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Review

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

Sam Geerts *, Dirk Raes

K.U.Leuven (University of Leuven), Division of Soil and Water Management, Celestijnenlaan 200 E, B-3001Leuven, Belgium

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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.

Contents

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.

* Corresponding author. Tel.: +32 16 32 97 54; fax: +32 16 32 97 60.
E-mail addresses: sam.geerts@biw.kuleuven.be, samgeerts@yahoo.com (S. Geerts).

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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 $\mathrm{kg\,m^{-3}}$ is defined as the ratio of the mass of marketable yield (Y_a) to the volume of water consumed by the crop (ET_a):

$$WP = \frac{Y_a}{ET_a} \quad (1)$$

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_{rel}: ratio of actual, Y_a, to maximum possible yield under given agronomic conditions, Y_m) versus relative evapotranspiration (ET_{rel}: ratio of actual evapotranspiration, ET_a, to crop ET under non-stressed, standard conditions, ET_c).

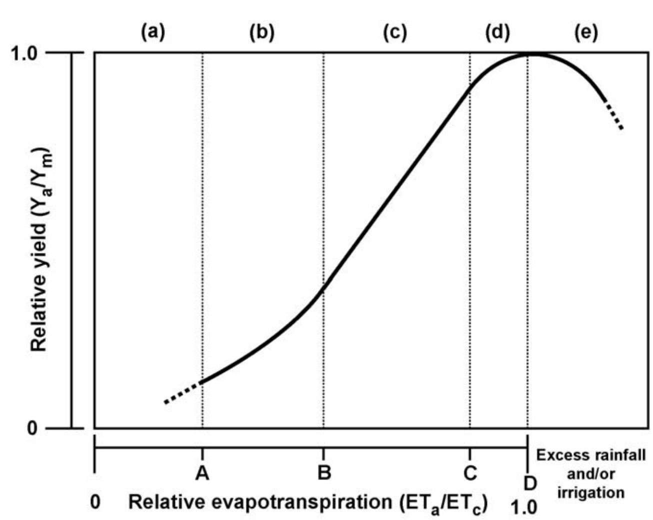

Fig. 1. General shape of a crop water production (CWP) function. Sections (*a*), (*b*), (*c*), (*d*) and (*e*) have variable relative widths. Relative yield is the ratio between actual (Y_a) and potential yield (Y_m) under given agronomic conditions, while relative evapotranspiration is the ratio between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

Within the CWP function, different sections can be distinguished that may vary in width or that may even be absent:

- Section *a*: If insufficient water is applied during the crop cycle, the crop will not develop fully, resulting in low-quality yield (shriveled grains or fruits with low market value) or even total loss of yield (Yazar and Sezen, 2006). In this section, WP is very low, and crop yield and WP can only be increased if a considerable amount of water is added and section *b* is reached (Geerts et al., 2008b). More research is needed to determine this lower limit for various crops.
- Section *b*: Once a minimum amount of water (*A*) is guaranteed by residual moisture, rainfall and/or irrigation, yields (and therefore WP) start to increase with increasing water levels. If this section is present, it has a concave shape: increasing water supply will always result in an increased WP from *A* to *B*.
- Section *c*: With additional water application, the production function can become nearly linear, with a slope ranging from mild to sharp. Doorenbos and Kassam (1979) point out that the relationship between Y_{rel} and ET_{rel} remains linear for ET_{rel} up to a lower limit of 0.5 (point *B* in Fig. 1), although this lower limit has not been defined for all crops.
- Section *d*: As observed for many crops, the slope of the CWP function often decreases once ET_{rel} is close to 1. Towards the upper limit of ET_{rel}, the proportional yield increase per unit ET gradually levels off. Possible reasons are highlighted in Section 3.4 of this review. Section *d* can be quite large, for crops such as alfalfa, sugar beets (Doorenbos and Kassam, 1979), wheat (Kang et al., 2002; Zhang et al., 2008; Sun et al., 2006) or cotton (Henggeler et al., 2002; Kanber et al., 2006; DeTar, 2008), while it may be almost absent for other crops, such as maize (Kipkorir et al., 2002; Farré and Faci, 2006; Payero et al., 2006). In the literature, this section is often described using combinations of linear functions (i.e. a 'broken stick' model).

  When the crop water function includes excess irrigation and/or rainfall, it has a more pronounced S shape (Fig. 1), creating an additional section:
- Section *e*: Applying more water than required by ET_c will not increase yield, as the water is lost through unproductive soil evaporation and/or deep percolation. If too much water is applied, yield might even decline as a result of water logging or leaching of nutrients from the root zone (Sun et al., 2006; Cabello et al., 2009). In this section, irrigation is therefore not required, unless the root zone needs to be leached to reduce salinity.

The level of ET_a or ET_{rel} corresponding with the highest WP can be found by first deriving the WP function (WP versus ET_a) and then setting the first order derivative of this function to zero. Maximum WP will be found at an ET_a level within section *c* or *d*. For the linear section *c*, WP is highest at point *B* if the extrapolated *Y*-intercept is positive and highest at point *C* or at a higher ET_a if the extrapolated *Y*-intercept is negative. If maximum WP is located in section *d* (Eq. (2)), it is located at the point where Eq. (3) equals zero.

$$WP_{section-d} = a * ET_a + b + c * ET_a^{-1} \quad (2)$$

$$\frac{d(WP_{section-d})}{dET_a} = a - c * ET_a^{-2} \quad (3)$$

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*).