Marginal cost curves for water footprint reduction in irrigated agriculture: guiding a cost-effective reduction of crop water consumption to a permit or benchmark level

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Abstract

Reducing the water footprint (WF) of the process of growing irrigated crop is an indispensable element in water management, particularly in water-scarce areas. To achieve this, information on marginal cost curves (MCCs) that rank management packages according to their cost-effectiveness to reduce the WF need to support the decision making. MCCs enable the estimation of the cost associated with a certain WF reduction target, e.g. towards a given WF permit (expressed in m^3 per hectare per season) or to a certain WF benchmark (expressed in m^3 per tonne of crop). This paper aims to develop MCCs for WF reduction for a range of selected cases. AquaCrop, a soil-water-balance and crop-growth model, is used to estimate the effect of different management packages on evapotranspiration and crop yield and thus WF of crop production. A management package is defined as specific combination of management practices: irrigation technique (furrow, sprinkler, drip or subsurface drip); irrigation strategy (full or deficit irrigation); and mulching practice (no, organic or synthetic mulching). The annual average cost for each management package is estimated as the annualised capital cost plus the annual costs of maintenance and operations (i.e. costs of water, energy, and labour). Different cases are considered, including: three crops (maize, tomato and potato); four types of environment (humid in UK, sub-humid in Italy, semi-arid in Spain, and arid in Israel); three hydrologic years (wet, normal and dry years) and three soil types (loam, silty clay loam and sandy loam). For each crop, alternative WF reduction pathways were developed, after which the most cost-effective pathway was selected to develop the MCC for WF reduction. When aiming at WF reduction one can best improve the irrigation strategy first, next the mulching practice and finally the irrigation technique. Moving from a full to deficit irrigation strategy is found to be a no-regret measure: it reduces the WF by reducing water consumption at negligible yield reduction, while reducing the cost for irrigation water and the associated costs for energy and labour. Next, moving from no to organic mulching has a high cost-effectiveness, reducing the WF significantly at low cost. Finally, changing from sprinkler or furrow to drip or sub-surface drip irrigation reduces the WF but at significant cost.

Key words: water abatement cost curve, water saving, irrigation practice, soil water balance, crop growth, crop modelling

1. Introduction

In many places, water use for irrigation is a major factor contributing to water scarcity (Rosegrant et al., 2002;Mekonnen and Hoekstra, 2016), which will be enhanced by increasing demands for food and biofuels (Ercin and Hoekstra, 2014). In many regions, climate change will aggravate water scarcity by affecting the spatial patterns of precipitation and evaporation (Vörösmarty et al., 2000;Fischer et al., 2007). Reducing the water footprint (WF) of crop production, i.e. the consumption of rainwater (green WF) and irrigation water (blue WF) per unit of crop, is a means of increasing water productivity and reduce water scarcity (Hoekstra, 2017). To ensure that the blue WF in a catchment remains within the maximum sustainable level given the water renewal rate in the catchment, Hoekstra (2014) proposes to establish a blue WF cap per catchment and issue no more blue WF permits to individual users than fit within the cap. This would urge water users to reduce their blue WF to a level that is sustainable within the catchment. Additionally, in order to increase water use efficiency, Hoekstra (2014) proposes water footprint benchmarks for specific processes and products as a reference for what is a reasonable level of water consumption per unit of production. This would provide an incentive for water users to reduce their WF per unit of product down to a certain reasonable reference level. The reduction of the WF in irrigated agriculture to the benchmark level relates to improving the physical water use efficiency or increasing water productivity (Molden et al., 2010), thus relieving water scarcity (Mekonnen and Hoekstra, 2014;Zhuo et al., 2016;Zwart et al., 2010). WF reduction in irrigated crop production can be achieved through a range of measures, including a change in mulching practice or in irrigation technique or strategy. Chukalla et al. (2015) studied the effectiveness of different combinations of irrigation technique, irrigation strategy and mulching practice in terms of WF reduction. No research thus far has been carried out regarding the costs of WF reduction. A relevant question though is how much it costs to reduce the WF of crop production to a certain target such as a WF benchmark for the water consumption per tonne of crop or a WF permit for the water consumption per area.

The current study makes a first effort in response to this question by analysing the cost effectiveness of various measures in irrigated crop production in terms of cost per unit of WF reduction and introducing marginal cost curves (MCC) for WF reduction. An MCC for WF reduction is a tool that presents how different measures can be applied subsequently in order to achieve an increasing amount of WF reduction, whereby measures are ordered according to their cost effectiveness (WF reduction achieved per cost unit). Every new measure introduced brings an additional (i.e. marginal) cost and an incremental (marginal) reduction of the WF. There are model-driven and expert-based approaches to develop an MCC. The two approaches have been applied extensively to assess the costs of carbon footprint reduction in various studies, focusing on various sectors and regions. Enkvist et al. (2007) show cost curves for reducing greenhouse gas emissions for different regions in the world. Lewis and Gomer (2008) develop an MCC for reducing greenhouse gas emissions of all sectors in Australia, and MacLeod et al. (2010) develop an MCC for the agricultural sector in the UK. A detailed method to derive MCCs for the most economically efficient reductions in greenhouse gas emissions in the agricultural sector is presented by Bockel et al. (2012). The weaknesses and strengths intrinsic to different methods of deriving MCCs of greenhouse gas reduction are reviewed in different papers (Kesicki, 2010;Kesicki and Strachan, 2011;Kesicki and Ekins, 2012).

The application of MCCs in the water sector is just starting. Addams et al. (2009) apply MCCs for closing the gap between water supply and demand in irrigated agriculture, particularly focussing on the reduction of irrigation water withdrawal. Khan et al. (2009) discuss two possible pathways to increase water productivity and energy use efficiency in food production. This work, however, does not explicitly specify the measures and their cost effectiveness, which would inform the unit cost of improving water and energy use efficiency. Other studies, like Gonzalez-Alvarez et al. (2006) and Samarawickrema and Kulshreshtha (2009) focus on the marginal cost of water, but don't develop MCCs. The first study mentioned studies how farmers would respond if the marginal cost of irrigation water is changed; the second study assesses the marginal value of irrigation water in the production of alternative crops in order to allocate the water based on the highest marginal value. In the area of WF reduction specifically, MCCs have been developed only once, not in the agricultural sector however, but in a case for some factories in different industrial sectors using the expert-based approach (Tata-Group, 2013). The current paper pioneers by developing and applying a model-driven MCC in the area of WF reduction in irrigated agriculture. It thus fills a gap of existing literature on WF reduction, which generally lacks the practical and economic component: what are the subsequent steps and associated costs to achieve increasing levels of water footprint reduction.

The objective of this study is to develop alternative WF reduction pathways and the MCC for WF reduction in irrigated crop production. We do so for a number of crops and environments. We apply the AquaCrop model, a soil-water-balance and crop-growth model that can be used to estimate the WF of crop production under different management practices, linked with a cost model that calculates annual costs related to different management practices, to systematically assess both WF and costs of twenty management packages. Four case study areas are considered: Rothamsted in the UK, Bologna in Italy, Badajoz in Spain, and Eilat in Israel. Based on the outcomes we construct WF reduction pathways and marginal cost curves. Finally, we illustrate the application of the MCC for WF reduction with a selected case with a certain WF reduction target given a situation where the actual WF needs to be reduced given a cut in the WF permit.

2. Method and data

2.1 Research set-up

We consider the production of three crops (maize, tomato and potato) under four environments (humid, sub-humid, semi-arid and arid), three hydrologic years (wet, normal and dry year) and three soil types (loam, silty clay loam and sandy loam). We distinguish twenty management packages, whereby each management package is defined as specific combination of management practices: irrigation technique (furrow, sprinkler, drip or subsurface drip); irrigation strategy (full or deficit irrigation); and mulching practice (no, organic or synthetic mulching).

We develop the marginal cost curves (MCCs) for WF reduction in irrigated crop production in four steps (Figure 1). First, we calculate the WF of growing a crop under the different environmental conditions and management packages using the AquaCrop model (Raes et al., 2013). Second, the total annual average cost for the management packages were calculated. Third, we constructed plausible WF reduction pathways starting from different initial situations. A WF reduction pathway shows a sequence of complementary measures, stepwise moving from an initial management package to management packages with lower WFs. Finally, MCCs for WF reduction were deduced based on reduction potential and cost effectiveness of the individual steps. This approach does not aim to represent a cost-benefit analysis from an agro-economic perspective. Reduced costs through water savings are included, but monetary benefits to the farmer through increased yield or product quality are not included. In this way, the approach fully focusses on costs to save water. Yield increases do have a direct impact on final results by reducing the WF per unit of product.

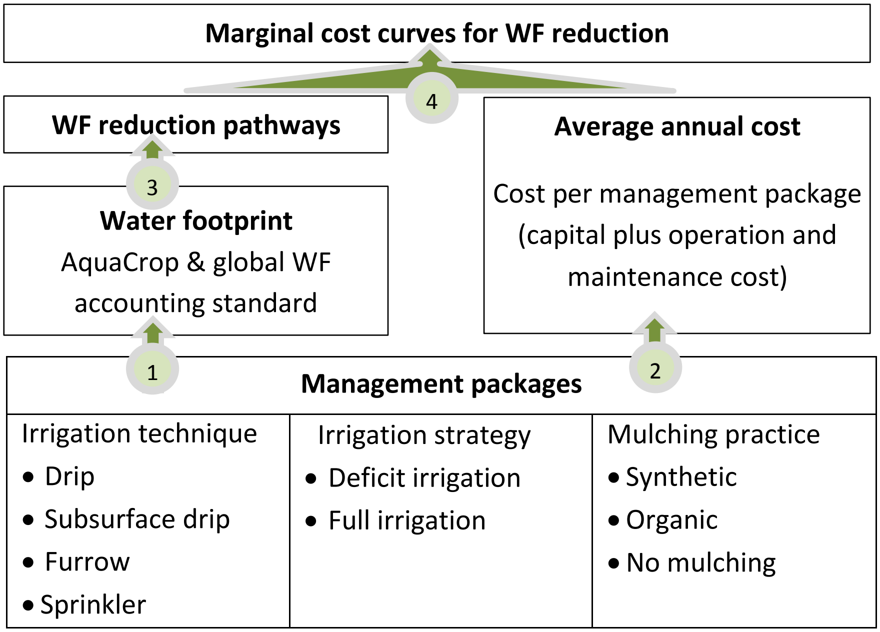

Figure 1. Flow chart for developing marginal cost curves for crop production

2.2 Management packages

Each management package is a combination of a specific irrigation technique, irrigation strategy and mulching practice. We consider four irrigation techniques, two irrigation strategies and three mulching practices. From the 24 possible combinations, we exclude four unlikely combinations, namely the combinations of furrow and sprinkler techniques with synthetic mulching (with either full or deficit irrigation), leaving 20 management packages considered in this study.

The four irrigation techniques differ considerably in the wetted area generated by irrigation (Ali, 2011). In the analysis, default values from the AquaCrop model are taken for the wetted area for each irrigation, as recommended by (Raes et al., 2013). For furrow irrigation, an 80% wetting percentage is assumed to be representative for a narrow bed furrow, from the indicative range of 60% to 100%. For sprinkler, drip and subsurface drip irrigation techniques, wetted areas by irrigation of 100%, 30% and 0%, respectively, are used.

Two irrigation strategies are analysed: full and deficit irrigation. Irrigation requires two principal decisions of scheduling: the volume of water to be irrigated and timing of irrigation. Full irrigation is an irrigation strategy in which the full evaporative demand is met; this strategy aims at maximizing yield. Its irrigation schedule is simulated through automatic generation of the required irrigation to avoid any water stress. The irrigation schedule in the no water stress condition is crop-dependent: the soil moisture is refilled to field capacity (FC) when 20%, 36% and 30% of readily available water (RAW) of the soil is depleted for maize, potato and tomato respectively (FAO, 2012). This scheduling results in a high irrigation frequency, which is impractical in the case of furrow and sprinkler irrigation. To circumvent such unrealistic simulation for the case of furrow and sprinkler irrigation, the simulated irrigation depths are aggregated in such a way that a time gap of a week is maintained between two irrigation events.

Deficit irrigation (DI) is the application of water below the evapotranspiration requirements (Fereres and Soriano, 2007) by limiting water applications particularly during less drought-sensitive growth stages (English, 1990). The deficit strategy is established by reducing the irrigation supply below the full irrigation requirement. We extensively tested various deficit irrigation strategies that fall under two broad categories: (1) regulated deficit irrigation, where a non-uniform water deficit level is applied during the different phenological stages; and (2) sustained deficit irrigation, where the water deficit is managed to be uniform during the whole crop cycle. In the analysis of simulations, the specific deficit strategy that is optimal according to the model experiments and for yield reduction not exceeding 2% is used. AquaCrop simulates water stress responses triggered by soil moisture depletion using three thresholds for a restraint on canopy expansion, stomatal closure and senescence acceleration (Steduto et al., 2009b).

Mulching is the process of covering the soil surface around a plant to create good-natured conditions for its growth (Lamont et al., 1993;Lamont, 2005). Mulching has various purposes: reduce soil evaporation, control weed incidence and its associated water transpiration, reduce soil compaction, enhance nutrient management and incorporate additional nutrients (McCraw and Motes, 1991;Shaxson and Barber, 2003;Mulumba and Lal, 2008). The AquaCrop model simulates the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. Soil evaporation under mulching practices is simulated by scaling the evaporation with a factor that is described by two variables (Raes et al., 2013): the fraction of soil surface covered by mulch (from 0 to 100%); and a parameter representing mulch material (f_m). The correction factor (CF) for the effect of mulching on evaporation is calculated as:

$$CF = (1 - f_m \times mc) \tag{1}$$

with mc being the fraction of the soil covered by mulch. We assume a mulching factor f_m of 1.0 for synthetic mulching, 0.5 for organic mulching and zero for no mulching as suggested by Raes et al. (2013). Further we take a mulch cover of 100% for organic and 80% for synthetic materials, again as suggested in the AquaCrop reference manual (Raes et al., 2013).

2.3 Calculation of water footprint per management package

The water footprint (WF) of crop production is a volumetric measure of fresh water use for growing a crop, distinguishing between the green WF (consumption of rainwater), blue WF (consumption of irrigation water or consumption of soil moisture from capillary rise) and the grey WF (water pollution) (Hoekstra et al., 2011). The green and blue WF, which are the focus in the current study, are together called the consumptive WF. To allow for a comprehensive and systematic assessment of consumptive WF, this study employs the AquaCrop model to estimate green and blue evapotranspiration (ET) and crop yield (Y) to calculate blue and green WF of crop production.

We use the plug-in version of AquaCrop 4.1 (Steduto et al., 2009a;Raes et al., 2011) and determine the crop growing period based in growing degree days. AquaCrop model simulates the soil water balance in the root zone with a daily time step over the crop growing period (Raes et al., 2012). The fluxes into and from the root zone are runoff, infiltration, evapotranspiration, drainage and capillary rise. The green and blue fractions in total ET are calculated based on the green to blue water ratio in the soil moisture, which in turn is kept track of over time by accounting for how much green and blue water enter the soil moisture, following the accounting procedure as reported in (Chukalla et al., 2015).

AquaCrop simulates actual ET and biomass growth based on the type of crop grown (with specific crop parameters), the soil type, climate data such as precipitation and reference ET (ET_o), and given water and field management practices. We estimate ET_o based on FAO's ET_o calculator that uses the Penman-Monteith equation (Allen et al., 1998). The model separates daily ET into crop transpiration (productive) and soil evaporation (non-productive).

Evaporation (E) is calculated by multiplying reference ET (ET_o) with factors that consider the fraction of the soil surface not covered by canopy, and water stress. When the soil surface is soaked by rainfall or irrigation or when soil moisture is beyond a level called readily evaporable water (RAW), the evaporation rate is fully determined by the energy available for soil evaporation (Ritchie, 1972). When soil moisture drops below RAW, the so-called falling rate stage, the evaporation is determined by the available energy and hydraulic properties of the soil. field Experimental studies in different environments have shown that the AquaCrop model reasonably simulates evaporation, transpiration and thus ET (Afshar and Neshat, 2013;Saad et al., 2014).

The crop growth engine of AquaCrop estimates the biomass by multiplying water productivity and transpiration and computes yield by multiplying biomass with the harvest index. Water productivity is assumed to respond to atmospheric evaporative demand and atmospheric CO_2 concentration (Steduto et al., 2009a).

We express the WF of crop production in two ways. The green and blue WF per unit of land (m^3/ha) are calculated as the green and blue evapotranspiration over the growing period of a crop. The green and blue WF per unit of production (m^3/tonne) are calculated by dividing green or blue evapotranspiration over the growing period of a crop (m^3/ha) by the crop yield (tonne/ha). The crop yield in terms of dry matter per hectare as obtained from the AquaCrop calculations is translated into a fresh crop yield (the marketable yield) per hectare. The dry matter fractions of marketable yield for tomato, potato and maize are estimated to be 7%, 25% and 100%, respectively (Steduto et al., 2012). The variability of green and blue WF are presented by calculating the standard deviation of the estimated WFs across different environments, hydrologic years and soil types.

2.4 Estimation of annual cost per management package

The overall cost of a management package includes initial capital or investment costs (IC), operation costs (OC), and maintenance costs (MC). Investment costs include costs of installing a new irrigation system and/or buying plastics for synthetic mulching. Operation cost refer to costs for irrigation water, energy and labour. Maintenance costs include labour and material costs. Both OC and MC are expressed as annual cost (US$/ha per year).

Figure 2 shows the average annual investment cost of irrigation techniques and their lifespan. The data are derived from different sources as specified in Appendices A and B. Investment costs that were reported as one-time instalment costs were converted to equivalent annual costs based on a 5% interest rate and the lifespan of the techniques. The average annual maintenance cost per irrigation technique – including costs for labour and material – is assumed to be equivalent to 2% of the annualised investment costs (Kay and Hatcho, 1992).

The average annual investment costs of US$ 1112 per ha for synthetic mulching is based on the sources as specified in Appendix C. We further assume an average operation and maintenance costs of US$ 140 per ha per year for synthetic mulching and US$ 200 per ha per year for organic mulching.

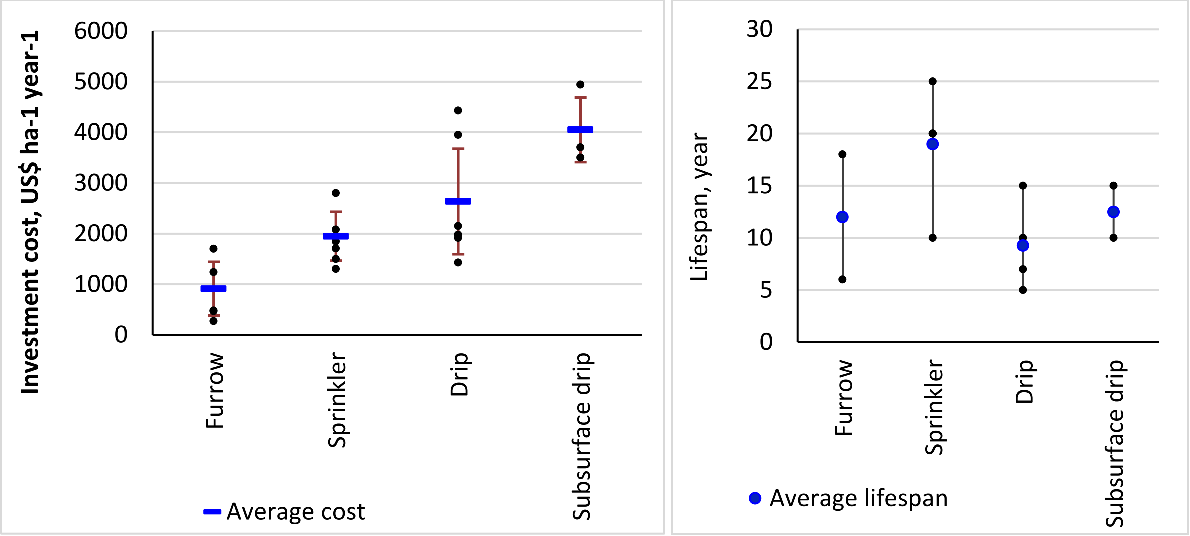

Figure 2. Annual investment cost and lifespan for irrigation techniques

The operational cost related to the use of irrigation water is calculated from the amount of irrigation water applied and an average unit price of water (0.09 ± 0.02 US$ per m^3, Appendix E). The amount of irrigation supply is calculated by dividing the irrigation volume applied at field level simulated by AquaCrop by the application efficiency (Phocaides, 2000). Application efficiency, the ratio of actually applied to supplied irrigation water, is different per irrigation technique (Table 1). The operational cost related to energy use for sprinkler, drip and subsurface drip irrigation is calculated as the total energy demand over the growing season multiplied by the cost of energy (Appendix F). The total energy demand (kWh) is calculated as follows (Kay and Hatcho, 1992):

$$\text{Seasonal energy demand } = \frac{I \times h}{367\,\eta} \tag{2}$$

where I is the volume of irrigation water to be pumped in a crop season (in m^3), h the pressure head (in m) given in Table 1 and η the pump efficiency. The pump efficiency can be between 40% and 80% for a pump running at optimum head and speed and is assumed at 60% here (Kay and Hatcho, 1992). Energy required to transport surface water to the field or to pump up groundwater is not included in the estimates.

The operational cost related to labour is calculated as the required labour hours per irrigation event times the number of irrigation events times the cost of labour per hour. The number of irrigation events in the crop growing period is simulated with AquaCrop. The required labour hours per irrigation event is shown in Table 1 and the cost of labour per hour is given in Appendix D.

Table 1. The application efficiency, labour intensity and pressure head required per irrigation technique.

Irrigation technique	Application efficiency (%)	Labour intensity (hour ha^{-1} per irrigation event)	Pressure head (m)
	Sources: Brouwer et al. (1989), Kay and Hatcho (1992), Phocaides (2000)	Source: Kay and Hatcho (1992)	Sources: Reich et al. (2009) and Phocaides (2000)
Furrow	60	2.0-4.0	0
Sprinkler	75	1.5-3.0	25
Drip	90	0.2-0.5	13.6
Subsurface drip	90	0.2-0.6	13.6

Uncertainties in the cost estimations are represented by their standard deviation. The standard deviations in the investment and maintenance costs and operational costs for water, energy and labour were systematically combined in calculating the standard deviation for the total cost estimation.

2.5 Marginal cost curves for WF reduction

After having calculated the total cost and WF associated with each management package, the MCC for reducing the WF per area or per unit of crop in irrigated agriculture is developed in two steps:

1. Identify alternative WF reduction pathways by arranging plausible progressive sequences of management packages from a baseline management package to a management package with the smallest WF.
2. Select the most cost-effective pathway for a certain baseline and derive from that pathway the MCC for WF reduction.

We consider two baseline management packages: the full irrigation strategy and no mulching practice combined with either furrow or sprinkler irrigation. These two management packages are the most widely deployed types of water and field management (Baldock et al., 2000).

The marginal cost (MC) of a unit WF reduction when shifting from one management package to another is calculated as:

$$\text{MC of a unit WF reduction} = \frac{(TC_2 - TC_1) + (R_1 - R_2)}{WF_1 - WF_2} \quad (3)$$

We consider both the additional annual cost of the new management package compared to the previous one and the reduced revenue due to crop yield reduction that may result from the new management package. In the equation, TC_x refers to the total annual cost of management package x, R_x to the revenue from crop production when applying management package x, and WF_x to the water footprint of management package x.

The MCC shows how subsequent WF reductions can be achieved in the most cost-effective way by moving from the baseline management package to another package, and further to yet another package and so on. It shows both cost and WF reduction achieved with each step. With each step, the marginal cost of WF reduction will increase.

2.6 Data

The WFs were calculated for four locations (UK, Italy, Spain and Israel), three hydrological years (wet, normal and dry years) and three soil types (loam, silty clay loam, sandy loam). The input data on climate and soil were collected from four sites: Rothamsted in the UK (52.26° N, 0.64°E; 69m above mean sea level), Bologna in Italy (44.57 ^{o}N, 11.53 ^{o}E; 19m amsl), Badajoz in Spain (38.88 ^{o}N, -6.83 ^{o}E; 185m amsl), and Eilat in Israel (29.33 ^{o}N, 34.57 ^{o}E; 12m amsl). These sites characterise humid, sub-humid, semi-arid, and arid environments respectively. Daily observed climatic data (rainfall, minimum and maximum temperature) were extracted from the European Climate Assessment and Dataset (ECAD) (Klein Tank et al., 2002). Wet, normal and dry years were selected from 20 years of daily rainfall data (observed data from the period 1993 to 2012). Daily ET_o for the wet, normal and dry years were derived using FAO's ET_o calculator (Raes, 2012). Soil texture data, which is extracted with the resolution of 1×1km^2 from European Soil Database (Hannam et al., 2009), is used to identify the soil type based on the Soil Texture Triangle calculator (Saxton et al., 1986). The physical characteristics of the soils are taken from the default parameters in AquaCrop. For crop parameters, by and large we take the default values as represented in AquaCrop. However, the rooting depth for maize at the Bologna site is restricted to the maximum of 0.7m to account for the actual local condition of a shallow groundwater table (average 1.5 m). The main components of the average annual cost per management package have been collected from literature. We use crop prices per crop and per country averaged over five years (2010-2015) from FAOSTAT (2017); the costs for water, labour and energy are averaged over data for Spain, Italy and the UK, i.e. from three of the four countries studied here. An overview of the costs and their sources are presented in Appendices A to F. In presenting the WF estimates per management package, we show averages over the different cases as well as the range of outcomes for the cases (different environments, hydrologic years and soil types). For developing the MCCs we use the averages.

3. Results

3.1 Water footprint and cost per management package

Figures 3 and 4 show the WF per area and WF per unit of crop, and the annual average costs corresponding to twenty management packages.

For each combination of a certain mulching practice and irrigation strategy, the consumptive WF and the blue WF in particular decrease when we move from sprinkler to furrow to drip and further to subsurface drip irrigation. Under given irrigation strategy and mulching practice, the WF in m^3/ha in case of subsurface drip irrigation is 6.2-13.3% smaller than in case of sprinkler irrigation. The annual average cost always increases from furrow to sprinkler and further to drip and subsurface drip irrigation. Under given mulching practice and irrigation strategy, the cost in case of furrow irrigation is 58-63% smaller than in case of subsurface drip irrigation. The cost of furrow irrigation is small particularly because of the relatively low investment cost, which is higher for sprinkler and even higher for drip and subsurface drip irrigation. The operational costs, on the contrary, are higher for sprinkler and furrow than for drip or subsurface drip irrigation, because of the higher water consumption and thus cost for sprinkler and furrow. Sprinkler has the highest operational cost because it requires a high pressure head to distribute the water (thus higher energy cost).

Under given irrigation technique and mulching practice, deficit irrigation (DI) always results in a slightly smaller WF in m^3/ha (in the range of 1.6-5.7%) and lower cost (in the range of 4-14%) as compared to full irrigation (FI). The decrease in cost is due to the decrease in water and pumping energy. The WF of crop production always reduces in a stepwise way when going from no mulching to organic mulching and then to synthetic mulching, while the costs increase along the move. This cost increase relates to the growing material and labour costs when applying mulching (most with synthetic mulching), but the net cost increase is tempered by the fact that less water and pumping energy will be required.

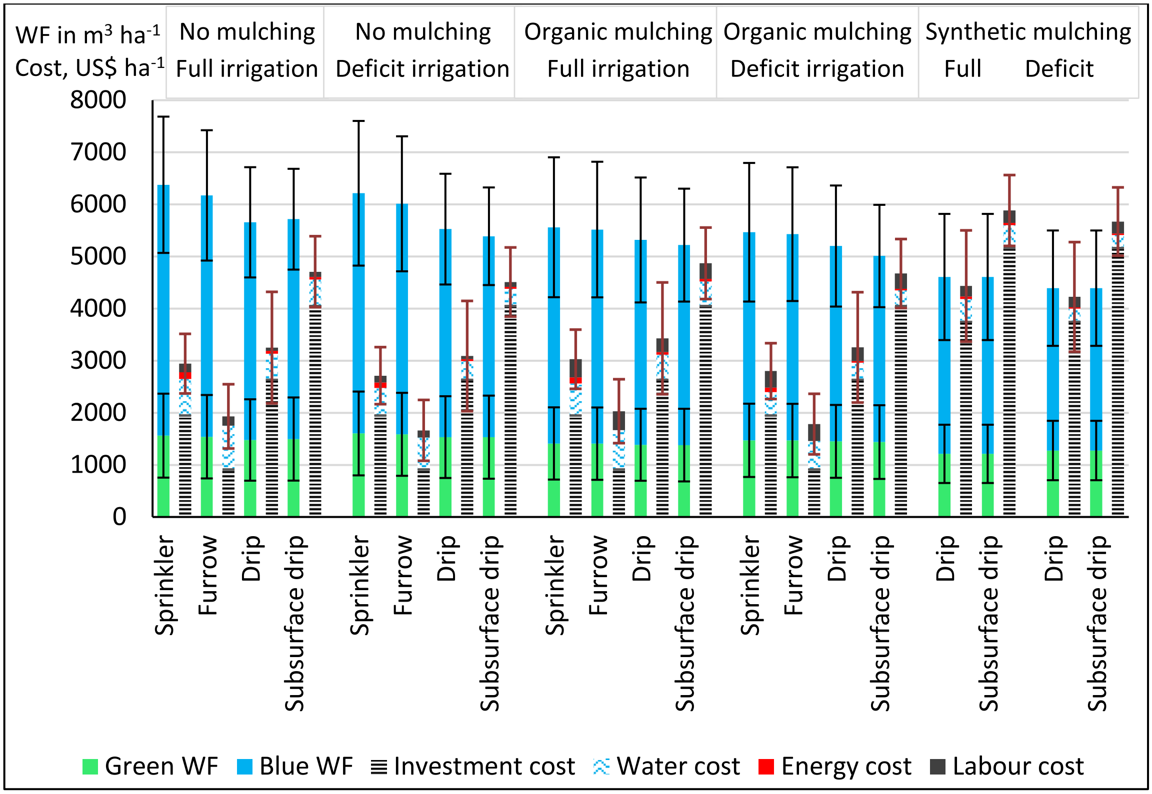

Figure 3: Average WF per area ($m^3\ ha^{-1}$) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers around cost estimates indicate uncertainties in the costs. WF estimates are split up in blue and green components; costs are split up in investment, water, energy and labour costs.

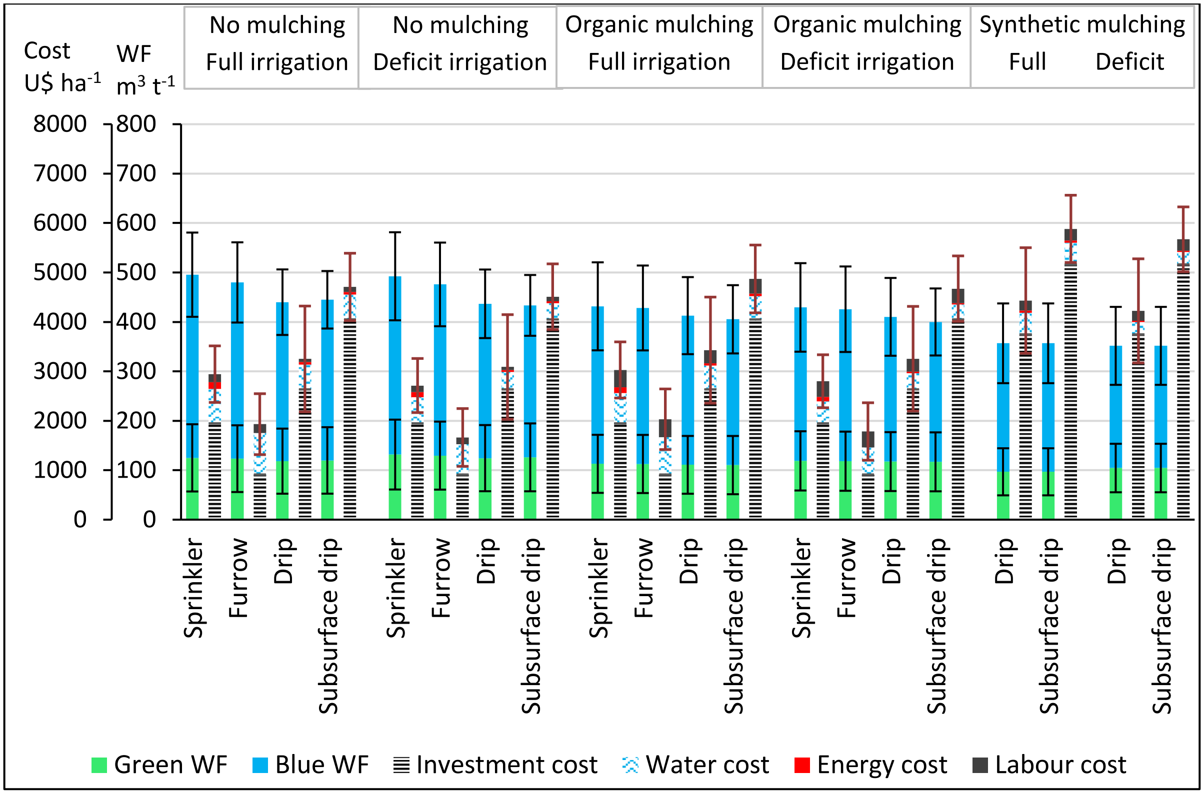

Figure 4: Average WF per product unit (m^3 t^{-1}) for maize production and average annual costs associated with 20 management packages. The whiskers around the WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers around cost estimates indicate uncertainties in the costs.

Figure 5 shows the scatter plot of the twenty management packages, the abscissa and ordinate of each point representing the average annual cost and average WF, respectively, of a particular management package. In this graph, the blue arrow indicates the direction of decreasing WF and costs. The points or management packages connected by the blue line are jointly called the Pareto optimal front or non-dominated Pareto optimal solutions. Moving from one to another management package on the line means that WF will reduce while cost increases, or vice versa, which implies that along this line there will always be a trade-off between the two variables. "Best solutions" may be identified using the MCC when policy goals are specified, for instance a certain WF reduction target in m^3/tonne or m^3/ha is to be achieved, or the largest WF reduction is to be achieved with a given limited budget. Each management package that is not on the line can be improved in terms of reducing cost or reducing WF at no cost for the other variable, or even WF reduction and cost decrease can be achieved simultaneously.

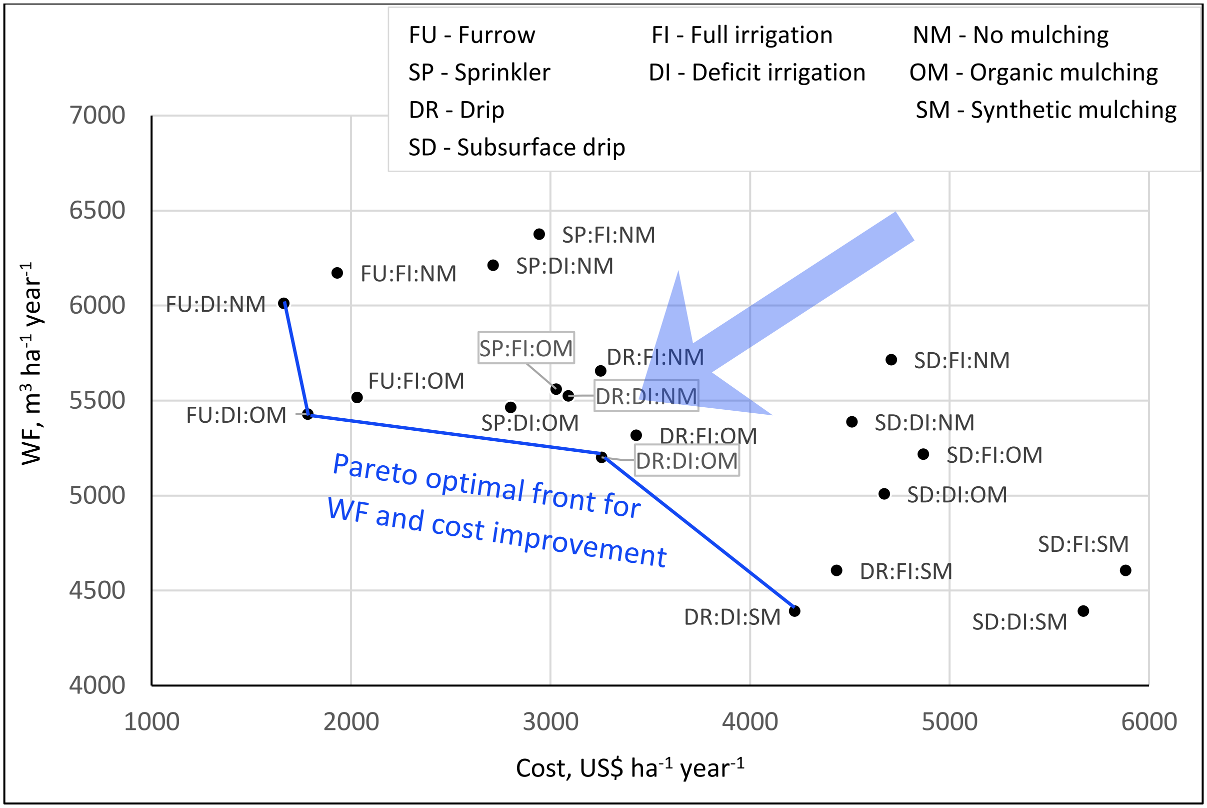

Figure 5: Pareto optimal front for WF and cost reduction in irrigated crop production. The dots represent the annual cost of maize production and the WF per area for twenty management packages. The line connects the Pareto optimal management packages.

3.2 Water footprint reduction pathways

In developing a new irrigation scheme or renovating an existing one in a water-scarce area, it would be rational to implement one of the management packages from the Pareto optimal set if the goal is to arrive at a cost-effective minimization of the WF of crop production. In an existing farm, where the management package is not in the Pareto optimal set, there can be alternative pathways towards reducing the WF. This involves a stepwise adoption of complementary measures that eventually leads to a management package in the Pareto optimal set.

Figure 6 shows alternative WF reduction pathways from the two most common baseline management packages: full irrigation and no mulching with either furrow or sprinkler irrigation. The figure shows four WF reduction pathways from the baseline with furrow irrigation and two pathways from the baseline with sprinkler irrigation. In all pathways, the WF of crop production is continually reduced by changing one thing at a time, i.e. either the irrigation technique, the irrigation strategy or the mulching practice. In some cases, a step may be accompanied by a cost reduction, but in the end most steps imply a cost increase. Logically, all pathways end at a point at the Pareto optimal front.

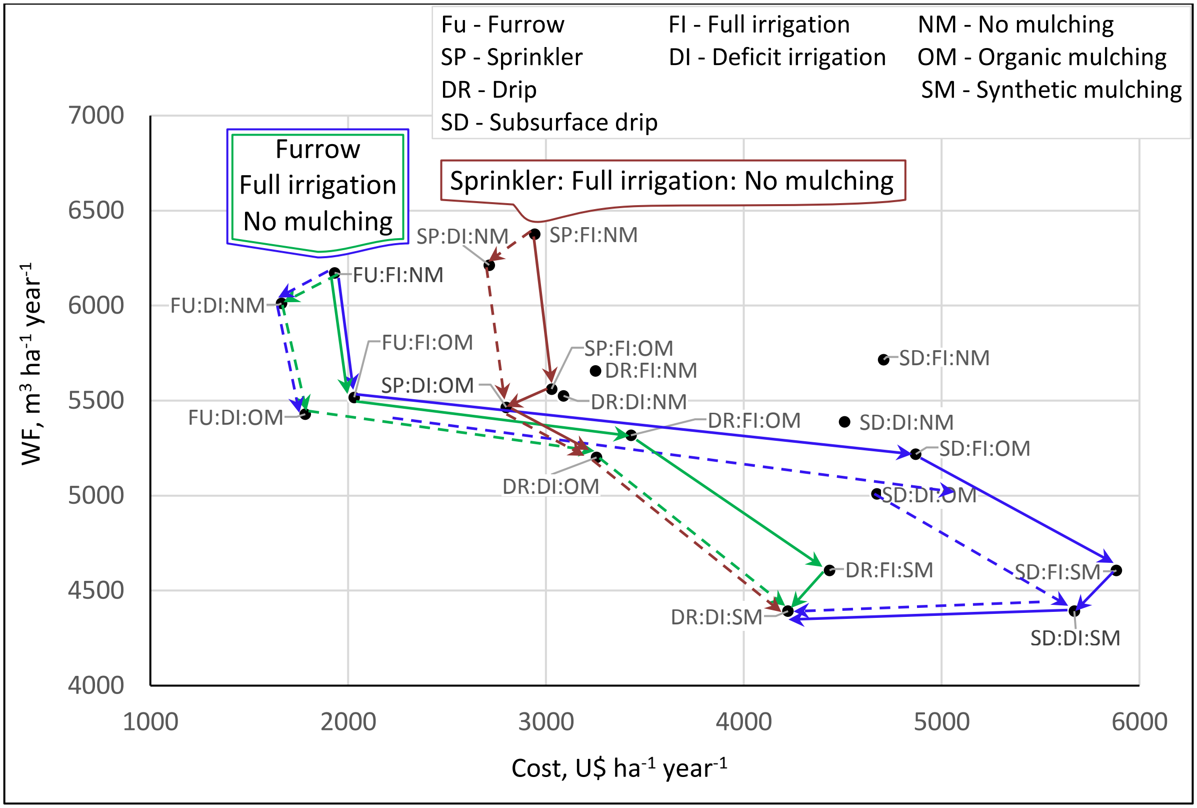

Figure 6: WF reduction pathways for maize from two baseline management packages: full irrigation and no mulching with either furrow or sprinkler irrigation.

3.3 Marginal cost curves for WF reduction

Not all alternative WF reduction pathways from a specific baseline are equally cost effective. In both cases it makes much sense to move from full to deficit irrigation first, because that reduces the WF and cost at the same time. Next, it is best to move from no to organic mulching because the cost-effectiveness of this measure is very high, which can be measured in the graph (Figure 6) as the steep slope (high WF reduction per dollar). Finally, the most cost-effective measure, in both cases, is to move towards drip irrigation in combination with synthetic mulching. One could also move to drip irrigation and stay with organic mulching, which is also Pareto optimal; the cost of this will be less, but the WF reduction will be less as well. However, moving to drip irrigation in combination with synthetic mulching is more cost-effective (higher WF reduction per dollar) than moving to drip irrigation while staying with organic mulching.

For both baseline management packages, we have drawn the MCCs in Figures 7 and 8 for the case of maize. The curves are shown both for reducing the WF per area (Figures 7a and 8a) and the WF per unit of product (Figure 7b and 8b). From these curves, we can read the most cost-effective measures that can subsequently be implemented. For each step we can read in the graph what is the associated marginal cost and what is the associated WF reduction. In both cases, the first step goes at a negative cost, i.e. a benefit, while next steps go at increasing marginal cost. Each step is shown in the form of a bar, with the height and width representing the cost per unit WF reduction and the WF reduction, respectively. The area under a bar represents the total cost of implementing the measure.

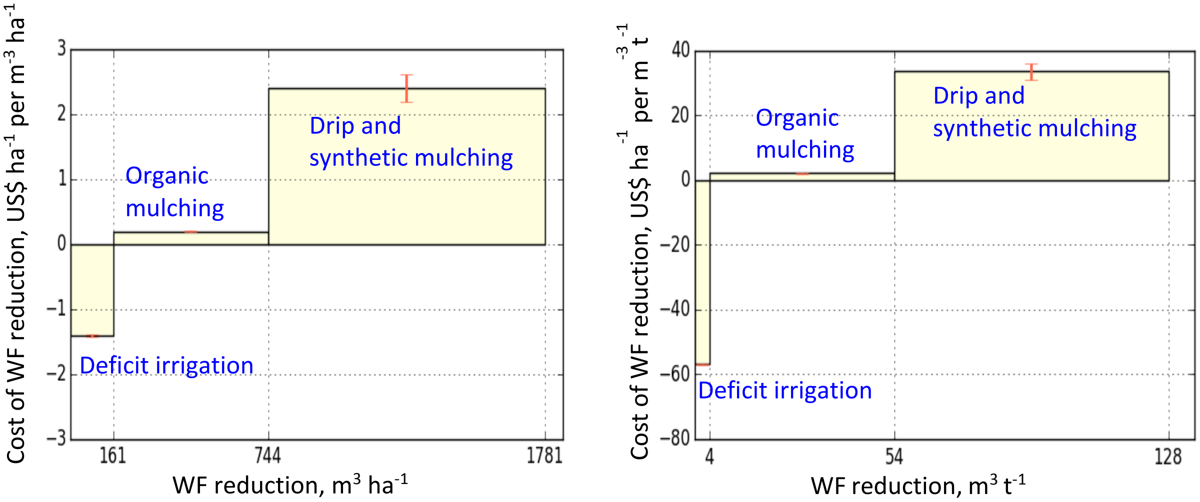

Figure 7: Marginal cost curves for WF reduction for maize for the baseline of furrow irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.

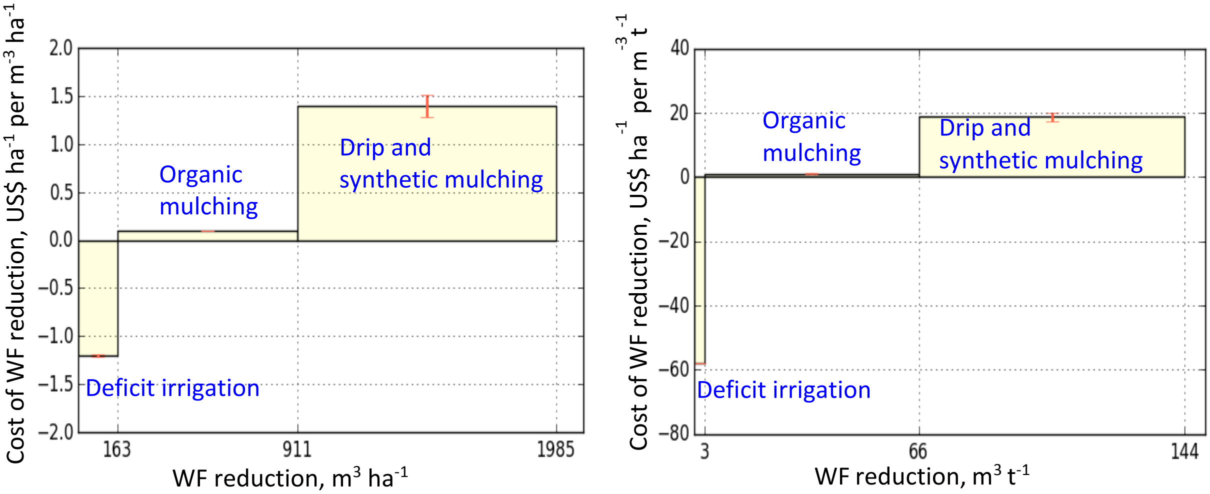

Figure 8: Marginal cost curve for WF reduction of maize for the baseline of sprinkler irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.

For tomato and potato we find similar results as for maize, as shown by the data presented in Appendix G.

3.4 Application of the marginal cost curve

In this section, we elaborate a practical application of an MCC for WF reduction, using a selected case with a certain WF reduction target given a situation where the actual WF needs to be reduced given a cut in the WF permit. The future introduction of WF permits to water users or WF benchmarks for products in water-scarce areas is likely if the sustainable development goals (SGDs) are to be met, particularly SDG 6.4, which reads: "by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity". Here we will illustrate how an MCC for WF reduction can help in achieving a certain WF reduction goal.

An MCC for WF reduction – ranking measures according to their cost-effectiveness in reducing WF – can be used to estimate what measures can best be taken and what is the associated total cost to achieve a certain WF reduction target. For farmers, it will not be attractive to go beyond the implementation of those WF reduction measures that reduce cost as well, but from a catchment perspective further WF reduction may be required. An MCC will show the societal cost associated with a certain WF reduction goal. Governments, food companies and investors can make use of this information to develop incentive schemes for farmers and/or investment plans to implement the most-cost effective measures in order to achieve a certain WF reduction in a catchment or at a given farm.

In a hypothetical example, the WF in the river basin exceeds the maximum sustainable level. Agriculture in the basin consists of irrigated maize production with a current consumptive WF on the farms of 6380 m^3 ha^{-1}. The farms apply sprinkler and full irrigation and no mulching. In order to reduce water consumption in the basin to a sustainable level, the river basin authority proposes various measures including a regulation that prohibits land expansion for crop production and the introduction of a WF permit to the maize farmers that allows them to use no more than 5200 m^3 ha^{-1}. This means they have to reduce the WF of maize production by 1180 m^3 ha^{-1}. Figure 9 shows how the MCC for WF reduction can help in this hypothetical example to identify what measures can best be taken to reduce the WF by the required amount and what costs will be involved.

As shown in the figure, we best implement deficit irrigation first (providing a total benefit of 189 USD ha^{-1}, which is the net result of a 231 USD gain from saved water and a 42 USD loss from crop yield decline), followed by organic mulching (with a total cost of 72 USD ha^{-1}). The third and last step to finally achieve the required WF reduction can be to implement drip irrigation combined with synthetic mulching on 25% of the maize fields (at a total cost of 366 USD ha^{-1}). The other 75% is then still with sprinkler and organic mulching, but the combined result is meeting the target. Alternatively, because in this particular case the cost-effectiveness of moving to drip irrigation with organic mulching is close to the cost-effectiveness of moving to drip irrigation with synthetic mulching, one could move in the third step on 100% of the fields to drip irrigation with organic mulching, which would result in a WF reduction of 1176 m^3 ha^{-1}. In order to meet the full target, a small percentage of the total fields would need to implement synthetic mulching in addition.

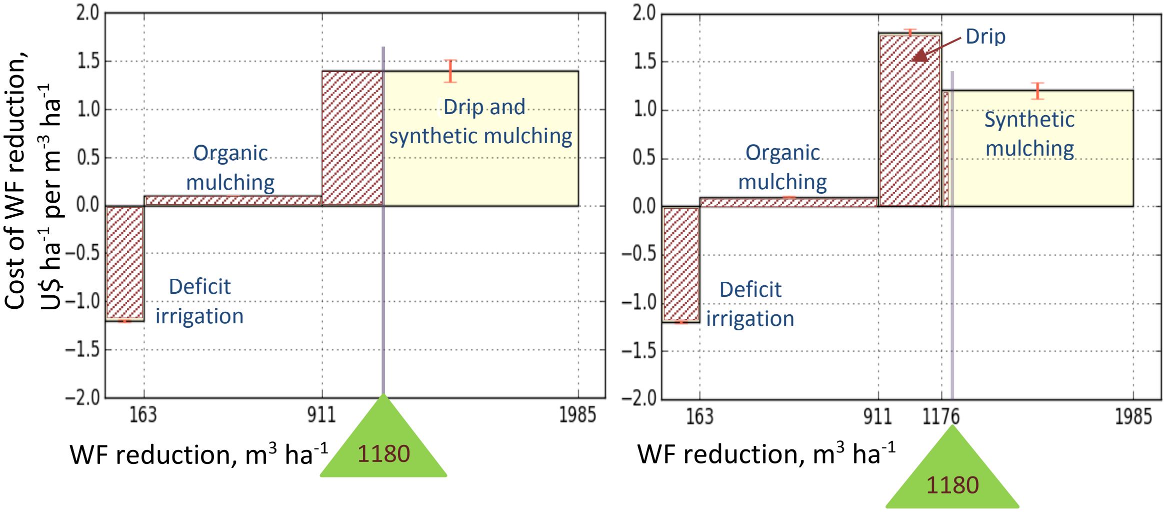

Figure 9: Application of the MCC in an example where the WF of maize production needs to be reduced. The baseline is sprinkler, full irrigation and no mulching with a WF of 6380 m^3 ha^{-1}. This needs to be reduced by 1180 m^3 ha^{-1} in order to meet a given local WF permit. Left: in the third step, drip irrigation combined with synthetic mulching is implemented on 25% of the area. Right: in the third step, drip irrigation (maintaining organic mulching) is implemented on 100% of the area, while in a fourth step synthetic mulching is implemented on 0.5% of the area.

4. Discussion

The current paper introduces the method for developing MCCs for WF reduction in irrigated agriculture, and shows how the MCCs can be applied to achieve a certain WF reduction target, like reducing the WF to a certain WF permit level (in m^3 ha^{-1}) or WF benchmark level (in m^3 t^{-1}). Water availability per catchment is limited to runoff minus environmental flow requirement (Hoekstra, 2014). When dividing the maximum amount of water available in a catchment over the croplands that need irrigation, one finds a maximum volume of water available per ha of cropland. This could be translated in water allocation policy into a maximum WF permit per hectare; this is just one way of promoting WF reduction in areas where that is needed. Another way is to create incentives to reduce the WF per unit of production to a certain benchmark level. Thus, the MCCs we develop can be used for analysing a cost-effective WF reduction pathway given either a target level for WF per hectare or a target level for WF per unit of crop.

By comparing the cost effectiveness of measures in reducing the WF of growing crops, we found that one can best improve first the irrigation strategy (moving from full to deficit irrigation), next the mulching practice (moving from no to organic mulching) and finally the irrigation technique (from furrow or sprinkler irrigation to drip or sub-surface drip irrigation). In our cost-effectiveness analysis, we did not include the cost of bringing irrigation water from source to field. The cost will be high when the source is a deep water well and/or far away, and low if irrigation water flows to a field by gravitational force or by natural pressure, for example from an artesian aquifer or an elevated reservoir. Given a certain source and distance, the total cost to bring irrigation water from source to field will depend on the volume of water to be transported, which varies across the management packages. We excluded this cost, because it does not affect the finding from the study as we will explain. The cost of supplying water will be highest for furrow irrigation (because this technique involves the largest irrigation water supply at field level), followed by sprinkler and drip or subsurface drip irrigation. Furthermore, the water supply cost is higher for full than for deficit irrigation. Finally, the water supply cost is highest in case of the no-mulching practice (which requires the highest irrigation water supply, because ET is highest), followed by organic and synthetic mulching. The water supply cost for transporting the water to the field thus decreases in the direction of decreasing WF, which implies that the order of changing management practices in order to reduce WFs in the most cost-effective way doesn’t change by including water supply costs in the equation. It implies, though, that we underestimated the cost savings associated with water supply to the field when reducing WFs.

The derivation of plausible WF reduction pathways requires insight in the agronomic plausibility of successive implementation measures in the field. Our findings suggest to first move from full to deficit irrigation, then from no to organic mulching, and finally from furrow or sprinkler irrigation to drip or sub-surface drip irrigation, which is a plausible pathway of changing management practices. Strictly spoken, it would also be cost-effective to first move from sprinkler to furrow and later on to drip irrigation, but in practice that is obviously not plausible given the fact that investment costs need to be spread over the lifespan of a technique. More plausible is to change irrigation technique only once.

One should be cautious in applying the reported specific values for costs and WF values in other areas than the ones studied here. The results may even change for the areas studied when prices change. In addition, we did not use field data for validating the simulated results. This puts a disclaimer to the simulated results, but we believe that the methods for developing MCCs for WF reduction pathways for irrigated agriculture, and the hypothetical example of this study provide a useful reference for similar future studies. The MCCs can be of interest to farmers who are seeking to or are incentivized to reduce the WF of their production. They can also be of interest to companies in the food and beverage sector, since there increasing interest in this sector to formulate water use efficiency targets for their supply chain and to stimulate farmers to reduce their WF. For investors, the MCCs help to explore the investment costs associated with certain WF reduction targets. Finally, the MCCs can be of interest to water managers responsible for water allocation to farmers, providing them with information on the costs to farmers if they reduce WF permits to farmers.

5. Conclusion

In this study, we have developed a method to obtain marginal cost curves for WF reduction in crop production. The method is innovative by employing a model that combines soil water balance accounting and a crop growth model and assessing costs and WF reduction for all combinations of irrigation techniques, irrigation strategies and mulching practices. This is a model-based approach to constructing MCCs, which has the advantage over an expert-based approach by considering the combined effects of different measures and thus accounting for non-linearity in the system (i.e. the effect of two measures combined doesn't necessarily equal the sum of the effects of the separate measures). While this approach has been used in the field of constructing MCCs for carbon footprint reduction (Kesicki, 2010), this has never been done before for the case of water footprint reduction.

Developing the MCC for WF reduction for three specific irrigated crops, we found that when aiming at WF reduction one can best improve the irrigation strategy first, next the mulching practice and finally the irrigation technique. Moving from a full to deficit irrigation strategy is found to be a no-regret measure: it reduces the WF by reducing water consumption at negligible yield reduction, while reducing the cost for irrigation water and the associated costs for energy and labour. Next, moving from no to organic mulching has a high cost-effectiveness, reducing the WF significantly at low cost. Finally, changing from sprinkler or furrow to drip or sub-surface drip irrigation reduces the WF but at significant cost.

Acknowledgments

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Appendices

Appendix A: Estimates of the investment cost of irrigation techniques (US$ ha^{-1} $year^{-1}$)

No	Irrigation techniques	Furrow	Sprinkler	Drip	Subsurface drip
1	Cost	467 - 1312	1844 - 2399	1429 - 2594	
	Remark	The techniques are named as surface pumped, sprinkler and localized pumped. The database focuses on the developing regions of the world for the year 2000.			
	Source	FAO (2016)			
2	Cost	1700	2800	3950	
	Remark	Average prices in Europe in 1997. The irrigation technologies are named as improved surface, sprinkler and micro irrigation			
	Source	Phocaides (2000)			
3	Cost	1242	2080	4429	
	Remark	The type of sprinkler is hand moved			
	Source	Custodio and Gurguí (1989)			
4	Cost	291	1500	1918	3500
	Remark	The one-time investment cost is annualized based on the average life span of the techniques and an interest rate of 5%			
	Source	Williams and Izaurralde (2006)			
5	Cost				3707 - 4942
	Source	Reich et al. (2009)			
6	Cost		1305	1976	
	Source	Zou et al. (2013)			
7	Cost	271	1706	2147	

	Remark	For a case in China for the year 2000. The irrigation techniques are named as improved surface, sprinkler and micro irrigation
	Source	Mateo-Sagasta et al. (2013)

Appendix B: Estimates of the lifespan of irrigation techniques from various sources

Irrigation techniques	Lifespan (years)						
Source	Oosthuizen et al. (2005)	Reich et al. (2009)		Williams and Izaurralde (2006)	Zou et al. (2013)		Average lifespan
Furrow	6			18			12
Sprinkler		20	25	20	10	20	19
Drip	7			10	5	15	9.25
Subsurface drip		10	15				12.5

Appendix C: Estimates for the cost of mulching (US$ ha^{-1} year^{-1})

Mulching	Average annual investment cost	Operation and maintenance cost	Sources
Plastic mulching	1227		Lamont et al. (1993)
	875 to 1750		Shrefler and Brandenberger (2014)
	585	140	Jensen and Malter (1995)
Average cost for plastic mulching cost ± SD	1112 ± 434	140	
Average cost for organic mulching		200 ± 100	Klonsky (2012)

Appendix D: Labour cost per hour, in European agriculture for selected countries

Country	Labour cost	Source
Italy (Euro h^{-1})	6.87	Agri-Info.Eu (2016)
Spain (Euro h^{-1})	4	
UK (Euro h^{-1})	8.6	
Average (Euro h^{-1})	6.5	
Average ± SD (US$ h^{-1})	7.2 ± 2.3	

Appendix E: Cost of water

Country	Water price	Source
UK (Euro m^{-3})	0.06	Lallana and Marcuello (2016)
Spain (Euro m^{-3})	0.07	Gómez ‐ Limón and Riesgo (2004)
Italy (Euro m^{-3})	0.1	Garrido and Calatrava (2010)
Average (Euro m^{-3})	0.08	
Average ± SD (US\$ m^{-3})	0.09 ± 0.02	

Appendix F: Cost of energy, Eurostat (2016)

Country	Year			Average
	2012	2013	2014	
Italy	0.178	0.172	0.174	0.17
Spain	0.12	0.12	0.117	0.12
UK	0.119	0.12	0.134	0.12
Average (Euro / kWh)				0.14
Average ± SD (US\$ / kWh)				0.15 ± 0.03

Appendix G: Summary of marginal cost and WF reduction per subsequent measure in the marginal cost curves for WF reduction in maize, tomato and potato production

Table G-I: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in maize production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha^{-1}
	US\$ ha^{-1} per m^3 ha^{-1}	US\$ ha^{-1} per m^3 t^{-1}	m^3 ha^{-1}	m^3 t^{-1}	
Deficit irrigation	-1.7	-66.7	161	4	-269
Organic mulching	0.2	2.4	583	50	120
Drip and synthetic mulching	2.4	32.9	1037	74	2441

Table G-II: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in maize production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha^{-1}
	US\$ ha^{-1} per m^3 ha^{-1}	US\$ ha^{-1} per m^3 t^{-1}	m^3 ha^{-1}	m^3 t^{-1}	
Deficit irrigation	-1.4	-70.9	163	3	-231
Organic mulching	0.1	1.4	748	63	87
Drip and synthetic mulching	1.3	18.3	1073	78	1424

Table G-III: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in tomato production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US$ ha^{-1}
	US$ ha^{-1} per m^{-3} ha^{-1}	US$ ha^{-1} per m^{-3} t^{-1}	m^{-3} ha^{-1}	m^{-3} t^{-1}	
Deficit irrigation	-0.4	-256.1	752	1	-331
Organic mulching	0.2	16.0	750	8	122
Drip and synthetic mulching	2.3	270.2	1094	9	2487

Table G-IV: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in tomato production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US$ ha^{-1}
	US$ ha^{-1} per m^{-3} ha^{-1}	US$ ha^{-1} per m^{-3} t^{-1}	m^{-3} ha^{-1}	m^{-3} t^{-1}	
Deficit irrigation	-0.4	-275.5	840	1	-323
Organic mulching	0.1	7.4	1045	10	73
Drip irrigation	1.4	143.2	1086	4	502
Synthetic mulching		153.7		6	983

Table G-V: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in potato production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US$ ha^{-1}
	US$ ha^{-1} per m^{3} ha^{-1}	US$ ha^{-1} per m^{3} t^{-1}	m^{3} ha^{-1}	m^{3} t^{-1}	
Deficit irrigation	-0.8	-40.8	191	4	-157
Organic mulching	0.5	11.9	323	12	146
Drip and synthetic mulching	6.2	174.8	429	15	2660

Table G-VI: Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in potato production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US$ ha^{-1}
	US$ ha^{-1} per m^{3} ha^{-1}	US$ ha^{-1} per m^{3} t^{-1}	m^{3} ha^{-1}	m^{3} t^{-1}	
Deficit irrigation	-0.7	-33.1	228	5	-157
Organic mulching	0.4	9.6	403	15	147
Drip and synthetic mulching	3.5	101.6	458	16	1623