19 Improving Water Productivity through Deficit Irrigation: Examples from Syria, the North China Plain and Oregon, USA

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Abstract

Improving water productivity is urgently needed in water-scarce dry areas. This chapter discusses crop–water production functions, i.e. the relationships between yield and water supply and water productivity. Using data from Syria, the North China Plain and Oregon, USA, crop–water production functions are developed from which the productivity of the applied water can be derived. After an initial sharp increase, the productivity reaches its maximum at a given amount of supplied water to the plant and then decreases or remains at a relatively high level with further increasing water supply. This chapter demonstrates that deficit irrigation produces a higher overall grain yield with the same amount of water resources compared with full irrigation and, therefore, has a higher productivity. Deficit irrigation can be considered as a key strategy for increasing on-farm water productivity in water-scarce dry areas. The risk associated with deficit irrigation can be minimized through proper irrigation scheduling (when and how much to irrigate) and by avoiding water stress during the growth stages when the crop is especially sensitive to water stress.

Introduction

Water scarcity is a real threat to food production for millions of people in arid and semiarid areas. As the world population continues to grow, the arable land area per capita will further decrease. The Food and Agriculture Organization (FAO, 1988) estimated that almost two-thirds of the increase in crop production needed in the next decades must come from higher yields per unit of land. Hence, rainfall and irrigation water must be used more efficiently and water productivity increased.

Theory of Crop–Water Production Function

The relationship between crop production and water received is called the crop–water production function. According to Vaux and Pruit (1983), research aimed at determining this function can be categorized into three groups, according to different considerations of what constitutes a desirable level of water use:

- Agronomists and other production-oriented scientists often aim for the level of water inputs necessary to achieve maximum yield per unit land area.

- Irrigation engineers, at least in theory, desire to maximize the efficiency of irrigation water use.
- Economists argue that water, to be used efficiently, should be applied up to the point where the price of the last unit of water applied is just equal to the revenue obtained as a result of its application.

A simple model of production can be used to demonstrate these three different goals, as presented in Fig. 19.1.

A production function in which crop yield (Y) is a function of the amount of water received by the crop in terms of rainfall (P) and irrigation (I) can be defined as follows:

$$Y = f\,(P, I) \tag{19.1}$$

The average yield $\bar{Y}$, which is output divided by input, can be written as

$$\bar{Y} = Y\,/(P + I) \tag{19.2}$$

The marginal yield ($\hat{Y}$) is defined as the change in production associated with the addition of one unit input. It can be written as

$$\hat{Y} = \partial Y/\partial(P + I) \tag{19.3}$$

The maximum yield is achieved when the marginal yield is equal to zero. Maximum water-use efficiency requires that the derivative of the average yield is equal to zero,

$$(P + I)^{-1}\,[\partial Y/\partial(P + I) - (Y/(P + I)] = 0 \tag{19.4}$$

Equation 19.4 shows that, as long as some quantity of water is applied, water-use efficiency is maximal where it is equal to the marginal production.

Case Studies of Crop–Water Production Functions

Crop–water production functions for wheat were derived from supplemental irrigation experiments conducted in Syria (Zhang and Oweis, 1999), the North China Plain (Zhang *et al.*, 1999) and Oregon state, USA (English and Nakamura, 1989) (Fig. 19.2a–d). The quadratic production function was used to describe the response of wheat yield to total applied water:

$$Y = b_0 + b_1(P + I) + b_2\,(P + I)^2 \tag{19.5}$$

where Y is wheat yield (t ha^{-1}), I is the irrigation water (mm), P is precipitation (mm)

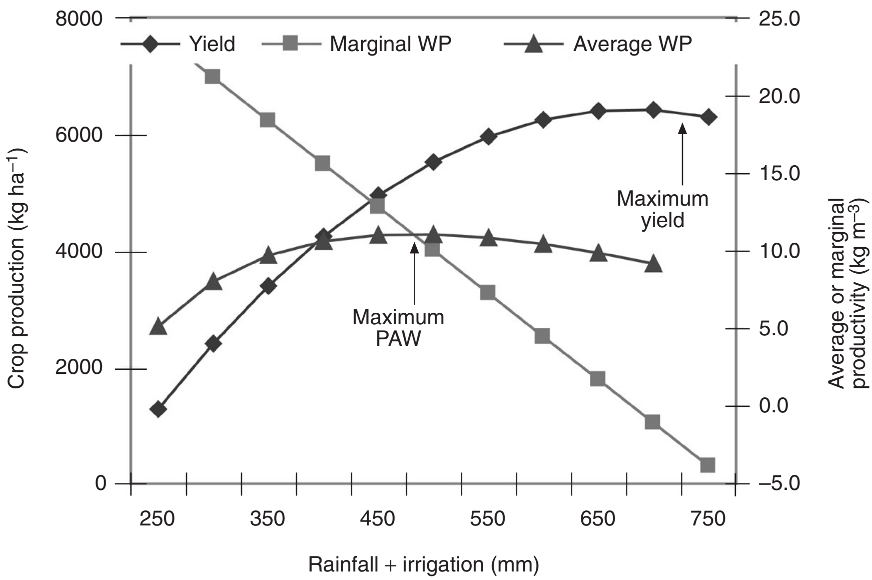

Fig. 19.1. Relation of crop production, productivity of applied water (PAW) and marginal productivity to the crop water supply. The arrows indicate that the maximum PAW value occurs at a lower value of applied water than maximum yield does.

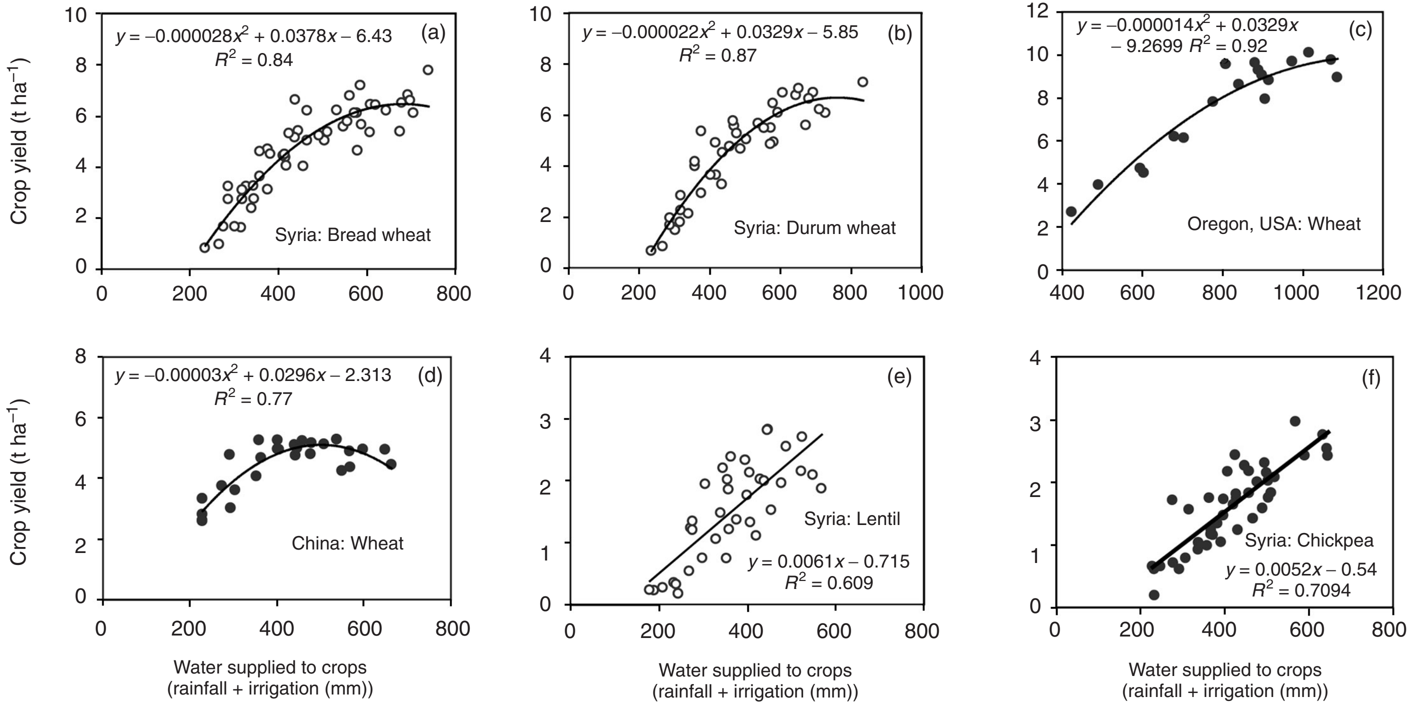

Fig. 19.2. Crop production functions for wheat in China, Oregon, USA, and Syria and for chickpea and lentil in Syria.

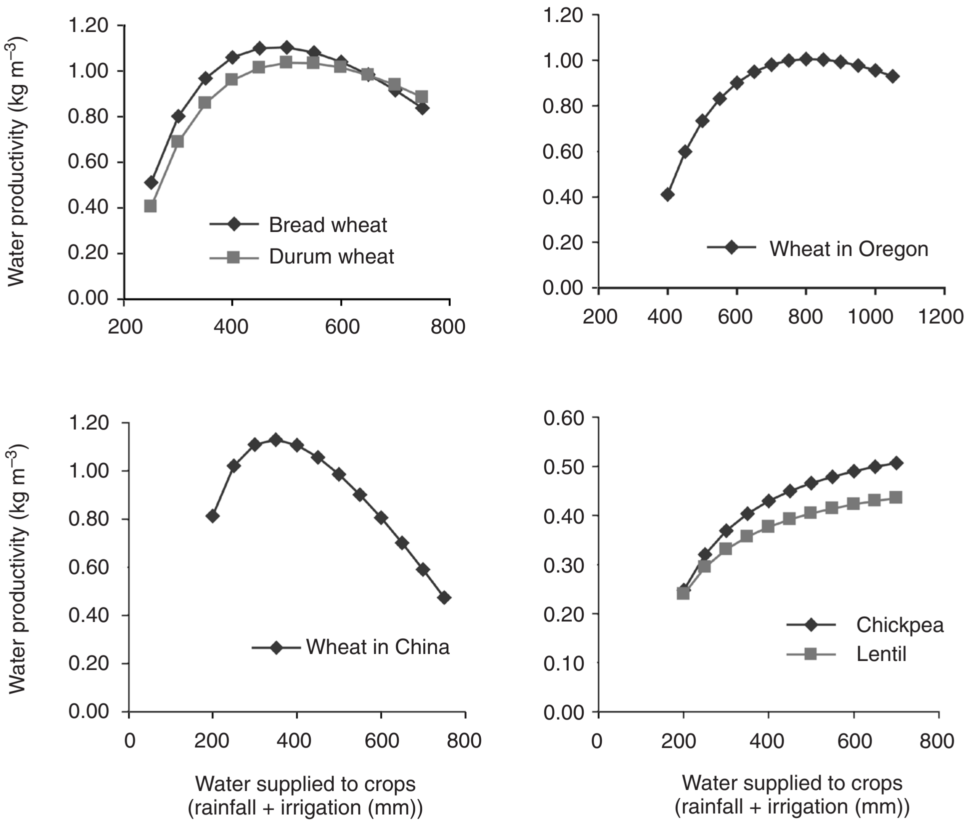

Fig. 19.3. Productivity of applied water for wheat and legumes from Fig. 19.2.

during the growing season, and b_0, b_1 and b_2 are the regression coefficients. The response of yield to total applied water showed very similar characteristics for wheat at all three locations. Initially, yield increased linearly with increasing water supply. As water supply increased further, yield reached a plateau and finally approached the maximum. Unlike wheat, the response of chickpea and lentil to the total amount of water received in northern Syria was linear (Fig. 19.2e–f). The difference in the response of yield to water supply might be related to the growth habit of the crops.

Water Productivity

The productivity of total applied water (PAW) is defined as crop yield per unit volume of water supply to the crops, following Molden (1997), and is estimated by dividing crop yield, estimated from crop production functions in Fig. 19.2, by total applied water (rainfall + irrigation). Figure 19.3 shows the relationship between PAW and the level of water application for wheat in northern Syria, the North China Plain and Oregon, USA, and for chickpea and lentil in northern Syria. The crop production functions in Fig. 19.2 were used to derive the productivity of the applied water. For wheat, PAW for these three locations, representing different climatic conditions, increases sharply at a low water-supply level and reaches a maximum at a certain level of water supply. After its maximum, PAW shows a decrease with increasing water supply, depending on the response of yield to water. The level of water application at the maximum PAW differs

Table 19.1. Comparison of water productivity (PAW) of irrigation levels for wheat and maize.

Irrigation level	Wheat, Texas, USA[a] Yield ($t\ ha^{-1}$)	Wheat, Texas, USA[a] PAW ($kg\ m^{-3}$)	Wheat, Syria Yield ($t\ ha^{-1}$)	Wheat, Syria PAW ($kg\ m^{-3}$)	Maize, Texas, USA[b] Yield ($t\ ha^{-1}$)	Maize, Texas, USA[b] PAW ($kg\ m^{-3}$)
Full	4.76	0.64	5.79	0.93	13.95	1.42
67% of full	4.74	0.76	5.24	1.19	11.36	1.53
33% of full	3.88	0.80	5.15	0.99	6.62	1.21
Rain-fed	2.19	0.61	3.27	0.93	1.36	0.43

[a]From Schneider and Howell (1996).
[b]From Howell *et al.* (1997).

considerably for the three locations. The most productive use of water was reached with about 440–500 mm of water supply (140–180 mm irrigation) in northern Syria, 400 mm (120–160 mm irrigation) in the North China Plain and 750–850 mm (350–450 mm irrigation) in Oregon, USA. For grain-legume crops in northern Syria, PAW gradually increases with increasing water supply and reaches a plateau at a maximum PAW. The maximum PAW is about 0.5 kg m^{-3} for chickpea and 0.4 kg m^{-3} for lentil.

Significant differences in the PAW have been observed between crops. In north Syria, wheat has a PAW (1 kg m^{-3}) twice as high as grain-legume crops (0.4–0.5 kg m^{-3}) (Zhang and Oweis, 1999; Zhang *et al.*, 2000). Although the three experiments represent very different climatic conditions, the maximum PAW for wheat is about 1–1.2 kg m^{-3}. Rice has a relatively low PAW of about 0.37–0.68 kg m^{-3} (Tuong and Bhuiyan, 1999). Maize has a relatively high PAW of about 1.2–1.5 kg m^{-3}. PAW values of 0.4 kg m^{-3} were reported for cotton (Droogers *et al.*, 2000).

Deficit Irrigation: an Efficient Way to Increase the Productivity of Applied Water

The relationships between crop yield (Fig. 19.2) and the productivity of applied water (Fig. 19.3) and water supply demonstrate that higher PAW is achieved at a water-supply level that is lower than that at maximum yield. Many irrigation experiments involving different irrigation levels have also shown that deficit irrigation usually has higher PAW than full irrigation. For example, two-thirds of full irrigation increased PAW by 19–28% for wheat and 8% for maize (Table 19.1). Using the principle developed by English and Raja (1996) and Zhang and Oweis (1999), we can derive different irrigation scenarios. Two of the most important scenarios are those for maximizing production and maximizing farmers' net profit under limited-water-resources conditions. The scenario for maximizing production is referred to as full irrigation (I_f) and the other scenario with water supply less than I_f is defined as deficit irrigation (I_d). The production, water application and water productivity for these two scenarios are presented in Table 19.2 for wheat in Syria and Oregon, USA, and maize in Zimbabwe. With the same amount of water available to the crops, I_d scenarios can improve the productivity of applied water by 12–20% for wheat. We conclude that deficit irrigation can increase the productivity of applied water by producing more yield with the same amount of water resources for crops.

The risk with deficit irrigation is low because the response curve of crop yield to water supply often has a wide plateau (Fig. 19.2); a considerable amount of water can be saved without a significant yield reduction compared with full irrigation. Zhang and Oweis (1999) reported that I_d strategy allows one to apply 40–70% less irrigation water for a grain-yield loss of only 13%. Similarly, English and Raja (1996) reported that deficit irrigation averaging 64% of full irrigation was found to be economically equivalent to full irrigation when water was the limiting factor, and deficit

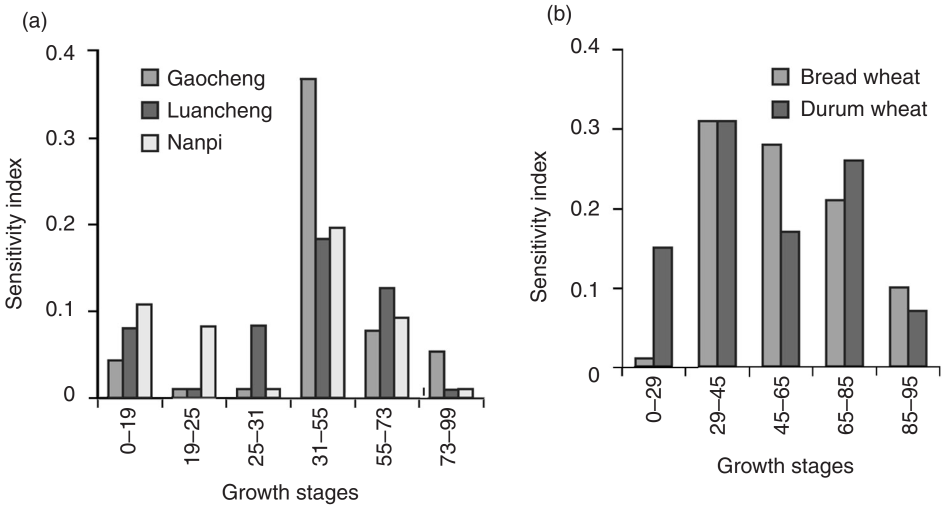

Fig. 19.4. Sensitivity indexes (λ value) of wheat to water stress during individual growing periods at three locations in (a) the North China Plain (winter wheat) and in (b) northern Syria (spring wheat). The growth stages are based on Zadoks *et al.* (1974).

irrigation in which only 30% of full irrigation was applied was found to be equivalent to full irrigation in land-limiting cases. If the saved water resources were allocated to other cropped areas, the total production and the productivity of the applied water would be increased, as indicated in Table 19.2. However, information is needed to guide farmers on when and how much to irrigate with deficit irrigation in order to reduce the unwanted effect of water stress on crop yield. Jensen (1968) developed a model to quantify the effect of water deficits during certain growth stages on grain yield, using the following equation:

$$\frac{Y}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_i}{ET_m} \right)^{\lambda_i} \tag{19.6}$$

where Y is grain yield (t ha^{-1}), Y_m is the maximum yield from the plot without water stress during the growing season, ET_i is the actual evapotranspiration (mm) during the growing stage *i*, ET_m is the maximum evapotranspiration corresponding to Y_m, λ_i is the sensitivity index of the crop to water stress and *i* is the growth stage. Using Jensen's (1968) model, the sensitivity indexes (λ values) of crop to water stress at different crop growth stages were quantified for wheat in northern Syria (Zhang and Oweis, 1999) and in the North China Plain (Zhang *et al.*, 1999). These authors concluded that the most sensitive stages for water stress for wheat are from the stem-elongation to the grain-filling stage (Fig. 19.4). The variation of λ values indicates that crop grain yield depends not only on total water use during the growing season, but also on water use during different growth stages. For example, a 40% decrease in evapotranspiration (ET) during the period from heading to milking reduced grain yield by 15% for winter wheat in the North China Plain, while this deficit in ET during the period from winter freezing to reviving reduced grain yield by only 3%. Similarly, a 40% deficit in ET during the period of stem elongation to grain-filling reduced yield by 15–20% for spring wheat in northern Syria, while this deficit in ET at seedling stage and late grain-filling stage hardly affected the grain yield at all.

Water-stress sensitivity indexes have an important implication for irrigation scheduling, in particular for deficit irrigation. Since water stress during growth stages with high

Table 19.2. Scenario analysis of total production and productivity of applied water at full (I_f) and deficit (I_d) irrigation.

	Irrigation scenarios	Water applied (I) (mm)	Yield (Y) ($t\ ha^{-1}$)	Area irrigated (ha)	Area rain-fed (ha)	Total area (ha)	Yield from irrigated (t)	Yield from rain-fed (t)	Total yield[a] (t)	PAW[b] ($kg\ m^{-3}$)
Wheat, Syria	Full	330	6.4	1.00	1.06	2.06	6.4	3.4	9.8	0.94
	Deficit	160	5.6	2.06	0	2.06	11.8	0	11.8	1.12
Wheat, Oregon, USA	Full	740	9.9	1.00	0.43	1.43	9.9	1.9	11.8	0.88
	Deficit	520	9.2	1.43	0	1.43	13.3	0	13.3	0.98
Maize, Zimbabwe	Full	525	6.0	1.00	1.44	2.44	6.0	–	–	–
	Deficit	215	4.1	2.44	0	2.44	10.1	0	10.1	–

[a]For full-irrigation scenarios, total yield $= A_f \times Y_f + (A_d - A_f) \times Y_{rain\text{-}fed}$. For deficit-irrigation scenarios, total yield $= A_d \times Y_d$, where subscripts f and d represent full and deficit irrigation, respectively.

[b]For full-irrigation scenarios, PAW $=$ total yield/$[I_f \times A_f +$ rainfall $\times (A_d - A_f)]$. For deficit-irrigation scenarios, PAW $=$ total yield/$[(I_d +$ rainfall$) \times A_d]$.

Table 19.3. Amount (mm) and timing of deficit irrigation for high productivity of the applied water under different rainfall conditions.

	Rainfall (mm)	Deficit irrigation (mm)	Time of irrigation
Northern Syria	250	160–260	Stem elongation, booting, flowering and grain-filling
	300	110–210	Stem elongation, flowering and/or grain-filling
	350	60–160	Flowering and/or grain-filling
	400	0–110	Grain-filling
North China Plain	80	160–240	Stem elongation, booting, flowering and grain-filling
	120	120–180	Stem elongation, flowering and grain-filling
	160	100–160	Stem elongation and flowering

λ values has a much greater effect on final yield, to prevent stress during these stages irrigation would be advisable and consequently a higher PAW could be achieved, especially in the areas where water resources are limited. Based on the production functions and the water-productivity analysis, an optimal irrigation scheduling for wheat crops in the North China Plain and northern Syria is proposed in Table 19.3. Such a schedule can only be followed if farmers have full control over the timing and amount of irrigation water they apply. This is usually the case when irrigation water comes from shallow tube wells that are operated by the farmers. However, in countries where irrigation water is supplied through canals according to a strict rotational schedule (as is the case, for example, in much of the Indian subcontinent), there is no flexibility in the delivery of irrigation water. The implication is that under these circumstances deficit irrigation cannot be practised.

Conclusions

This chapter concludes that deficit irrigation leads to higher productivity of the water (rainfall and irrigation) than can be attained with full irrigation and can, therefore, be used for improving the productivity of water in semi-arid areas. Deficit irrigation requires more control over the amount and timing of water application than full irrigation practice. Information on when and how much to irrigate is needed in order to reduce unwanted effects of water stress on production. With reliable crop–water production functions and knowledge of the stages of the crop that are sensitive to water stress, optimal deficit irrigation can be scheduled with a minimum yield reduction compared with full irrigation and, therefore, limited water resources can be utilized more efficiently. In addition, when the crop production functions are known, it is possible to appropriately allocate limited water resources between crops where crops compete for scarce water in dry areas.

References

Droogers, P., Kite, G. and Murray-Rust, H. (2000) Use of simulation models to evaluate irrigation performances including water productivity, risk and system analyses. *Irrigation Science* 19, 139–145.

English, M.J. and Nakamura, B.C. (1989) Effects of deficit irrigation and irrigation frequency on wheat yields. *Journal of American Society of Civil Engineering* 115(IR2), 172–184.

English, M.J. and Raja, S.N. (1996) Perspectives on deficit irrigation. *Agricultural Water Management* 32, 1–14.

FAO (1988) *World Agriculture toward 2000: an FAO Study*. Belhaven Press, London.
Howell, T.A., Schneider, A.D. and Evett, S.R. (1997) Subsurface and surface microirrigation: corn – Southern High Plains. *Transaction of ASAE* 40, 635–641.
Jensen, M.E. (1968) Water consumption by agricultural plants. In: Kozlowski, T.T. (ed.) *Water Deficits and Plant Growth,* Vol. 2. Academic Press, New York, pp. 1–22.
Molden, D. (1997) *Accounting for Water Use and Productivity*. SWIM Paper 1, International Irrigation Management Institute, Colombo, Sri Lanka.
Schneider, A.D. and Howell, T.A. (1996) Methods, amounts, and timing of sprinkler irrigation for winter wheat. *Transaction of ASAE* 40, 137–142.
Tuong, T.P. and Bhuiyan, S.I. (1999) Increasing water-use efficiency in rice production: farm-level perspectives. *Agricultural Water Management* 40, 117–122.
Vaux, H.J. and Pruit, W.O. (1983) Crop–water production functions. In: Hillel, D. (ed.) *Advances in Irrigation*, Vol. 2. Academic Press, New York, pp. 61–97.
Zadoks, J.C., Chang, T.T. and Konzak, C.F. (1974) A decimal code for the growth stages of cereals. *Weed Research* 14, 415–421.
Zhang, H. and Oweis, T. (1999) Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management* 38, 195–211.
Zhang, H., Wang, X., You, M. and Liu, C. (1999) Water-yield relations and water-use efficiency of winter wheat in the North China Plain. *Irrigation Science* 19, 37–45.
Zhang, H., Pala, M., Oweis, T. and Harris, H. (2000) Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. *Australian Journal of Agricultural Research* 51, 295–304.