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Review

Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas

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ABSTRACT

Deficit irrigation (DI) has been widely investigated as a valuable and sustainable production strategy in dry regions. By limiting water applications to drought-sensitive growth stages, this practice aims to maximize water productivity and to stabilize – rather than maximize – yields. We review selected research from around the world and we summarize the advantages and disadvantages of deficit irrigation. Research results confirm that DI is successful in increasing water productivity for various crops without causing severe yield reductions. Nevertheless, a certain minimum amount of seasonal moisture must be guaranteed. DI requires precise knowledge of crop response to drought stress, as drought tolerance varies considerably by genotype and phenological stage. In developing and optimizing DI strategies, field research should therefore be combined with crop water productivity modeling.

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1. Rationale

To sustain the rapidly growing world population, agricultural production will need to increase (Howell, 2001), yet the portion of fresh water currently available for agriculture (72%) is decreasing (Cai and Rosegrant, 2003). Hence, sustainable methods to increase crop water productivity are gaining importance in arid and semi-arid regions (Debaeke and Aboudrare, 2004). Traditionally, agricultural research has focused primarily on maximizing total production. In recent years, focus has shifted to the limiting factors in production systems, notably the availability of either land or water. Within this context, deficit irrigation (DI) has been widely investigated as a valuable strategy for dry regions (English, 1990; Pereira et al., 2002; Fereres and Soriano, 2007) where water is the limiting factor in crop cultivation. We review recent research on the maximization of productivity per unit of water by DI and we discuss crop water productivity modeling as a tool for assessing and designing DI strategies.

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2. Crop water productivity

2.1. The concept

Crop water productivity (WP) or water use efficiency (WUE), as reviewed by Molden (2003), is a key term in the evaluation of DI strategies. Water productivity with dimensions of kg m\(^{-3}\) is defined as the ratio of the mass of marketable yield (\(Y_a\)) to the volume of water consumed by the crop (\(ET_a\)):

\[
WP = \frac{Y_a}{ET_a}
\]  

\(ET_a\) refers to water lost either by soil evaporation or by crop transpiration during the crop cycle. Since there is no easy way of distinguishing between these two processes in field experiments, they are generally combined under the term of evapotranspiration (ET) (Allen et al., 1998).

In water-scarce regions, crops with high WP should be preferred, although this is not the only factor. Indeed, while high-energy fruit and grain crops (e.g. crops with high protein content) may have a lower absolute WP value (Steduto and Albrizio, 2005), their nutritional value is higher, which should be considered when assessing these crops for use in drought-prone areas. WP values reported in literature vary according to whether authors express the denominator as the amount of water applied (the sum of rainfall and irrigation) or as the amount of water transpired (unproductive soil evaporation is not taken into account).

2.2. The crop water production function

The crop water production function (CWP function) expresses the relation between obtained marketable yield (\(Y_a\)) and the total amount of water evapotranspired (\(ET_a\)) (Stewart et al., 1977; Hexem and Heady, 1978; Doorenbos and Kassam, 1979; Taylor et al., 1983). The highest water efficiency level in the CWP function is determined using WP as a benchmark. As shown in Fig. 1, the CWP function has a logistic shape (Hanks et al., 1969; Hanks, 1974). Its axes are made dimensionless by plotting relative yield (\(Y_a\) relative to maximum possible yield under given agronomic conditions, \(Y_m\)) versus relative evapotranspiration (\(ET_a\) relative to crop ET under non-stressed, standard conditions, \(ET_c\)).

![Fig. 1. General shape of a crop water production (CWP) function. Sections (a), (b), (c), (d) and (e) have variable relative widths. Relative yield is the ratio between actual (\(Y_a\)) and potential yield (\(Y_m\)) under given agronomic conditions, while relative evapotranspiration is the ratio between the seasonal amount of water that is evaporated (\(ET_a\)) and seasonal crop water requirements (\(ET_c\)).](Image)

\[ WP_{\text{section-d}} = a \cdot ET_a + b + c \cdot ET_a^{-1} \]  

\[ \frac{d(WP_{\text{section-d}})}{dET_a} = a - c \cdot ET_a^{-2} \]

The distinction between drought-tolerant and -sensitive crops is not straightforward and depends on the range of \(ET_a\), within which it is defined (Fig. 2). In Fig. 2a maximum WP is reached for \(ET_a\) lower than \(ET_c\), whereas in Fig. 2b WP increases until full water requirements are met (point D).
If water shortage (\( \text{ET}_{\text{rel}} < 1 \)) is evenly distributed over the cropping cycle, the corresponding yield decline can be derived from the seasonal \( \text{ET}_{\text{rel}} \). Figs. 1 and 2 indeed show such seasonally determined CWP functions (CWP function). However, for many crops, drought tolerance varies strongly between growth stages (e.g., Martyniak, 2008). Hence, the CWP functions for these individual growth stages will differ in shape from the CWP function, as the relationship does not account for the effect of the timing of water application. Combining various CWP functions per phenological stage is difficult, in part because there are different combination methods, particularly with linear CWP functions (section c) (Jensen, 1968; Hiller and Clark, 1971; Hanks, 1974; Stewart et al., 1977; Varlev et al., 1996), and each method has advantages and disadvantages. If a combined CWP function (CWPc function) could be constructed, differentiating drought stress levels over the phenological stages, the general shape would remain similar to that of the CWP function, but increased scatter would make it more difficult to establish general guidelines. In this context, crop water productivity modeling becomes a valuable tool.

3. Deficit irrigation: deliberately tolerating drought stress

3.1. The concept of deficit irrigation

Deficit irrigation is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop. Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water. Water restriction is limited to drought-tolerant phenological stages, often the vegetative stages and the late ripening period. Total irrigation application is therefore not proportional to irrigation requirements throughout the crop cycle. While this inevitably results in plant drought stress and consequently in production loss, DI maximizes water productivity, which is the main limiting factor (English, 1990). In other words, DI aims at stabilizing yields and at obtaining maximum WP rather than maximum yields (Zhang and Oweis, 1999).

In the literature, the terms ‘supplemental irrigation’ and ‘deficit irrigation’ are both used. The first term generally refers to a rain-fed crop receiving additional irrigation during the whole season or during sensitive growth stages, whereas DI generally refers to fully irrigated crops from which water is withheld during certain tolerant growth stages. Both terms are often used interchangeably, which may cause confusion. To avoid ambiguity, “deficit irrigation” is therefore used as the only term throughout this review.

Since drought tolerance varies considerably by genotype and by phenological stage, DI requires precise knowledge of crop response to drought stress for each of the growth stages (Kirda et al., 1999). In addition, correct application of DI requires a thorough assessment of the economic impact of the yield reduction caused by drought stress (English, 1990; English and Raja, 1996; Sepaskhah and Akbari, 2005; Sepaskhah et al., 2006). In areas where water is the most limiting factor, maximizing WP may be economically more profitable for the farmer than maximizing yields (English, 1990). For instance, water saved by DI can be used to irrigate more land (on the same farm or in the water user’s community), which—given the high opportunity cost of water—may largely compensate for the economic loss due to yield reduction (Kipkorir et al., 2001; Ali et al., 2007). Even water transfers from water-rich to water-poor areas are possible, as recently demonstrated in California, where DI was used for alfalfa (Hanson et al., 2007). As these examples suggest, DI requires a highly integrated approach to agricultural water policy.

3.2. Research results for different crops

3.2.1. Seasonal crop water production functions

This section discusses a number of studies in which irrigation applications or levels of tolerated drought stress did not differ between phenological stages. The resulting seasonal CWP function has the theoretical shape shown in Fig. 1, with variable section widths. If different shapes are presented in the literature, this may be due to the fact that the drought stress in the experimental design did not cover the complete relative ET range (Fabeiro et al., 2002; Oweis et al., 2004), that certain sections may have been small or even absent (Payero et al., 2006), or that certain sub-sections were approximated by (a combination of) linear functions.

The general framework presented in Fig. 1 allows us to compare the efficiency of DI versus rain-fed cultivation and/or full irrigation (FI) for a particular crop in a particular location. In many (semi)-
and Oweis, 1999)) and in Bangladesh (Ali et al., 2007). The latter authors report that DI caused an average increase in yield of 1.6 Mg ha\(^{-1}\) over the different experimental years in comparison with the rain-fed treatments.

- As for experiments with seasonally distributed drought stress, most authors (Table A1) find that maize responded rather poorly to DI differentiated by phenological stage and suggest that FI is generally preferable. Pandey et al. (2000a,b), for example, conducted experiments on the combined effect of fertilizer application (N-rates) and DI on maize. The highest WP was obtained with FI or deficits limited to the early vegetative stages. This coincided with almost linear CWP\(_c\) functions for the different N-fertilizer levels.

Many less common and horticultural crops listed in Table A1 often respond favorably to DI. Field experiments conducted in the semi-arid to arid Bolivian Altiplano (Geerts et al., 2006b) found that DI was able to stabilize quinoa yields at a level of 1.6 Mg ha\(^{-1}\) with excellent grain size (Geerts et al., 2008a). This could be achieved by applying only half of the irrigation water required for FI. Irrigation only needed to be applied during the most drought-sensitive stages, i.e. plant establishment, flowering and early grain filling for quinoa (Garcia, 2003; Geerts et al., 2006a). Geerts et al. (2008b) established that in very arid regions, such as the Southern Bolivian Altiplano, several boundary conditions need to be fulfilled to guarantee the success of DI: a minimum of the seasonal crop water requirements must be covered by rainfall and/or irrigation (i.e. section a in Fig. 1) and due attention should be paid to the risk of salinization. An additional beneficial effect of DI on quinoa is that the farmer has greater control of the timing of flowering and harvest, allowing better planning of agricultural activities throughout the season (Geerts et al., 2008c).

When large increases in WP due to DI are observed for trees and deep rooted crops, it should be borne in mind that, unless otherwise indicated, soil water depletion from deeper soil layers is generally not assessed in these experiments (Iniesta et al., 2008). If this additional soil water were taken into account, the actual increase in WP might be lower than reported. Similarly, positive effects of partial root zone drying (PRD) are sometimes exaggerated if differences between initial and final soil water content are not properly considered. In this regard, Liu et al. (2006) report that DI of potato crops had greater effect on WP than PRD, as the latter technique was unable to produce a net WP increase. Wakrim et al., 2005 and Kirda et al., 2005 reject the hypothesis that PRD would cause higher WP than conventional DI for common bean and maize, respectively. On the other hand, positive effects (e.g. on mango fruit size, Speer et al., 2009) are also reported.

### 3.3. Advantages and constraints of deficit irrigation

The main advantage of DI is that it maximizes the productivity of water. Although a certain reduction in yield is observed, the quality of the yield (e.g. sugar content, grain size) tends to be equal or even superior to rain-fed or FI cultivation (e.g. Fabeiro et al., 2003b; Zhang et al., 2004; Zhang et al., 2006; Marouelli and Silva, 2007; Speer et al., 2007; Cui et al., 2008; Hueso and Cuevas, 2008).

In areas where water is the limiting factor for crop production, maximizing WP by DI is often economically more profitable for the farmer than maximizing yield. Moreover, irrigated yields can be stabilized at a particular level, guaranteeing a stable income for the farmer and allowing economic planning. An additional advantage is that DI creates a less humid environment around the crop than FI, decreasing the risk of fungal diseases (e.g. Cicognà et al., 2005).
Reducing irrigation applications over the crop cycle will also reduce nutrient loss through leaching from the root zone, resulting in improved ground water quality (e.g., Ünlü et al., 2006) and lower nutrient loss through leaching from the root zone, resulting in reduced depletion of irrigation water. Over-fertilization may cause crops to be more susceptible to dry spells and may lead to decreased harvest indexes (Garabet et al., 1998). On the other hand, FI can only result in high yields if sufficient N-fertilizer is applied (Garabet et al., 1998; Oweis et al., 1998; Pandey et al., 2000a,b; Geerts et al., 2008a; Di Paolo and Rinaldi, 2008). This indicates that each DI strategy has its optimum fertilizer level (Tavakkoli and Oweis, 2004; Cabello et al., 2009). Hence, DI is most effective if different management factors are considered in parallel (Oweis et al., 1998). What is often labeled as the win–win effect of DI and reduced fertilizer application (Fox and Rockström, 2000, 2003) is the fact that combining DI and optimum fertilizer application leads to a higher yield increase (higher WP) than the sum of the separate yield increases obtained by both factors.

Another benefit of DI is the possibility of controlling sowing dates by irrigation, which allows improved planning of agricultural practices (Corbeels et al., 1998; Oweis et al., 1998). If a common irrigation strategy is adopted in a region, peaks in irrigation water supply will occur during drought-sensitive stages. This might result in under-irrigation of land at the tail end of the irrigation network, causing more severe yield reductions than anticipated. Using modeling, Oweis and Hachum (2001) demonstrate that thanks to the higher level of crop cycle control and the lower sensitivity to climate resulting from (deficit) irrigation, sowing dates can be staggered, thus reducing peak supply by 20%. In this way, basin-wide WP is increased.

Due to drought stress in particular growth stages, the length of the cropping cycle might change under rain-fed cultivation. Farré and Faci (2006) report a delay in flowering (7 and 17 days) and maturity (5 and 12 days) for sorghum and maize, respectively, under water deficit conditions. McMaster and Wilhelm (2003) find that drought decreases crop cycle length for wheat and barley. Geerts et al. (2008c) demonstrate that differences in the crop cycle length of quinoa between DI and FI are negligible. Under rain-fed conditions, the crop cycle length of quinoa may increase substantially if severe drought stress occurs before flowering. By controlling the length of the crop cycle (deficit) irrigation allows improved planning of agricultural activities.

Along with these advantages, DI also entails a number of constraints. The use of DI requires that the following conditions are met:

- Crop response to drought stress should be studied carefully (Hsiao, 1973). Determining optimal timing of irrigation applications is particularly difficult for crops with CWP functions in which maximal WP is found within a small optimum range of ET;
- irrigators should have unrestricted access to irrigation water during sensitive growth stages. This is not always the case in large block designs (Zhang, 2003) or during periods of water shortage;
- a minimum quantity of irrigation water should always be available for application (Zhang and Oweis, 1999; Kang et al., 2002; Fereres and Soriano, 2007; Geerts et al., 2008b).
- This is not always possible in extremely dry regions where irrigation water is scarce (Enfors and Gordon, 2008).

An additional issue refers to individual versus communal benefits. In many communities, the available water supply is inadequate to irrigate all of the available land. In those cases, farmers might consider the communal benefits of allowing sub-optimal yields on their individual fields, by practicing DI, so that the water saved might be used to irrigate additional land in the community (Kipkorir et al., 2001). In some areas, water markets and other financial incentives might be implemented to encourage farmers to implement DI strategies that will enhance communal production values.

Finally, DI can only be successful if measures are taken to avoid salinization. By using DI strategies, over-irrigation only rarely occurs. Therefore, leaching of salts from the root zone is lower under DI than under FI (Ragab, 1996; Sarwar and Bastiaanssen, 2001; Kaman et al., 2006; Hsiao et al., 2007; Geerts et al., 2008b).

3.4. Reasons for increased water productivity under deficit irrigation

The literature reviewed suggests that increased WP can be attributed to the following reasons:

- water loss through evaporation is reduced;
- the negative effect of drought stress during specific phenological stages on biomass partitioning between reproductive and vegetative biomass (harvest index) (Fereres and Soriano, 2007; Hsiao et al., 2007; Reynolds and Tuberosa, 2008) is avoided, which stabilizes or increases the number of reproductive organs and/or the individual mass of reproductive organs (filling) (Karam et al., 2009);
- WP for the net assimilation of biomass (Eq. (1), with biomass in the numerator and with $T_1$ in the denominator) is increased as drought stress is mitigated or crops become more hardened. This effect is thought to be rather limited given the conservative behavior of biomass growth in response to transpiration (de Wit, 1958; Steduto et al., 2007);
- WP for the net assimilation of biomass is increased due to the synergy between irrigation and fertilization. (Steduto and Albrizio, 2005); This includes cases where irrigation is reduced if fertilizer levels and native fertility are low (Geerts et al., 2008a);
- negative agronomic conditions are avoided during crop growth, such as pests, diseases, anaerobic conditions in the root zone due to water logging, etc. (Pereira et al., 2002; Geerts et al., 2008a).

4. Modeling as a tool for assessing and developing deficit irrigation strategies

Examining the yield response to different water applications in field and/or controlled experiments is laborious and expensive. Nor can such experiments cover all possible combinations of differential drought stress or all environmental aspects affecting yield. Moreover, differential response to drought stress during different phenological stages can cause considerable scatter in the CWP, function. Against this background, modeling can be a useful tool to study and develop promising DI strategies (Zairi et al., 2000; Kipkorir et al., 2001; Lobell and Ortiz-Monasterio, 2006; Benli et al., 2007; Heng et al., 2007; Lorite et al., 2007; Pereira et al., 2009).

Models allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios (Pereira et al., 2002; Liu et al., 2007). Furthermore, they allow differentiating ET$_b$ between $T$ and $E$ and splitting up crop production in different sub-models (e.g. Raes et al., 2006a; Geerts et al., 2009; Raes et al., 2009; Steduto et al., 2009), which may help elucidate the mechanisms underlying increased WP under DI.

Frequency analysis on long time series of climatic data (Raes et al., 2006b) can lead to the development of a stochastic model.
increases in the output generated per unit of water used in farm-level water management strategies, with consequent of agriculture. Deficit irrigation will play an important role in livestock production activities, while ensuring the sustainability strategies carefully to maximize the value of their crop and water resources. Farmers must choose crops and irrigation and farmers strive to increase the productivity of their limited land production, deficit irrigation will gain importance over time as productivity under different irrigation strategies.

Calculating the ET level required to reach maximum water, and these can only be derived from qualitative field work. To integrate differential responses of crops to drought stress during different phenological stages, it is suggested that field research be combined with thoroughly calibrated and validated during different phenological stages, it is suggested that field experiments. The agronomic usefulness of applying deficit irrigation in a specific situation.

To integrate differential responses of crops to drought stress during different phenological stages, one should always be aware of the boundary conditions that were used when a particular model was developed and calibrated.

5. Conclusion

Considerable field information is available on the use of deficit irrigation for common and less common crops. In line with the reference works of Hanks et al. (1969), Hanks (1974), Stewart et al. (1977), Doorenbos and Kassam (1979) and Taylor et al. (1983), the relation between crop evapotranspiration and yield is proposed as a framework for evaluating the drought sensitivity of a particular crop during the season or during a specific growth stage. These crop water production functions are non-linear, crop-specific, and they often differ by phenological stage, genotype and location. Calculating the ET level required to reach maximum water productivity within these functions allows a first appraisal of the agronomic usefulness of applying deficit irrigation in a specific situation.

In areas where the available water supply limits agricultural production, deficit irrigation will gain importance over time as farmers strive to increase the productivity of their limited land and water resources. Farmers must choose crops and irrigation strategies carefully to maximize the value of their crop and livestock production activities, while ensuring the sustainability of agriculture. Deficit irrigation will play an important role in farm-level water management strategies, with consequent increases in the output generated per unit of water used in agriculture.

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Appendix A

Table A1 Summary of experimental results on the sensitivity of different crops to drought stress during specific phenological stages, advisable DI strategies and the shape of their combined crop water production functions.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Location</th>
<th>Advisable DI strategy</th>
<th>Stage of CWP function</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat (Triticum aestivum L.)</td>
<td>Iran</td>
<td>Allow drought stress during: Early growth (MD)</td>
<td>Convex, quadratic</td>
<td>Pandey et al. (2000a, b)</td>
</tr>
<tr>
<td>Potato (Solanum tuberosum L.)</td>
<td>Spain</td>
<td>Allow drought stress during: Vegetative and flowering stage</td>
<td>Concave quadratic</td>
<td>Fabeiro et al. (2001)</td>
</tr>
<tr>
<td>Corn (Zea mays L.)</td>
<td>Turkey</td>
<td>Allow drought stress during: Early growth (MD)</td>
<td>Convex, quadratic</td>
<td>Kirda et al. (1999)</td>
</tr>
<tr>
<td>Sugar beet (Beta vulgaris L.)</td>
<td>Turkey</td>
<td>Allow drought stress during: Early growth (MD)</td>
<td>Convex, quadratic</td>
<td>Kirda et al. (1999)</td>
</tr>
<tr>
<td>Crop Name</td>
<td>Location</td>
<td>Stage</td>
<td>Model Type</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------</td>
<td>--------------------------------</td>
<td>------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Potato (Solanum tuberosum L.)</td>
<td>Peshawar, Pakistan</td>
<td>Ripening</td>
<td>Positively linear, positive Y-intercept (d)</td>
<td>Mohsin Iqbal et al. (1999)</td>
</tr>
<tr>
<td>Potato (Solanum tuberosum L.)</td>
<td>Oregon, USA</td>
<td>n.r.</td>
<td>Tuber bulking</td>
<td>Positively linear, positive Y-intercept (a)</td>
</tr>
<tr>
<td>Tomato (Solanum lycopersicum L.)</td>
<td>Brazil district</td>
<td>Vegetative stages</td>
<td>Convex quadratic (d)</td>
<td>Marouelli and Silva (2007)</td>
</tr>
<tr>
<td>Cotton (Gossypium hirsutum L.)</td>
<td>Çukurova, Turkey</td>
<td>Flowering and yield formation</td>
<td>Positive linear, positive Y-intercept (a)</td>
<td>Kanber et al. (2006)</td>
</tr>
<tr>
<td>Cotton (Gossypium hirsutum L.)</td>
<td>Santiago del Estero, Argentina</td>
<td>Yield formation (MD) and ripening</td>
<td>Convex quadratic</td>
<td>Prieto and Angueira (1999)</td>
</tr>
<tr>
<td>Cotton (Gossypium hirsutum L.)</td>
<td>Bornova-Izmir, Turkey</td>
<td>Boll formation</td>
<td>Positively linear, variable Y-intercept</td>
<td>Anaç et al. (1999)</td>
</tr>
<tr>
<td>Soy Bean (Glycine max L.)</td>
<td>Bekaa Valley Lebanon</td>
<td>LD during full bloom (R2) or mature seed stage (R7)</td>
<td>Logistic, negative Y-intercept for linear stage</td>
<td>Bekele and Tilahun (2007)</td>
</tr>
<tr>
<td>Soy Bean (Glycine max L.)</td>
<td>Greenhouse (Indonesia)</td>
<td>Vegetative stage (up to 0.8 ET&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>Positive linear, positive Y-intercept (d)</td>
<td>Karam et al. (2005)</td>
</tr>
<tr>
<td>Soy Bean (Glycine max L.)</td>
<td>Turkey</td>
<td>Flowering and pod filling</td>
<td>Positive linear, negative Y-intercept (d)</td>
<td>Calvache and Reschardt (1999)</td>
</tr>
<tr>
<td>Common bean (Phaseolus vulgaris L.)</td>
<td>Tumbaco, Ecuador</td>
<td>Flowering</td>
<td>Convex quadratic (d)</td>
<td>Fabio et al. (2002)</td>
</tr>
<tr>
<td>Muskmelon (Cucumis melon L.)</td>
<td>Albacete, Spain</td>
<td>Fl. or LD during early vegetative stage</td>
<td>Concave quadratic (a)</td>
<td>Fabeiro et al. (2003a)</td>
</tr>
<tr>
<td>Garlic (Allium sativum L.)</td>
<td>Albacete, Spain</td>
<td>Vegetative development (0.7 ET&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>Concave quadratic (a); for higher ET&lt;sub&gt;c&lt;/sub&gt;, convex quadratic (d)</td>
<td>Fabeiro et al. (2003a)</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus L.)</td>
<td>Bekaa valley, Lebanon</td>
<td>Early seed formation</td>
<td>Positive linear, positive Y-intercept (d)</td>
<td>Karam et al. (2007)</td>
</tr>
<tr>
<td>Olive (Olea europea L.)</td>
<td>Benevento, Italy</td>
<td>Early and mid flowering</td>
<td>Positive linear, positive Y-intercept (d)</td>
<td>Tognetti et al. (2006)</td>
</tr>
<tr>
<td>Sugarcane (Saccharum officinarum L.)</td>
<td>Ferkessédougou, Ivory Coast</td>
<td>Tilling</td>
<td>Positive linear, positive Y-intercept (d) (a)</td>
<td>Pene and Edi (1999)</td>
</tr>
<tr>
<td>Groundnut (Arachis hypogaea L.)</td>
<td>Serdang, Malaysia</td>
<td>The 3rd of 4 growth stages</td>
<td>Convex quadratic (d)</td>
<td>Ahmad (1999)</td>
</tr>
<tr>
<td>Groundnut (Arachis hypogaea L. spp. Fastigiata var. vulgaris)</td>
<td>Junagadh, India</td>
<td>Flowering</td>
<td>Convex quadratic (d)</td>
<td>Nauriyal et al. (2002)</td>
</tr>
<tr>
<td>Alfalfa (Medicago sativa L.)</td>
<td>Davis, USA</td>
<td>n.r.</td>
<td>Fi for subsequent crop after a crop with DI (limited stress)</td>
<td>Hanson et al. (2007)</td>
</tr>
<tr>
<td>Grapevine (Vitis vinifera L. cv. Sauvignon blanc)</td>
<td>Columbia River Valley, USA</td>
<td>Before veraison&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Berry ripening period</td>
<td>Wample and Smithyman (2002)</td>
</tr>
<tr>
<td>Quinoa (Chenopodium quinoa Willd.)</td>
<td>Altiplano, Bolivia</td>
<td>Vegetative, late grain filling and ripening</td>
<td>Establishment, flowering and early grain filling</td>
<td>Geerts et al. (2006a, 2008a, b)</td>
</tr>
<tr>
<td>Sugarbeet (Beta vulgaris L.)</td>
<td>Central Anatolia, Turkey</td>
<td>Late yield formation and ripening</td>
<td>Emergence and early growth</td>
<td>Kirda et al. (1999)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Crop water production function only available as applied water versus total yield; <sup>d</sup> crop water production function derived from presented data. LD: limited drought. MD: moderate drought. SD: severe drought. DI: deficit irrigation. FI: full irrigation. TAW: totally available water in the root zone between field capacity and permanent wilting point. SWC: soil water content in the root zone. FC: field capacity. ET<sub>c</sub>: crop evapotranspiration under non-limiting soil water conditions.

<sup>4</sup> Advisable DI strategy based on the best water productivity value. Water pricing or product value is not considered.

<sup>5</sup> Combined crop water production function (CWP<sub>c</sub> function in Mg ha<sup>-1</sup> mm<sup>-1</sup>): total marketable yield versus total water volume (rainfall, irrigation and/or residual moisture) consumed by the plant, as a result of drought stress differentiated over the season.

<sup>d</sup> n.r.: not reported.

<sup>e</sup> Fruit veraison: change from berry growth to berry ripening.


Vesala, T., Dirmiotto, P., Pienest, E., 1996. Irrigation scheduling for conjunctive use of rainfall and irrigation based on yield-water relationships. In: Food and Agri-