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Agronomic concepts in water footprint assessment: A case of study in a fertirrigated melon crop under semiarid conditions

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ABSTRACT

This paper compares the assessment of previous methodologies to calculate blue and gray water footprint and includes agronomic concepts that reflect the semiarid scenarios of fertirrigated crops with low water quality. We describe how we have employed these methodologies in a three-year field experiment. The latter involves a fertirrigated melon crop under mineral fertilization, using eleven different N rates ranging from 11 to 393 kg ha^{-1} N in semiarid conditions, where irrigation is necessary to maintain production. We found that the different methodologies do not consider the scenario where green water footprint is zero, because the effective rainfall is negligible, and the irrigation water has high salt content, requiring the application of larger volumes of water to avoid salt accumulation in the soil and consequent loss yield. We propose modifications to the calculation of water footprint to consider this scenario. In our calculation the blue water footprint includes: (i) the extra consumption of irrigation water that the farmer has to apply to compensate the lack of uniformity in drips discharge; (ii) the water requirement to consider percolation losses and salts leaching, which depends on the salt tolerance of the crop, soil and quality of irrigation water, needed to ensure the fruit yield. With respect to gray water footprint, all N sources susceptible to being lost were considered, the N fertilizer rate and N content in the irrigation water and in the soil (mineral N and mineralized N during the crop period). Therefore, besides considering all these parameters, our proposal takes into account the drained water, given with a water balance, and the nitrates amount below the roots and susceptible to being washed. The methodologies of previous studies underestimate the water footprint resulted in our experiment. With the new considerations proposed, the treatments with the optimum N dose obtained a total water footprint between 127.8 and 151.7 m^3 t^{-1}. Higher values than those were presented in the treatments with the least N dose (145.7 and 158.4 m^3 t^{-1}), although the highest values of water footprint were obtained in treatments with a N excess (226.0 and 355.0 m^3 t^{-1}).

Abbreviations: WF$_t$, total water footprint; WF$_{blue}$, WF$_{green}$ and WF$_{gray}$, blue, green and gray water footprint respectively; ETc, crop evapotranspiration; CWR, crop water requeriment; Kc, is crop coefficient; ETo, reference evapotranspiration; Eta, is adjusted crop evapotranspiration; Ks, is a dimensionless transpiration reduction factor; CWU$_{blue}$, is blue component in crop water use; FY, is fruit yield; ET$_{blue}$ and ET$_{green}$, are blue and green water evapotranspiration respectively; P_{eff}, is effective rainfall; IR, is irrigation requirement; I$_{eff}$, effective irrigation; ΔS$_{IR}$, is the change of soil moisture; I, is the irrigation water application; R$_{IR}$, is runoff; PETc, is potential crop evapotranspiration; AETC$_{IR}$, is actual crop evapotranspiration; CWU$_{green}$, is green component in crop water use; α, is the fraction of N that leaches or runs off; AR, is N application rate; c_{max}, is the maximum acceptable concentration of N; c_{nat}, is the natural concentration of N in the receiving water body; Eff$_{sys}$, is the efficiency of the system; D, is drainage; Rf, is runoff; N$_g$, is the N loss by denitrification; N$_l$, is N leaching; N$_{ap}$, is N applied; N$_f$, is N supplied with the fertilizer; N$_w$, is N applied with the irrigation water; Nav, is N available; N$_s$, initial is the mineral N in the soil before transplanting the melon plants; DAT, is days after transplanting; Irr, is the applied water quantity; $\Delta\theta_\nu$, is the volumetric soil water content.

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1. Introduction

In recent times, there has been a major increase in the intensity of water and fertilizer use in order to increase agricultural production, while at the same time there has increased the evidence that the aquifer levels have been reduced and that the water resources have been degraded as a result of pollution by agricultural fertilizers (I.G.M.E., 1985; D.O.C.M., 2001; Domínguez and de Juan, 2008). Consequently, best management practices are needed for much of the cropped, irrigated and fertirrigated land, to avoid contamination of fresh water and groundwater. Recently, the concept of "water footprint" introduced by Hoekstra (2003) and subsequently elaborated by Hoekstra and Chapagain (2008) has been proposed as an indicator of the total volume of direct and indirect freshwater used, consumed and/or polluted. The water footprint of a product is defined as the total volume of freshwater that is used to produce the crop product (Hoekstra, 2009). Mekonnen and Hoekstra (2010, 2011) defined the blue water footprint as the volume of surface water and groundwater consumed (evapotranspirated) as a result of production; green water footprint is referred to the rainwater consumed; and gray water footprint as the volume of freshwater that is required to assimilate the load of pollutants based on existing water quality standards. The methodology to account the water footprint had been incorporated into an ISO standard (ISO, 2014).

Irrigation water and N are crucial in crop production to increase yields and their optimal use will avoid the possible nitrate leaching to the aquifer and consequently its highly probable contamination. The aim of this study is to compare the assessment of blue and gray water footprint following previous studies and to include agronomic concepts that reflect the semiarid scenarios of fertirrigated crops with low water quality.

2. Methodologies to calculate water footprint

The total water footprint (WF_t) is expressed as volume of water per unit of product (usually $m^3\,t^{-1}$) and is the sum of WF_{blue}, WF_{green} and WF_{gray}:

$$WF_t = WF_{blue} + WF_{green} + WF_{gray} \quad (1)$$

Hoekstra et al. (2011) proposed two methods to calculate the blue and green components: the crop water requirement option and the irrigation schedule option. The crop water requirement option does not place limitations on crop irrigation, so crop evapotranspiration (ETc) equals the crop water requirement (CWR) (Eq. (2)).

$$ETc = CWR = Kc \times ETo \quad (2)$$

where Kc is the crop coefficient and ETo is the reference evapotranspiration.

The irrigation schedule option considers crop evapotranspiration under both optimal and non-optimal conditions over the total growing season using a daily soil water balance approach, to obtain the adjusted crop evapotranspiration (ETa) which may be smaller than ETc, due to non-optimal conditions (Eq. (3)).

$$ETa = Ks \times ETc = Ks \times Kc \times ETo \quad (3)$$

where Ks is a dimensionless transpiration reduction factor dependent on available soil water with a value between zero and one.

Hoekstra et al. (2011) calculated the blue water footprint as the blue component in crop water use (CWU_{blue}, $m^3\,ha^{-1}$) divided by the crop yield (FY) ($t\,ha^{-1}$). The CWU_{blue} is the accumulation of daily blue water evapotranspiration (ET_{blue}) over the whole growing period. The ET_{blue} is estimated as the difference between the total crop evapotranspiration (ETc) and the total effective rainfall (P_{eff}). When P_{eff} is greater than ETc, ET_{blue} is set equal to zero (Eqs. (4) and (5)).

$$WF_{blue} = \frac{ET_{blue}}{FY} \quad (4)$$

$$ET_{blue} = \max(0, ETc - P_{eff}) \quad (5)$$

Aldaya et al. (2010) calculated WF in the Mancha Occidental Region of Spain and calculated ET_{blue} as the minimum of the irrigation requirement (IR) and the effective irrigation (I_{eff}), which refers to the amount of irrigation water that is available for plant uptake (Eq. (6)).

$$ET_{blue} = \min(IR, I_{eff}) \quad (6)$$

where IR is zero if the effective rainfall is equal or larger than the CWR, otherwise being equal to the difference between CWR and P_{eff}. They indicated that in practice, little is generally known about I_{eff}, so they considered that ET_{blue} is equal to IR for irrigated areas. These authors stated in irrigated lands, the crop irrigation requirements are not actually completely satisfied at each single time and that these uncertainties can only be reduced if more detailed irrigation data are available. However, they assumed that I_{eff} is equal to IR since in their studies of basin groundwater irrigation the farmers pump practically always the water needed, and the capacity of the existing huge reservoirs almost always guarantee the irrigation requirements. Over the last decades, groundwater irrigation has become commonplace in many arid and semiarid regions worldwide; and compared with surface water irrigation, groundwater irrigation offers more reliable supplies, lesser vulnerability to droughts, and ready accessibility for individual users (Garrido et al., 2006). Irrigation efficiency depends on the type of irrigation technique used by the farmer: localized or drip irrigation is the most efficient system with a 0.9 coefficient, followed by sprinkler irrigation with 0.7 and finally, surface flood irrigation with 0.5 (Aldaya et al., 2010).

In their study, Siebert and Döll (2010) included the soil water balance to estimate blue WF. They calculated CWU_{blue} as the difference between potential crop evapotranspiration (PETc) and actual crop evapotranspiration ($AETc_{IR}$) (Eq. (7)).

$$CWU_{blue} = PETc - AETc_{IR} \quad (7)$$

With respect to green water footprint, Hoekstra et al. (2011) calculated it as the green component in crop water use (CWU_{green}, $m^3\,ha^{-1}$) divided by the crop yield (FY). The CWU_{green} is the accumulation of daily green water evapotranspiration (ET_{green}) over the complete growing period. The ET_{green} was calculated as the minimum of ET_c and P_{eff} (Eqs. (8) and (9)).

$$WF_{green} = \frac{ET_{green}}{FY} \quad (8)$$

$$ET_{green} = \min(ETc, P_{eff}) \quad (9)$$

Aldaya et al. (2010) calculated ET_{green} as the minimum of CWR and P_{eff} (Eq. (10)).

$$ET_{green} = \min(CWR, P_{eff}) \quad (10)$$

Siebert and Döll (2010) calculated CWU_{green} as $AETc_{IR}$ (Eq. (11)).

$$CWU_{green} = AETc_{IR} \quad (11)$$

Hoekstra et al. (2011) calculated the *gray* water footprint by quantifying the volume of water needed to assimilate the nutrients that reach ground- or surface water. For this, Hoekstra et al. (2011) multiplied the fraction of N that leaches or runs off (α) (average 10%) by the N application rate (AR) and divided this by the difference between the maximum acceptable concentration of N (c_{max}) and the natural concentration of N in the receiving water body (c_{nat}) (Eq. (12)). The maximum acceptable concentration of N

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