in trees at Ortal decreased with increasing crop load in the 1 mm day^{-1} treatment, decreased slightly with crop load in the 3 mm day^{-1} treatment and was unaffected by crop load in the 7 mm day^{-1} treatment (Figure 3). In contrast, midday stem water potential in trees at Matityahu decreased with increasing crop load at all irrigation rates, with the extent of the decrease lessening with increasing irrigation rate (Figure 3).

Fruit number per hectare was higher at Matityahu than at Ortal (Table 1). In each orchard, fruit number per hectare was similar in the three irrigation treatments in trees carrying low and medium crop loads (thinned), whereas crop load varied with irrigation treatment in the control (unthinned) trees. Total crop yield increased with increasing irrigation rate and with increasing crop load in both orchards (Table 1), with the higher crop yields at Matityahu than at Ortal reflecting the higher fruit number per hectare. In both orchards, mean fruit mass decreased with decreasing irrigation rate and with increasing crop load (Table 2). In general, trees at Ortal had higher fruit mass than trees at Matityahu, except for trees in the medium crop load × 1 mm day^{-1} irrigation treatment which had lower fruit mass. Fruit mass of trees in the high crop load × 3 mm day^{-1} irrigation treatment was much lower at Matityahu than at Ortal (Table 2).

Fruit size distribution shifted to smaller fruits with increasing crop load in the 1 mm day^{-1} treatment, and the shift was more pronounced at Matityahu than at Ortal (Figure 4, Table 2). In the higher irrigation treatments, fruit size distribution was similar in the low and medium crop loads and was shifted to smaller fruits only in trees bearing a high crop load. Total crop yield at Ortal and Matityahu responded similarly to crop load (Figure 5, Table 1) except for two cases. First, trees at Matityahu bearing a high crop load in the 3 mm day^{-1} treatment had similar crop yield as trees at Ortal despite the large difference in crop loads (Table 1). Second, trees at Ortal bearing a medium crop load in the 1 mm day^{-1} treatment had lower crop yield than trees at Matityahu despite their similar crop loads (Table 1).

Mean fruit mass was highly correlated with midday stem water potential in midsummer (Figure 6). Similar correlations were apparent at both orchards with trees bearing low and medium crop loads having similar responses, whereas the unthinned trees bearing a high crop load had lower mean fruit

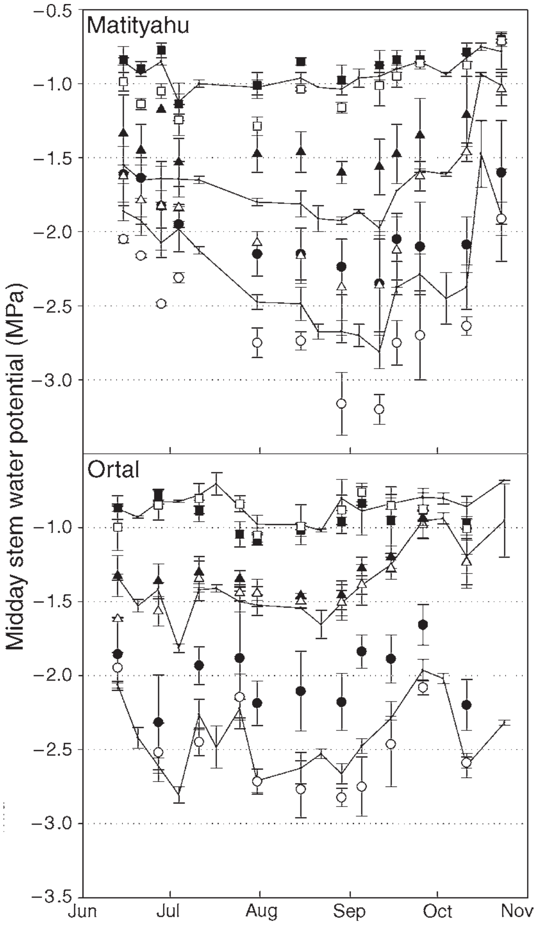

Figure 2. Effects of irrigation rate and crop load on midday stem water potentials in *Malus domestica* trees at Ortal and Matityahu in 2006. The irrigation regimes were: 1 mm day^{-1} (●, ○); 3 mm day^{-1} (▲, △); and 7 mm day^{-1} (■, □). The crop loads were: low, medium and high denoted by open symbols connected by lines and filled symbols, respectively. Bars denote standard error.

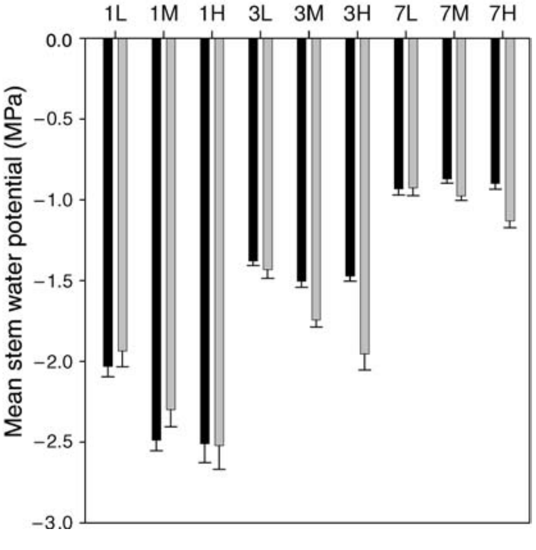

Figure 3. Effects of irrigation rate and crop load on mean midday stem water potentials in *Malus domestica* trees up to harvest at Ortal (black bars) and Matityahu (gray bars). Numbers on the *x*-axis are irrigation rates (mm day^{-1}) and letters denote crop loads (low, L; medium, M; and high, H). Bars denote standard error.

Table 1. Mean (± standard error) crop load and total crop yield of *Malus domestica* trees at Ortal and Matityahu in 2006 in response to irrigation (1, 3 and 7 mm day^{-1}) and fruit thinning treatments.

Irrigation up to harvest (mm)	Fruit per hectare/1000			Total crop yield (Mg ha^{-1})		
	Low	Medium	High	Low	Medium	High
Ortal						
101	87.3 (7.4)	275.5 (32.3)	913.5 (59.2)	10.1 (0.9)	17.4 (0.9)	43.0 (3.0)
285	98.8 (3.2)	276.7 (5.7)	1075 (52.8)	16.8 (0.18)	44.8 (1.7)	106.3 (6.8)
665	84.7 (1.6)	255.1 (4.5)	1177 (53.7)	17.3 (0.42)	50.3 (1.5)	144.4 (7.2)
Matityahu						
80	114.3 (7.7)	282.9 (11.0)	1295 (120.4)	13.1 (0.7)	28.4 (1.7)	49.2 (5.4)
292	111.1 (7.4)	304.8 (12.7)	1630 (79.6)	16.8 (1.3)	40.3 (2.5)	96.6 (6.7)
661	117.1 (7.7)	310.5 (18.4)	1224 (121)	22.1 (1.8)	52.5 (3.0)	140.1 (10.9)

mass for each water potential value (Figure 6). The difference in fruit mass between trees bearing a high crop load and trees bearing the lower crop loads increased with increasing midday stem water potential. At both orchards, the relative yield of fruit larger than 70 mm in diameter was highly correlated with midsummer midday stem water potential (Figure 7). Relative yields of trees bearing the two lower crop loads responded similarly to midday stem water potential, whereas the unthinned trees with the higher crop loads had lower relative yields at each stem water potential (Figure 7).

Discussion

It is well known that fruiting deciduous orchards have higher stomatal conductance, and thus higher transpiration rates, than de-fruited trees (Hansen 1971, Fuji and Kennedy 1985, DeJong 1986, Erf and Proctor 1989, Gucci et al. 1991, Wibbe and Blanke 1995, Giuliani et al. 1997, Wünsche et al. 2000, Marsal et al. 2005). As confirmed in Figures 2 and 3, lower midday stem water potentials are expected at high crop loads (Berman and DeJong 1996, Naor et al. 1997) because of the higher transpiration and the high resistance to water flow from the soil to the trunk xylem.

In our study, midday stem water potential decreased with increasing crop load but the response varied between orchards. In both orchards, crop load affected midday stem water potential in the 1 mm day^{-1} treatment; however, at Ortal, unlike Matityahu, no effect was apparent in trees in the 3 and 7 mm day^{-1} treatments (Figure 3). In another study in the Golan Heights, Israel where the crop load was similar to that at Matityahu, midday stem water potential responded to crop load at an irrigation rate of ~3 mm day^{-1} (Naor et al. 1997). Higher hydraulic resistance in the M9 rootstock (Cohen et al. 2007) and the higher crop load at Matityahu may explain the effect of crop load on midday stem water potential at Matityahu in the 3 and 7 mm day^{-1} treatments. Palmer et al. (1997) and Wünsche et al. (2000) reported an upper limit in crop load beyond which no further increase in stomatal conductance occurred in response to increased crop load, contrasting with our observed stem water potential response to increasing crop loads.

Midday stem water potential may decrease as a result of soil water depletion in response to long-term higher transpiration rates in heavily cropping trees. Under such conditions, increasing crop load is expected to result in a greater decrease in midday stem water potentials at low irrigation rates than at high irrigation rates. The difference in midday stem water potentials between the high and low crop loads at Matityahu was –0.59, –0.52 and –0.2 MPa in the 1, 3 and 7 mm day^{-1} irrigation treatments, indicating that water availability plays a role in the response of midday stem water potential to crop load. The difference in midday stem water potential between trees bearing high and low crop loads at Ortal was –0.48, –0.09 and 0.01 in the 1, 3 and 7 mm day^{-1} irrigation treatments. Similar responses of stem water potential to crop load were apparent in both orchards in the 1 mm day^{-1} treatment; however, unlike the Matityahu trees, the Ortal trees showed practically no response at the two highest irrigation treatments. It may be that differences in water application efficiency between the orchards and therefore differences in water availability accounted for the different responses of midday stem water potential to crop load.

The low crop load × high irrigation rate treatment (~20 Mg ha^{-1}) represents non-limiting conditions where potential fruit size is probably achieved. Fruit mass of trees in the high crop

Table 2. Mean fruit mass (g; ± standard error) of *Malus domestica* trees at Ortal and Matityahu in 2006 in response to irrigation (1, 3 and 7 mm day^{-1}) and fruit thinning treatments.

Irrigation up to harvest (mm)	Low	Medium	High
Ortal			
101	116.7 (7.9)	67.4 (9.5)	51.5 (4.6)
285	171.3 (5.7)	161.8 (4.7)	98.6 (2.6)
665	204.6 (4.5)	197.3 (2.6)	122.5 (1.6)
Matityahu			
80	116.2 (5.1)	101.3 (6.8)	37.8 (1.1)
292	152.1 (8.6)	132.2 (5.2)	59.4 (3.1)
661	188.8 (7.2)	169.3 (3.2)	115.8 (3.5)

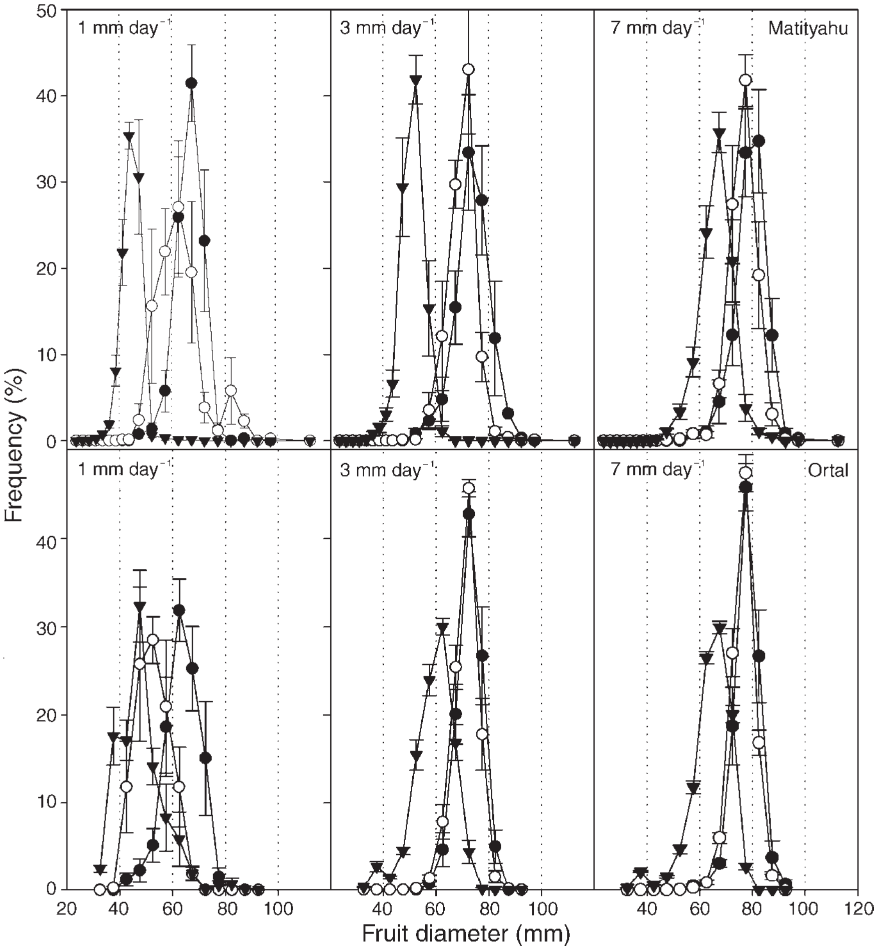

Figure 4. Effects of irrigation rate and crop load (low, ●; medium, ○; and high, ▼) on fruit size distribution in *Malus domestica* trees in 2006 at Ortal and Matityahu. Bars denote standard error.

load × low irrigation rate treatment was 38 and 52 g at harvest at Matityahu and Ortal, respectively, and it was ~22% of the potential fruit size, indicating a severe limitation of assimilate

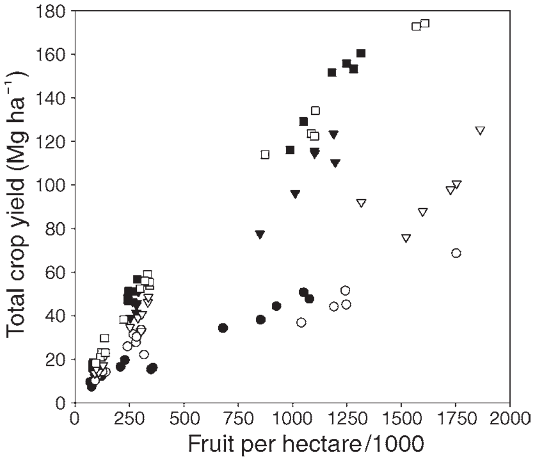

Figure 5. Effects of crop load on total crop yield of *Malus domestica* trees in 2006 at Ortal (filed symbols) and Matityahu (open symbols) subjected to three daily irrigation regimes (1 mm day^{-1} (●, ○); 3 mm day^{-1} (▼, ▽); and 7 mm day^{-1} (■, □)) and three crop loads. Each value represents a single tree.

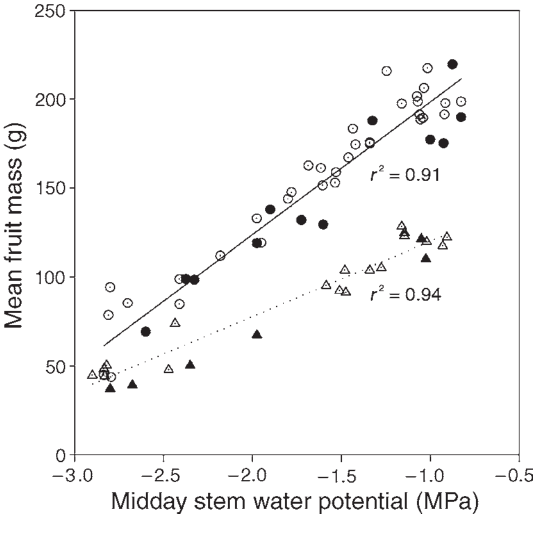

Figure 6. Effects of midsummer midday stem water potential of *Malus domestica* trees at Ortal (July 31, 2006; open symbols) and Matityahu (August 15, 2006; filled symbols) bearing one of the three crop loads (Low, L; medium, M; and high, H) on mean fruit mass at harvest. Symbols: L and M (●, ○); and H (▲, △).

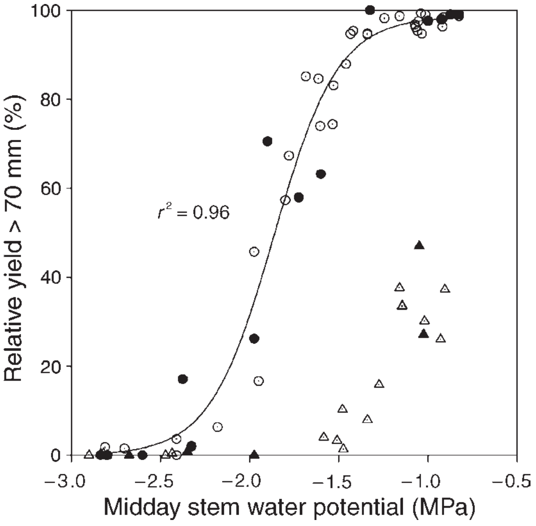

Figure 7. Effects of midsummer midday stem water potential of *Malus domestica* trees at Ortal (July 31, 2006; open symbols) and Matityahu (August 15, 2006; filled symbols) bearing one of three crop loads (Low, L; medium, M; and high, H) on relative yield of fruit > 70 mm in diameter (% of total crop yield). Symbols: L and M (●, ○); and H (▲, △).

availability to the crop. In this treatment, midday stem water potentials were lower than –2.5 MPa, a water status where stomata are expected to be closed (Naor 1998). Both crop load and tree water status determine fruit size (Table 2), but neither alone is able to predict fruit size (Figures 5 and 6). In contrast, starch content in the perennial stem predicted mean fruit mass, independently of whether source capacity (irrigation rate) or sink capacity (crop load) was manipulated (Naschitz et al., unpublished observations). These findings may indicate that assimilate availability, and not changes in fruit turgor potential with irrigation or any hormonal effect associated with variations in crop load, is the predominant mechanism through which irrigation and fruit thinning affect fruit size.

In general, total crop yield in both Ortal and Matityahu trees responded similarly to crop load (Figure 4, Tables 1 and 2) with two exceptions: similar crop yields in the Ortal and Matityahu trees in the high crop load × 3 mm day^{-1} treatment despite large difference in crop loads (Figure 4); and higher crop yield in Matityahu trees than in Ortal trees at a similar crop load (Figure 4, ~250,000 fruit ha^{-1}) in the 1 mm day^{-1} irrigation treatment (Figure 4, Tables 1 and 2). These exceptions might be explained by differences in tree water status—the fruit mass of Ortal trees bearing a high crop load in the 3 mm day^{-1} treatment was almost double that of the fruit mass of Matityahu trees—given that midday stem water potentials were –1.44 and –2.16 MPa in the Ortal and Matityahu trees, respectively. Fruit mass of trees in medium crop load × 1 mm day^{-1} treatment at Matityahu was 25% more than that at Ortal, and midday stem water potentials were –2.71 and –2.49 MPa in the Ortal and Matityahu trees, respectively.

Thus, the discrepancies in the response of crop yield to crop load between orchards can be explained by tree water status, and this is reflected in the high correlations between midday stem water potential and mean fruit mass within each crop load (Figure 6) and with relative yield of fruit > 70 mm in diameter (Figure 7). These results indicate the importance of tree water status in explaining the variability in crop loads and the importance of water availability, and thus provide a means for adjusting tree water status in orchards with variable crop loads and water availability. These findings apply to crop loads in the low and medium ranges (Figure 6) which cover the common commercial apple crop yields.

Similar responses of fruit size to midday stem water potential at Ortal and Matityahu (Figures 6 and 7) were apparent despite differences in rootstock, tree size, tree age, topographical situation and row spacing between orchards, suggesting that thresholds of midday stem water potential are transferable among orchards at least on a within-region basis. We conclude that transferability of thresholds of midday stem water potential is justified once the relationships between stem water potential and assimilation rate are similar, because the availability of assimilates is the predominant mechanism through which fruit size is affected by both irrigation and crop load (Naschitz et al., unpublished observations).

What may limit the transferability of thresholds? The relationships between water potential and stomatal conductance change during the season (Lakso 1979, Moller et al. 2007), probably through osmotic adjustment. Climatic conditions may affect the degree of osmotic adjustment and therefore the relationships between water potential and assimilation rate. Different air temperatures and therefore respiration rates or different solar irradiances (clouds) or day lengths (latitudes) may affect net assimilation rate at similar tree water status.

The maximum midday stem water potential that we measured (~0.9 MPa) is close to the maximal expected value considering the evaporative demand in the region (McCutchan and Shackel 1992), and may indicate that any deviation from minimum water stress may decrease fruit size (Figures 6 and 7). In addition, the demand for assimilates at high crop loads is beyond the maximum assimilate production rate under conditions of minimum water stress and therefore potential fruit size is not reached even at high irrigation rates. Our data suggest that when growers are forced to use deficit irrigation they could apply fruit thinning to minimize the reduction in fruit size (Figures 6 and 7, Tables 1 and 2). The response curves of mean fruit mass (Figure 6) and relative yield of > 70 mm in diameter (Figure 7) to midday stem water potential provide growers with information on the expected commercial crop yield for any given water status. It should be noted, however, that these responses are not universal and may change from one year to another because of differences in potential fruit size resulting from variable temperature regimes during the cell division stage (Warrington et al. 1999).

References

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrig. Drain. Paper 56, United Nations Food and Agriculture Organization, Rome, 301 p.

Berman, M.E. and T.M. DeJong. 1996. Water stress and crop load effects on fruit fresh and dry mass in peach (*Prunus persica*). Tree Physiol. 16:859–864.

Cohen, S., A. Naor, J. Bennink, A. Grava and M. Tyree. 2007. Hydraulic resistance components of mature apple trees on rootstocks of different vigours. J. Exp. Bot. 58:4213–4224.

DeJong, T.M. 1986. Effects of reproductive and vegetative sink activity on leaf conductance and water potential of *Prunus persica* L. Batsch. Sci. Hortic. 29:131–137.

Erf, J.A. and T.A. Proctor. 1989. Growth, mineral nutrition, and leaf water status of mature apple trees subjected to various crop loads and soil water conditions. J. Am. Soc. Hortic. Sci. 114:191–196.

Fereres, E. and D.A. Goldhamer. 2003. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. J. Hortic. Sci. Biotechnol. 78:139–144.

Fuji, J.A. and R.A. Kennedy. 1985. Seasonal changes in photosynthetic rate in apple trees. Plant Physiol. 78:519–524.

Giuliani, R., L. Coreli-Grappadeli and E. Magnanini. 1997. Effects of crop load on apple photosynthetic responses and yield. Acta Hortic. 451:303–311.

Giuliani, R., E. Magnanini and L. Corelli-Grapadelli. 1998. Whole canopy gas exchange and light interception of three peach training systems. Acta Hortic. 465:309–317.

Goldhamer, D.A. and E. Fereres. 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20:115–125.

Goldhamer, D.A., E. Fereres, M. Mata, J. Girona and M. Cohen. 1999. Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. J. Am. Soc. Hortic. Sci. 124:437–444.

Goldhamer, D.A., E. Fereres, M. Cohen, J. Girona and M. Mata. 2000. Comparison of continuous and discrete plant-based monitoring for detecting tree water deficits and barriers to grower adoption for irrigation management. Acta Hortic. 537:431–445.

Gucci, R., C. Xiloyannis and J.A. Flore. 1991. Gas exchange parameters, water relations and carbohydrate partitioning in leaves of field-grown P*runus domestica* following fruit removal. Physiol. Plant. 83:497–505.

Hansen, P. 1971. The effect of fruiting upon transpiration rate and stomatal opening in apple leaves. Physiol. Plant. 25:181–183.

Intrigliolo, D.S. and J.R. Castel. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. Irrig. Sci. 23:93–102.

Lakso, A.N. 1979. Seasonal changes in stomatal response to leaf water potential in apple. J. Am. Soc. Hortic. Sci. 104:58–60.

Marsal, J., G. Lopez, J. Girona, B. Basile and T.M. DeJong. 2005. Heterogenity in fruit distribution and stem water potential variations in peach trees under different irrigation conditions. J. Hortic. Sci. Biotechnol. 80:82–86.

McCutchan, H. and K.A. Shackel. 1992. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv French). J. Am. Soc. Hortic. Sci. 117:607–611.

Möller, M., V. Alchanatis, Y. Cohen, M. Meron, J. Tsipris, A. Naor, V. Ostrovsky, M Sprintsin and S. Cohen. 2007. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. J. Exp. Bot. 58:827–838.

Naor, A. 1998. Relationships between leaf and stem water potentials and stomatal conductance in three field-grown woody species. J. Hortic. Sci. Biotechnol. 73:431–436.

Naor, A. 2006. Irrigation scheduling and evaluation of tree water status in deciduous orchards. Hortic. Rev. 32:111–166.

Naor, A. and S. Cohen. 2003. The sensitivity and variability of maximum trunk shrinkage, midday stem water potential, and transpiration rate in response to withholding of irrigation in field-grown apple trees. Hortscience 38:547–551.

Naor, A., I. Klein and I. Doron. 1995. Stem water potential and apple fruit size. J. Am. Soc. Hortic. Sci. 120:577–582.

Naor, A., I. Klein, I. Doron, Y. Gal, Z. Ben-David and B. Bravdo. 1997. The effect of irrigation and crop load on stem water potential and apple fruit size. J. Hortic. Sci. 72:765–771.

Naor, A., I. Klein, H. Hupert, Y. Grinblat and M. Peres. 1999. Irrigation and crop load interactions in relation to nectarine yield, fruit size distribution and water potentials. J. Am. Soc. Hortic. Sci. 124: 189–193.

Naor, A., M. Peres, Y. Greenblat, I. Doron, Y. Gal and R.A. Stern. 2000. Irrigation and crop load interactions in relation to pear yield and fruit-size distribution. J. Hortic. Sci. Biotechnol. 75:555–561.

Naor, A., Y. Gal and M. Peres. 2006. Inherent variability of a few water stress indicators in apple, nectarine and pear orchards, and the validity of a commercial leaf-selection procedure for water potential measurements. Irrig. Sci. 24:129–135.

Palmer, J.W. 1993. Recent developments on light and fruit tree canopies. Acta Hortic. 349:99–109.

Palmer, J.W., R. Giuliani and H.M. Adams. 1997. Effect of crop load on fruiting and leaf photosynthesis of 'Braeburn'/M.26 apple trees. Tree Physiol. 17:741–746.

Robinson, T. and A.N. Lakso. 1991. Bases of yield and production efficiency in apple orchard systems. J. Am. Soc. Hortic. Sci. 116: 188–194.

Warrington, I.J., T.A. Fulton, E.A. Halligan and H.N. de Silva. 1999. Apple fruit growth and maturity are affected by early season temperatures. J. Am. Hortic. Sci. 124:468–477.

Wibbe, M.L. and M.M. Blanke. 1995. Effects of defruiting on source–sink relationship, carbon budget, leaf carbohydrate content and water use efficiency of apple trees. Physiol. Plant. 94: 529–533.

Wünsche, J.N., A.N. Lakso and T. Robinson. 1995. Comparison of four methods for estimating total light interception by apple trees of varying forms. HortScience 30:272–276.

Wünsche, J.N., J.W. Palmer and D.H. Greer. 2000. Effect of crop load on fruiting and gas exchange characteristics of 'Braeburn'/M.26 apple trees at full canopy. J. Am. Soc. Hortic. Sci. 125:93–99.