Irrig Sci (2009) 27:183–190
DOI 10.1007/s00271-008-0141-0

REVIEW

Does partial root-zone drying improve irrigation water productivity in the field? A meta-analysis

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Received: 16 September 2008 / Accepted: 10 December 2008 / Published online: 31 December 2008

Abstract Partial root-zone drying improves irrigation water productivity (IWP, yield per unit applied irrigation water) with respect to controls receiving substantially more water, but similar gains are often achieved with conventional deficit irrigation. This paper presents a meta-analysis of IWP for a broad range of horticultural crops and environments. Two comparisons were preformed: (a) crops managed with either partial root-zone drying or conventional deficit irrigation against controls receiving substantially more water than the two water-saving techniques, (b) crops managed with partial root-zone drying and their counterparts with conventional irrigation where both received similar amounts of irrigation. In relation to controls receiving substantially more water, conventional deficit irrigation increased IWP by an average 76% and partial root-zone drying by 82%; the gains from both water-saving methods were statistically undistinguishable. Yield per unit applied irrigation water of crops under partial root-zone drying was significantly ($P = 0.007$) but modestly (5%) higher than in their counterparts with conventional irrigation where both received similar amounts of irrigation. In 80% of cases the difference in IWP between the two methods was in the ±20% range. Considering the cost and management complexity of implementing partial root-zone drying, it is critical to identify the rare conditions where this method could be economically justified.

Communicated by E. Fereres.

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Introduction

Ingenious experiments with split-root systems were instrumental in advancing our understanding of root-to-shoot stress signalling (Zekri and Parsons 1990; Zhang et al. 1987) and eventually lead to the concept of partial root-zone drying, an irrigation technique aimed at improving yield per unit applied irrigation water. The core of this approach is alternating irrigation in space and time to generate wet-dry cycles in different sections of the root system. This seeks to promote chemical signals from roots in dry soil, thus reducing stomatal conductance, transpiration and shoot growth, while maintaining crop water supply from roots in the wet soil fraction, thus avoiding severe water deficit (Davies et al. 2002; Morison et al. 2008).

Partial root-zone drying clearly improved yield per unit of applied water with respect to conventional irrigation using higher rates of irrigation (Davies et al. 2002; Dry 1997; Dry et al. 2001; Kirda et al. 2007b; Morison et al. 2008). However, many of the studies where partial root-zone drying outperformed conventional irrigation lacked proper controls and therefore confounded two effects: the amount of water, which was usually much less in partial root-zone drying than in conventionally irrigated crops, and the key principle of generating wet-dry cycles in different parts of the root system (Bravdo et al. 2004).

The aim of this paper is to provide a collective, quantitative comparison of irrigation water productivity (IWP, yield per unit applied irrigation water) in field-grown horticultural crops managed with partial root-zone drying and conventional deficit irrigation using similar amounts of irrigation. The effects of irrigation method on quality traits are out of the scope of this study (De Souza et al. 2005; dos Santos et al. 2005, 2007; Kirda et al. 2007b).

Method

I compiled a data set of IWP searching the Web of Science database for "partial root-zone drying" with alternative formats, and reports from our own databases. Two exclusion criteria were applied to constrain our data set to agronomically realistic conditions. First, experiments with potted plants or in controlled environments were excluded; these artificial conditions are known to generate a range of artifacts (Ben-Porath and Baker 1990; McConnaughay and Bazzaz 1991; Passioura 2006; Sachs 2006; Sadras et al. 1993a, b; Wise et al. 1990). Second, field experiments with obvious confounded factors were excluded, e.g. partial root-zone drying and regular irrigation treatments using different irrigation equipment (Spreer et al. 2007), shallow water tables (Kang et al. 2002) or where high irrigation rates indicated that runoff was likely (Gencoglan et al. 2006). The resulting data set is summarised in Table 1.

Two comparisons were preformed. First, IWP of crops managed with either partial root-zone drying or conventional deficit irrigation was compared against controls receiving substantially more water than the two water-saving techniques. Second, IWP of crops managed with partial root-zone drying and their counterparts with conventional irrigation where both received similar amounts of irrigation were compared. The null hypotheses of these two comparisons were

1. Decreasing irrigation rates, i.e. deficit irrigation, increases the yield per unit applied irrigation water (Fereres and Soriano 2007). Statistically, the expectation is that the slopes of the regressions between IWP for partial root-zone drying vs control, and conventional deficit irrigation vs control are greater than 1.
2. Partial root-zone drying increases IWP at similar rates of irrigation. Statistically, the expectation is that the slope of the regression between IWP for partial root-zone drying vs controls is greater than 1, i.e. alternating wet-dry cycles in different root-zone sections contributes to water use efficiency beyond the effects of reduction in water input.

In addition to yield per unit applied irrigation water, I compared midday leaf or xylem water potential and stomatal conductance between partial root-zone drying and conventional irrigation receiving similar amounts of water as in partial root-zone drying. In all comparisons, IRENE software (Fila et al. 2003) was used to derive model II regressions (reduced major axis) necessary to account for errors in both y and x (Niklas 1994). Model II regression is particularly appropriate for these comparisons because: (1) it is symmetric in x and y, i.e., if the x and y axes are interchanged, the slope is replaced by its reciprocal and the line remains stationary about the data points; (2) it is scale independent, and (3) it is robust to clusters of observations in the frequency distributions of data, i.e. the line usually describes the central trend even when the sample is not bivariate normal. In the papers analysed, standard errors for yield per unit applied irrigation water, stomatal conductance and water potential were not always reported so no attempt was made to account for variable errors among experiments (Hunter and Schmidt 1990).

Results

Yield per unit applied irrigation water

Figure 1 compares conventional irrigation and partial root-zone drying under deficit irrigation against controls receiving substantially more irrigation. The regression analyses showed that IWP was much higher in partial root-zone drying (82%) and conventional deficit irrigation (76%) treatments than in controls receiving substantially more irrigation (Fig. 1). The improvements in IWP in the conventional irrigation and partial root-zone drying under deficit irrigation were statistically undistinguishable: no difference in slopes and no difference in intercepts were detected (Fig. 1). This indicates that the significant improvement in IWP, around 80%, is attributable to irrigation rate, rather than to the irrigation technique.

Figure 2a compares IWP under partial root-zone drying with that for crops conventionally irrigated with similar amounts of water. Yield per unit applied irrigation water under partial root-zone drying was significantly ($P = 0.009$) but slightly (5%) higher than under conventional irrigation. A complementary analysis indicated that in 80% of cases the difference between the two irrigation methods was in a ±20% range (shaded area in inset of Fig. 2a). In 20% of cases, partial root-zone drying outperformed deficit irrigation by 20% or more (unshaded area in inset of Fig. 2a).

The relatively large data set for grapevine allowed a crop-specific analysis showing no significant difference in IWP between partial root-zone drying and conventional irrigation (Fig. 2b).

Stomatal conductance and water potential

Our analysis indicated a significant ($P < 0.05$) but small (5%) difference in stomatal conductance between conventional irrigation and partial root-zone drying at similar irrigation rates (Fig. 3a). Differences in stomatal conductance were more pronounced below 200 mmol m^{-2} s^{-1} (Fig. 3a). This range was dominated by the study of Marsal et al. (2008) and re-analysis of the data set excluding this

Table 1 Summary of experiments used in the comparison of crops under different irrigation regimes

Crop	Variety	Region	Irrigation treatments	Other sources of variation	References
Grapevine	Chardonnay	SE Australia	C (control), PRD (partial root-zone drying), DI (deficit irrigation) 1.6:1:1[a]	Season, mulching	Richards et al. (2008)
	Shiraz, Riesling, Cab. Sauvignon	SE Australia	C, PRD 1.9:1	Season, location	Dry et al. (2001)
	Chardonnay	SE Australia	Full (F), full partial root-zone drying (FPRD), split (S), deficit (D) and deficit partial root-zone drying (DPRD) 1.4:1.4:1:1:1	Season	Pudney and McCarthy (2004)
	Shiraz	SE Australia	Control, DI, PRD 2.1:1:1		Chalmers et al. (2004)
	Shiraz	SE Australia	DI, PRD (several rates) 1:1	Season, location	Fuentes (2006)
	Moscatel, Castelão	S Portugal	C, PRD, DI, NI (rainfed) 2 : 1 : 1 : 0	Season	dos Santos et al. (2003)
	Moscatel	S Portugal	C, PRD, DI, NI 2:1:1:0		dos Santos et al. (2007)
	Sauvignon blanc	California, USA	C, PRD (factorial with 0.4 and 0.8 of crop evapotranspiration) 1:1	Season	Gu et al. (2004)
	Monastrel	SE Spain	C, PRD 1:1	Season	De la Hera et al. (2007)
	Tempranillo	N Spain	C, PRD, DI (two variants each) 1.9:1:1	Season	Marsal et al. (2008)
	Merlot	Israel	PRD, DI 1:1	Season	Bravdo et al. (2004)
Pear	Williams Bom Chretein	SE Australia	C, PRD at two rates, DI 1.9:1.9:1:1	Season	O'Connell and Goodwin (2007b)
Mandarin	Marisol	Adana, Turkey	TR (traditional irrigation), C, three variants of PRD (1PRD30, 1PRD50, 2PRD50), DI 4.6:1.9:1.4:1:1:1	Season	Kirda et al. (2007a)
Strawberry	Honeoye	Denmark	C, PRD, DI 1.7:1:1		Liu et al. (2007)
Tomato	F1 Fantastic	Arana, Turkey	C, two variants of PRD (1PRD30, 1PRD50, 2PRD50), two variants of DI (DI30, DI50) 2:1.4:1:1.4:1		Kirda et al. (2004)
Potato	Folva	Denmark	C, two variants of PRD (PRD1, PRD2), DI 1.4:1.2:1:1		Shahnazari et al. (2008)
Apple	Pink Lady	SE Australia	C, PRD, DI 2:1:1	Season	O'Connell and Goodwin (2007a)
	Fuji	NW USA	C, PRD, DI 1.4:1:1.1	Season	Leib et al. (2006)
Orange	Bellami	SE Australia	C, PRD, DI 1.8:1:1.1	Season, rootstock	Treeby et al. (2007)
Raspberry	Glen Ample and Glen Prosen check	Scotland	C, PRD (two rates), DI 4:2:1:1		Grant et al. (2004)
Peach	September Snow	California, USA	C, PRD (two rates), DI (two rates) 1.2–1.4:1:1	Timing of irrigation	Goldhamer et al. (2002)

[a] Approximate average ratios of amount of irrigation for the specified treatments

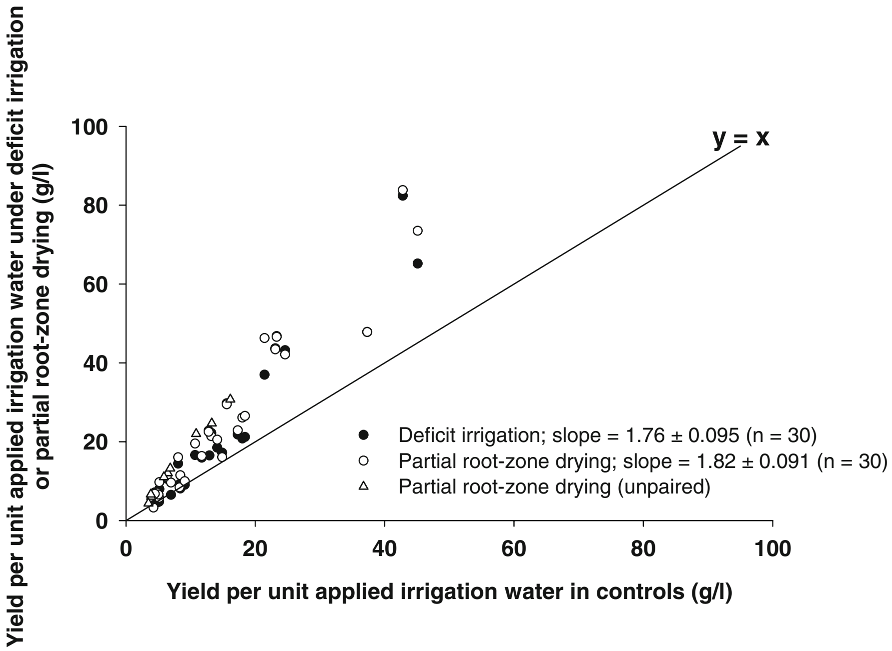

Fig. 1 Comparison of yield per unit applied irrigation water in crops managed with deficit irrigation (DI) or partial root-zone drying (PRD) in relation to controls that received substantially more water (Table 1). Circles are from experiments were both treatments were included and received similar amount of water. *Triangles* are from experiments where DI was not implemented, and were not included in calculations. Slopes, derived from Model II regressions to account for the errors in both *y* and *x*, were significantly greater than 1 for both DI and PRD ($P < 0.0001$) and were statistically similar for both DI and PRD ($P > 0.05$). Intercepts were not different from zero for DI ($P > 0.61$) and PRD ($P > 0.68$)

study showed no difference in stomatal conductance between treatments (slope = 1.03 ± 0.03). The two irrigation techniques had similar xylem or leaf water potential (Fig. 3b). The relationship for water potential had a significant quadratic term ($P < 0.0001$) indicating that differences attributable to partial root-zone drying were more marked in a range from −1 to −2 MPa.

Discussion

Does partial root-zone drying improve water use efficiency?

Davies et al. (2002) and Morison et al. (2008) reviewed the principles and practical results of partial root-zone drying. These reviews used a narrative approach (sensu Hunter and Schmidt 1990), whereas a considerable body of data now allows for a meta-analysis, the approach used in this paper. I compared partial root-zone drying and conventional irrigation at similar irrigation rates using a large data set encompassing a wide range of environments and diverse horticultural species and cultivars, including perennials and annuals. Deficit irrigation applied by either the partial root-zone drying technique or by the conventional irrigation increased the yield per unit applied irrigation water by ~80% relative to controls receiving substantially more irrigation (Fig. 1).

The direct comparison of IWP under partial root-zone drying and conventional methods at similar irrigation rates showed a statistically significant, but modest advantage (average 5%) of partial root-zone drying (Fig. 2a). Restricting the analysis to grapevine, the species with the largest number of studies, revealed no benefit of partial root-zone drying (Fig. 2b). Our analysis thus reinforces the notion that the improvement in yield per unit applied irrigation water reported in early field tests of partial root-zone drying was due to the lower irrigation rates applied in relation to conventional irrigation controls rather than to the technique per se (Figs. 1, 2).

Different number of emitters in the two methods and different spacings may affect water losses either by deep percolation or soil surface evaporation. Partial root-zone drying usually involves fewer emitters active at any given time and higher amounts of water are irrigated through each of them (usually twice). A priori, one would expect higher likelihood of deep percolation and lower soil surface evaporation in partial root-zone drying, but the actual rates depend on complex interactions with factors such as soil hydraulic properties, irrigation frequency and rate, and evaporative demand. In any case different proportions of water losses in the two techniques

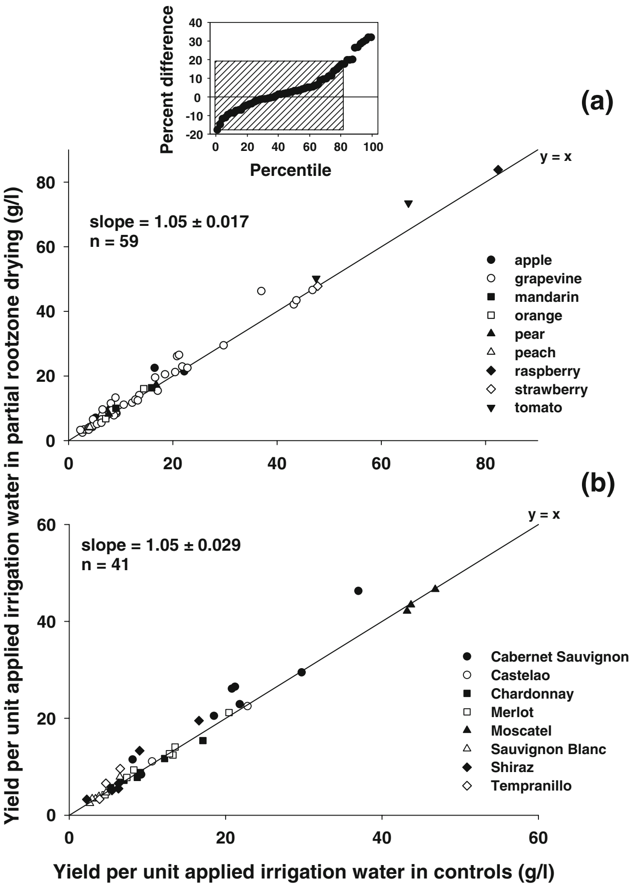

Fig. 2 **a** Comparison of yield per unit applied irrigation water between crops managed with partial rootzone drying and conventionally irrigated crops with similar amounts of water. The slope, derived from Model II regression to account for the errors in both y and x, was significantly greater than 1 ($P = 0.009$) and the intercept was not different from zero ($P > 0.89$). *Inset* shows the frequency distribution of the percent difference in yield per unit applied irrigation water between partial root-zone drying and controls where the shaded area represents the ±20% range. **b** Detail of grapevine cultivars. The slope was not different from 1 ($P > 0.09$) and the intercept was not different from zero ($P > 0.92$)

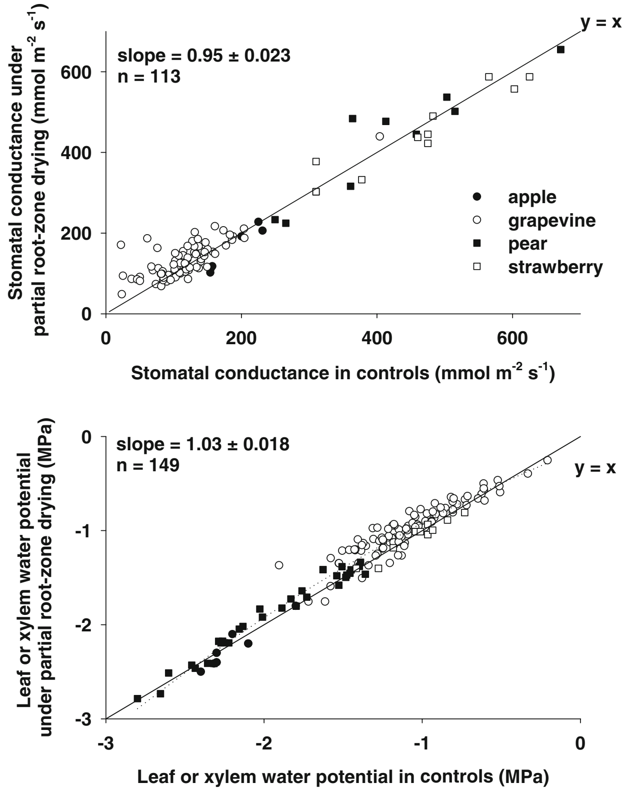

Fig. 3 Comparison of stomatal conductance and leaf or xylem water potential between crops under partial root-zone drying, and control crops receiving similar amount of irrigation. The slope, derived from Model II regressions to account for the errors in both y and x, was different from 1 ($P < 0.05$) for stomatal conductance and not different from 1 for water potential ($P > 0.05$). Intercepts were not different from zero in both cases ($P > 0.64$ for stomatal conductance, $P > 0.74$ for water potential). The *dotted line* is a quadratic model highlighting a statistically significant departure from linearity ($P < 0.0001$) in the relationship of water potentials

may affect actual irrigation water available for the crop and water use efficiency.

The top 20% of the frequency distribution of the difference between irrigation methods showed substantial benefits of partial root-zone drying (inset Fig. 2). Considering the complexity of management involved in implementing partial root-zone drying, it is critical to identify the conditions where this technology could generate this sort of improvement in water use efficiency. Ad hoc explanations can be formulated to account for the conditions required for partial root-zone drying to outperform conventional deficit irrigation, e.g. sandy soils (Marsal et al. 2008) or acclimation including plastic root responses (Abrisqueta et al. 2008; Soar and Loveys 2007); but no tests were performed so far to examine those criteria. It is suggested that improving *crop* models of responses to water deficit are required to make progress in this direction.

Why crops do not match the theory?

The mismatch between the predictions of a sound physiological theory on root chemical and hydraulic signals (Davies et al. 2002; Ren et al. 2007; Tardieu and Davies 1993; Tardieu et al. 1996) and the actual yield-to-irrigation ratios summarised in Fig. 2 is suggested to be partially related to the gap between short-term *plant* responses and season-long *crop* responses in complex field environments (Hammer et al. 2004; Sinclair et al. 2004).

In Fig. 4, the mechanisms of *crop* responses to water deficit are grouped in three classes. Pathway 1 involves root-to-shoot and shot-to-root hydraulic and chemical signals, which have attracted profuse attention. Pathway 2 involves a very strong reinforcing loop, whereby initial

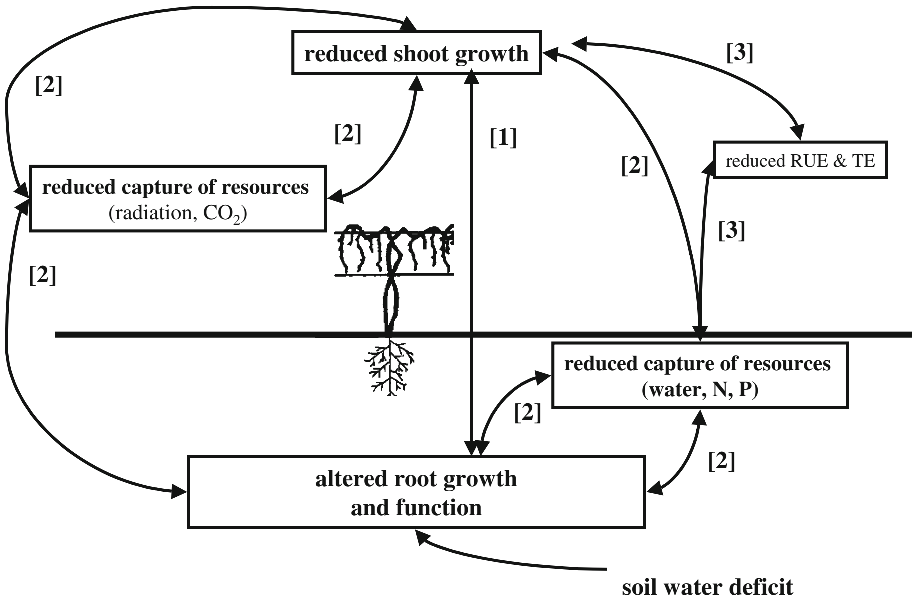

Fig. 4 Physiological mechanisms of crop responses to soil water deficit. Pathway [1] involves direct root perception of soil water deficit, and root signals inducing reduction in shoot growth mediated by reduced stomatal conductance, reduced leaf expansion or both; the two-way arrow allows for shoot-to-root signalling. Pathway [2] involves a strong, reinforcing loop of reduced shoot and root growth, which is mediated by impairment of the ability of root systems and canopies to capture resources. Pathway [3] involves reductions in the efficiency in the use of resources, as exemplified by radiation use efficiency (RUE) and transpiration efficiency (TE). Adapted from Sadras et al. (2005)

reduction in growth of shoot, root or both, forms a loop that may eventually override other processes. Pathway 3 involves changes in radiation use- and transpiration efficiency; these efficiencies are stable except in conditions of severe stress (Sinclair and Muchow 1999; Steduto et al. 2007). Emphasis in Pathway 1, whereby root signals are seen as a critical element in the response of the crop to soil water deficit, lead to the concept of partial root-zone drying, but Pathway 2 has been largely neglected. It maybe that deficit irrigation is sufficient to trigger the putative signals which supposedly confers advantages to partial root-zone drying (Bravdo et al. 2004) (Fig. 3). Alternatively, it may be that irrespective of how crops initially respond to soil water deficit, resource capture is the ultimate, overriding mechanism underling production under water deficit.

Specific elements that are relevant to a more robust crop-level model of responses to irrigation include (a) the relative importance of the different mechanisms of control of transpiration, and how they vary with ontogeny, crop species and variety, (b) scaling up of control mechanisms from leaf to canopy, and (c) genotype by environment interactions. At the crop-level, transpiration (T) is (Sadras et al. 1993b):

$$T = L \times \mathrm{IR} \cdot L^{-1} \times T \cdot \mathrm{IR}^{-1} \qquad (1)$$

where L is leaf area index, and IR is intercepted radiation. When grapevine Cabernet Sauvignon (Pellegrino et al. 2006) and sunflower (Connor and Sadras 1992; Sadras et al. 1991) leaves are actively expanding, L is a more sensitive point of control of transpiration than stomatal regulation affecting $T\ \mathrm{IR}^{-1}$. Matthews et al. (1988) illustrate the role of $\mathrm{IR\ L}^{-1}$ in peanut crops where transient wilting markedly reduced transpiration during dry periods in dry-wet cycles. Scaling up from leaf to canopy needs to account for the degree of coupling between canopy and atmosphere (Aires et al. 2008; Jarvis and McNaughton 1986). Inter- and intra-specific variation in the mechanisms of control of transpiration and their relative sensitivity to soil water deficit are important, as illustrated by Casadebaig et al. (2008) in sunflower and Schultz (2003) in grapevine. Genotype by environment interactions influencing the relative roles of chemical and hydraulic signalling are poorly understood (Ren et al. 2007). Schwinning and Ehleringer (2001) remains one of the best examples on how environmental conditions, i.e. pattern of water supply, could revert the pattern of traits conferring adaptive advantages under water deficit.

Conclusion

In common with individual studies using proper controls (Bravdo et al. 2004; Fuentes 2006; Goldhamer et al. 2002; Gu et al. 2004; O'Connell and Goodwin 2007a; Pudney and McCarthy 2004), our meta-analysis supported the conclusion that substantial improvement in water use efficiency can be achieved by closely monitored deficit irrigation, without the complexity and additional cost of partial root-zone drying. Pairwise comparisons indicated that in 80% of cases, the difference in yield per unit applied irrigation water between the two irrigation methods was in the ±20% range. Identifying the rare conditions where partial root-zone drying might improve water use efficiency beyond that of conventional deficit irrigation requires improved crop-level models of responses to water deficit.

Acknowledgments I thank Amos Naor for substantial input into this paper; Mark O'Connell, Sigfredo Fuentes and Jordi Marsal for data and useful comments; Peter Dry and Ben Ami Bravdo for useful discussions and the River Murray Improvement Program for financial support.

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