- The list of relevant changes that were made in the manuscript: the introduction section is expanded; the discussion section is added to the manuscript; the equation to calculate the cost of WF reduction is modified to additionally consider the reduced revenue due to crop yield reduction and thus figure 7, 8 and 9, and reported values in the manuscript are updated. In addition all the minor comments are incorporated and the changes are highlighted.
- All the changes in the manuscript are marked in yellow.

Reply to Anonymous Referee #1

We thank Referee #1 for the comments; below we give the reply to the comments.

Comment

The manuscript presents the first attempt to derive MCC for WF reduction. This way the authors add the cost dimension to the water footprint assessment that has not been done before. This is a very timely study and could be interesting for wider audience. The paper needs further revision before it got accepted. The introduction and the discussion section need to further expanded. Please look my detailed comments below:

The introduction section is very limited. The authors argue that the MCC has not been used in the WF study (Line 474-475) but they fail to carry out a good literature review of the existing literature in the MCC in irrigation water and energy use in irrigated agriculture. **I suggest to include some more literature review on the MCC analyses in general and the application of the MCC in irrigation water in particular.** There are a number of studies that have been carried out to assess the MC of irrigation water eg. **Gonzalez-Alvarez et al. (2006); Samarawickrema and Kulshreshtha (1999).** This way, you will put your study in perspective.

Reply: We agree to the reviewer's comment on the originality and timeliness of introducing MCCs for WF reduction, and to the comment on the literature context being presented limitedly. The following remarks will be incorporated in the revised version of the paper.

MCC for WF reduction is a tool showing measures that are ordered according to their cost effectiveness (WF reduction achieved per cost unit) to achieve an increasing amount of WF reduction. Every measure comes with an additional (i.e. marginal) cost and contributes an incremental (marginal) reduction of the WF in crop production. The MCC has been applied extensively in carbon footprint reduction, its application in the area of water footprint is just starting in the industry sector (Tata-Group, 2013).

Previous studies in other thematic domains add the cost dimension to e.g. the management of irrigation water. Addams et al. (2009) apply the MCCs for increasing water supply to close 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 reduce the environmental footprints of water and energy inputs in food production: improving water productivity and energy use efficiency. 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. Gonzalez-Alvarez et al. (2006) and Samarawickrema and Kulshreshtha (2009) consider the cost dimension in analyzing the management of scarce water resources: the first study makes implications about how farmers would respond if the marginal cost of irrigation water is changed, and 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.

Comment

line 250: you are leaving out the major component of the irrigation curve. This is especially very relevant in those water scarce regions where water is pumped from deep groundwater or from faraway places (Knutson et al., 1977)! I expect this will change the whole analysis of your MCC. This will further brings up what is the water source, how deep is the groundwater, how far is the surface water, what energy is required to pump the water? The question is then if you include the energy required to bring the water to the field, how will your conclusion change? Do you think, the relative cost saving will warrant the relative yield loss?

Reply: We agree with the referee's comment that 'the cost of bringing irrigation water from the source to the field is significant, especially in water scarce regions where water is brought from deep groundwater and/or far away'. The cost of bringing irrigation water to a field is affected by different variables, of which the two most important are the volume of irrigation water and the energy cost required to transport a unit volume of irrigation water. The volume of irrigation water required to grow crops varies with the management at field level (irrigation technology and strategy), while the energy cost to bring a unit volume of irrigation water from a particular source can fairly be assumed equal irrespective of the type of management at field level. The total cost to bring irrigation water from the source to the field, the energy cost per unit volume of water multiplied by the total volume of irrigation water, varies with the source of the irrigation water: the cost is high when the source of water is a deep water well and/or far away, and the cost is low or zero if irrigation water flows to a field due to gravitational force or natural pressure, for example from an artesian aquifer or an elevated reservoir.

In the current study, we are interested to compare the cost effectiveness of measures in reducing the WF of growing crops at field scale, and thus we consider WF of growing a crop and cost of a measure at field scale. The energy cost to bring the water from a source to a field and the water consumption while transporting water between the source and the field level are worth to include, these are however case specific and beyond the scope of the current study. Besides, including these costs would not change the conclucions from the study as we will explain. The overall annual cost per measure increases if we add the cost of energy to bring irrigation water from a source to a field to the annual cost of a measure at field level. The cost increase will depend on the measure (see Fig. 1): the cost increase is highest for furrow irrigation, followed by sprinkler and drip or subsurface drip irrigation; furthermore, the cost increase is more with full irrigation than with deficit irrigation; and finally, the cost increase is most with no-mulching followed by organic and synthetic mulching). One can see that the additional cost related to energy for transporting the water to the field decreases in the direction of decreasing WF. Thus, this does not affect the order of measures ranked based on their cost effectiveness in reducing WF.

We did not include the cost of yield losses because our aim is a cost effectiveness analysis: to see what can be done best at least cost to achieve a certain desired WF reduction.

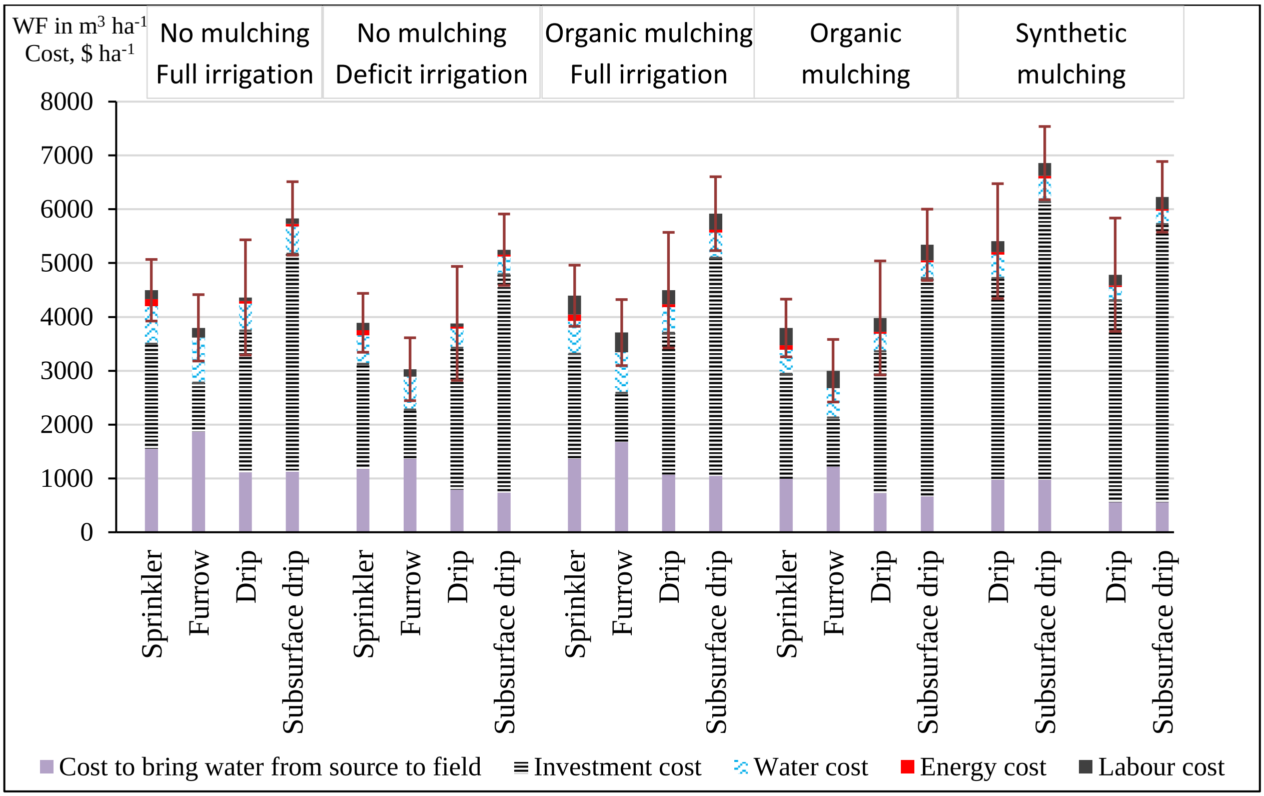

Figure 1: Average WF per area (m^3 ha^{-1}) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, soils and hydrologic years). The whiskers around cost estimates 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. The energy cost to bring irrigation water from a source to a field is calculated by multiplying the volume of irrigation water by a cost of energy, assumed 0.2 $ per m^3.

Comment

Pareto optimal state that an allocation is optimal if an action makes someone better off and putting no one worse off. Its weakness is that it doesn't clearly tell which of the Pareto optimal outcomes is best. Besides, **it doesn't require equitable** use of the water. If that is the case, won't you think it is against one of the pillar of

water management “Equitable share” suggested by Hoekstra (2013)Please clearly define the concept clearly and comment on its usefulness to the current study. You might think of using other term.

Reply:

Cost-effective WF reduction means to reduce WF at least cost. In the scatter plot showing cost and WF reduction for different management packages, the Pareto optimal set consists of management packages whereby moving from one to another management package will reduce either cost or WF but increase the other, thus implying a trade-off between the two variables. In the uncommon case of the existence of one “best” solution (no trade-off), the Pareto set would consist of one point. Commonly in multi-objective optimization the Pareto optimal involves trade-offs between the different objectives. “Best solutions” may be identified using the MCC when policy goals are specified e.g. requiring a target WF reduction to be achieved, or a budget to be best spent in reducing WFs.

Comment

Even in irrigated fields, the contribution of the rainwater (green water) is very significant. To measure the contribution of irrigation to the water use efficiency (water productivity), Bos (1980) suggest the following equations (Howell, 2001):

WUEi = (Yi – Yr)/ I

WUEet = (Yi – Yr)/ (ETi – ETr)

where WUEi and WUEet are the contribution of irrigation water to the water use efficiency (WUE) in terms of applied irrigation and actual evapotranspiration, respectively. Yi and Yr, the crop yield under irrigated and rain-fed condition, respectively; ETi and ETr, the actual evapotranspiration from irrigated crops and rain-fed crops, respectively.

You can define your WF as inverse of the above equations and test it if provides a better insight. At least provide a good argument for choosing to use the WF as in Eqn (3).

Reply:

In assessing the performance of agricultural management in irrigated crop production, a wide variety of indicators may be used, each stressing a different aspect of what is considered good performance. This may include considering the yield gain per unit of irrigation water applied or per unit of additional ET as a result of irrigation (the two indicators suggested by the reviewer). The introduction of the water footprint, as a policy-relevant indicator, can be found in the first paragraph of the introduction (lines 38-56). The goal of the indicator is to relate human consumption of commodities to appropriation of ET. The choice to subsequently use WF in equation (3) is simply because the goal of the paper is to analyse reductions in water footprints in relation to the costs to achieve these reductions. Lines 176-182 explain that the WF analysed includes both green and blue components. Replacing WF by WUEi, WUEet or yet another performance indicator would yield marginal cost curves that would also be useful, serving different goals. A remark in this direction will be added in the conclusion section.

Comment

The manuscript could benefit by further discussion of the result, the limitations and recommendations for future improvement or further development and application of the MCC in the WF assessment.

Reply:

This paper aims to introduce the methodological development of MCC for WF reduction. In addition we give insights in the interpretation of the MCC by giving a synthetic example. We are not claiming the reported specific values for costs and WF to be valid for any case study; we applied the method for a few specific crops, locations and soils only. Data on costs are taken from various literature sources and averaged over three countries. The average cost of water for the case of the three countries (UK, Spain and Italy) is 0.09 US$ per m^3. The cost of water in UK and Spain is lower than the average while the cost of water in Italy is higher than the average cost.

Minor comments: (all minor comments are incorporated)

Line 59 McCraw and Motes missing year

line 68: add "to" to read “... relation to WF reduction...”

line 69; add "the" to read "... the need to enhance ..."

#line 303: please insert “used is” for “not is used”

#line 461: please delete “the” from “. . . to meet a given the local WF permit.”

References:

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Addams, L., Boccaletti, G., Kerlin, M., and Stuchtey, M.: Charting our water future: economic frameworks to inform decision-making, McKinsey & Company, New York, 2009.

Bos, M.: Irrigation efficiencies at crop production level, International Commission on Irrigation and Drainage, Bulletin, 29, 18-60, 1980.

Gonzalez-Alvarez, Y., Keeler, A. G., and Mullen, J. D.: Farm-level irrigation and the marginal cost of water use: Evidence from Georgia, Journal of Environmental Management, 80, 311-317, 2006.

Howell, T. A.: Enhancing water use efficiency in irrigated agriculture, Agronomy journal, 93, 281-289, 2001.

Khan, S., Khan, M., Hanjra, M., and Mu, J.: Pathways to reduce the environmental footprints of water and energy inputs in food production, Food policy, 34, 141-149, 2009.

Samarawickrema, A., and Kulshreshtha, S.: Marginal value of irrigation water use in the South Saskatchewan River Basin, Canada, Great Plains Research, 73-88, 2009.

Tata-Group: Tata Industrial Water Footprint Assessment: Results and Learning, 2013.

Reply to Anonymous Referee #2

We thank Referee #2 for the comments; below we give the reply to the comments.

Comment

The manuscript is very interesting and focuses on a very important topic: WF reduction studied with the application of MCC for analysing the economic side of strategies improvement for water use reduction. The study is well balanced and clearly written, therefore I suggest accepting it after solving few comments.

Specific comments:

In the introduction literature is lacking, more details should be given on MCC, on possible studies that tried to perform something similar, and better explaining the advantages and innovation of introducing such an assessment (e.g., pay more attention on lines 67-70). In addition, the references reported are written often together (line 64: 4 references in the brackets) and explaining their single specific role as reference would be helpful.

Reply: We agree to the reviewer's comment on the importance of introducing the cost side of analysing WF reduction, and to the comments on explaining the MCC with additional literature. The following explanations will be incorporated in the revised version of the paper.

The MCC for WF reduction ranks WF reduction measures according to their cost-effectiveness (WF reduction achieved per USD) and shows the most cost-effective set of measures for a certain WF reduction target. The MCC has been applied extensively for carbon footprint reduction in various studies, focusing on various sectors and regions. Enkvist et al. (2007) show cost curves for reducing greenhouse gas emissions of different regions globally. 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. Tata-Group (2013) **developed expert** driven MCCs for WF reduction in some factories. Addams et al. (2009) apply MCCs for closing the gap between water supply and demand in irrigated agriculture. Khan et al. (2009) discuss two possible pathways to reduce the environmental footprints of water and energy inputs in food production: improving water productivity and energy use efficiency. 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. In the current study, we apply MCCs for WF reduction and show the cost effectiveness of measures as well as the most cost efficient pathway to reduce water consumption to a certain WF reduction target, e.g. towards a given WF permit or to a certain WF benchmark.

Comment

Lines 208-213: what are the average yields for the crops? Maize is considered cultivated in Italy only, or also in Spain for example? What about the other crops? With this point in mind, are the Figures 4-5 referred to maize production in one single country or in more? Understanding the country would make possible to connect these results with the values reported in the Appendix.

Reply:

In lines 208 -2013 we state that the WF of crop production is expressed in two ways: WF per tonne of crop production (expressed in m^3 per tonne of crop), or WF per unit area (expressed in m^3 per hectare per season). Maize, tomato and potato are cultivated in Italy, Spain, Israel and UK. In a previous paper we show the water footprint of each crop for each country (Chukalla et al., 2015). Figures 4-5 in the current paper illustrate the average WF (m^3 per tonne) for maize over different cases (four countries, three hydrologic years and three soil types). The whiskers around the WF estimates in Figure 4 show the range of outcomes for the different cases. The WF and cost values reported in Appendix G are also average over the cases and the countries respectively. In the current paper, we consider the average WF estimates, which means that the MCCs are not case specific; this does not affect the goal of the study, which is to introduce the methodological development of an MCC and show its application by giving a hypothetical example.

Comment

Line 250-251: not considering energy for transport and pumping is a very important simplification and surely affects the results. Please motivate your choice.

Reply:

We agree with the referee's comment. The energy costs to bring water from a source to the field (and the water losses during transport) are worth to include, but these are case specific and beyond the scope of the current study. We constrained the study to costs at field level. This does not affect the conclusions from the study as we will explain. The overall annual cost per measure increases if we add the cost of energy to bring irrigation water from a source to a field to the annual cost of a measure at field level. The cost increase will depend on the measure (Figure 1): the cost increase is highest for furrow irrigation, followed by sprinkler and drip or subsurface drip irrigation; furthermore, the cost increase is more with full irrigation than with deficit irrigation; and finally, the cost increase is most with no-mulching followed by organic and synthetic mulching). One can see that the additional cost related to energy for transporting the water to the field decreases in the direction of decreasing WF. Thus, this does not affect the order of measures ranked based on their cost effectiveness in reducing WF.

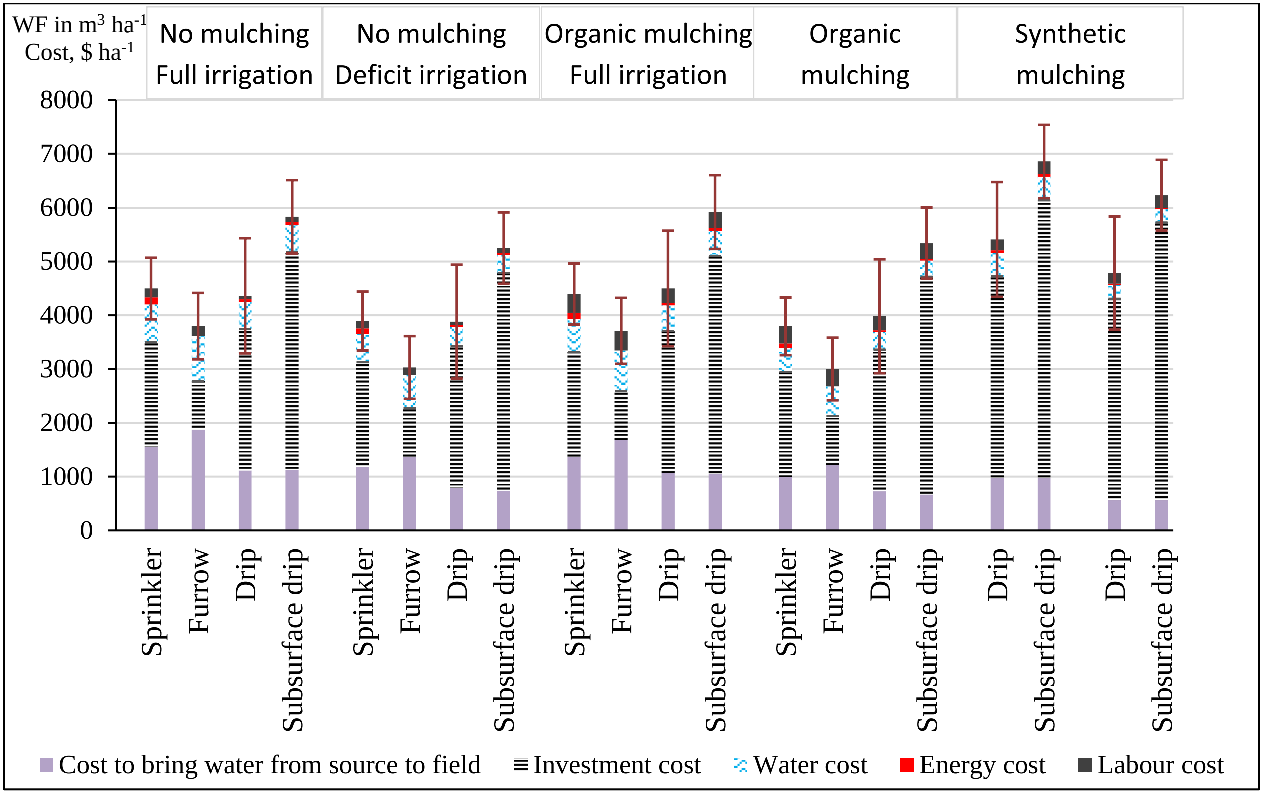

Figure 1: Average WF per area (m^3 ha^{-1}) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, soils and hydrologic years). The whiskers around cost estimates 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. The energy cost to bring irrigation water from a source to a field is calculated by multiplying the volume of irrigation water by a cost of energy, assumed 0.2 $ per m^3.

Comment

Finally, a discussion paragraph is missing, which would be helpful for better discussing literature, the benefits of this new method applied to WF and the possible limits met by authors.

Reply:

In the revised paper we will add the following discussion points: (a) discussion of the challenge of developing MCCs for each specific case, requiring a modelling effort for each specific case, (b) discussion of uncertainties involved when assessing the effect of certain measures through modelling, and the variability of effects related to climate variability, (c) a reflection on the problems of obtaining case-specific data on costs, (d) the potential to derive more general conclusions on the ranking of specific measures regarding their cost-effectiveness in WF reduction through more research across cases (different crops and different regions), and (e) the future relevance of MCCs for WF reduction once companies start aiming to reduce the WF of their crop products down to sector-agreed regional-specific benchmark levels and once governments are going to apply farm-specific WF permits based on the maximum sustainable WF in a catchment.

Technical comments: (all minor comments are incorporated)

Line 21: write "are" instead of "is" in "different cases are considered..."

Line 68: add "to" for "in relation to WF reduction"

Line 304: write "... the soils are taken from..." deleting is used

Figures 7-8: the text on the Y axis is put in the middle of the graph and cannot be read.

References:

Addams, L., Boccaletti, G., Kerlin, M., and Stuchtey, M.: Charting our water future: economic frameworks to inform decision-making, McKinsey & Company, New York, 2009.

Bockel, L., Sutter, P., Touchemoulin, O., and Jönsson, M.: Using marginal abatement cost curves to realize the economic appraisal of climate smart agriculture policy options, Methodology, 3, 2012.

Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrol. Earth Syst. Sci., 19, 4877-4891, 10.5194/hess-19-4877-2015, 2015.

Enkvist, P., Nauclér, T., and Rosander, J.: A cost curve for greenhouse gas reduction, McKinsey Quarterly, 1, 34, 2007.

Kesicki, F.: Marginal abatement cost curves for policy making–expert-based vs. model-derived curves, Energy Institute, University College London, 2010.

Kesicki, F., and Strachan, N.: Marginal abatement cost (MAC) curves: confronting theory and practice, Environ Sci Policy, 14, 1195-1204, DOI 10.1016/j.envsci.2011.08.004, 2011.

Kesicki, F., and Ekins, P.: Marginal abatement cost curves: a call for caution, Clim Policy, 12, 219-236, Doi 10.1080/14693062.2011.582347, 2012.

Khan, S., Khan, M., Hanjra, M., and Mu, J.: Pathways to reduce the environmental footprints of water and energy inputs in food production, Food policy, 34, 141-149, 2009.

Lewis, A., and Gomer, S.: An Australian cost curve for greenhouse gas reduction, Report for McKinsey and Company Australia, 2008.

MacLeod, M., Moran, D., Eory, V., Rees, R., Barnes, A., Topp, C. F., Ball, B., Hoad, S., Wall, E., and McVittie, A.: Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK, Agricultural Systems, 103, 198-209, 2010.

Tata-Group: Tata Industrial Water Footprint Assessment: Results and Learning, 2013.

Reply to Anonymous Referee #2 (second round)

We thank Referee #2 for the comments; below we give the reply to the comments.

Comment

Thanks to the Authors for the reply. I feel they answered to all points. However, I still have a question. I can understand this is an example of the methodology adopted and that the focus is not specifically on the single crops of the single countries, but maize cannot be cultivated in UK due to local weather and temperatures. Saying that maize is cultivated there is a conceptual mistake and I cannot understand how you could find data to calculate its Water Footprint.

Reply:

The referee's comment is correct in that UK grows little grain maize and the majority used in the country is imported (Statistics-GOV.UK, 2017b). However, maize is still cultivated under both rain-fed and irrigation conditions; according to FAOSTAT (2017) the irrigated maize is sown in April and covering 4,300 ha in 2007. The total maize cultivation in UK covered 197,000 ha in 2016 (Statistics-GOV.UK, 2017a). According to (Statistics-GOV.UK, 2017a, b) most of the maize production in UK is used for fodder, followed by bioenergy and grain maize: 76% fodder maize, 19% bioenergy maize, and 5% grain maize in 2015. Water footprint calculations were done based on simulations with the AquaCrop model using general validated crop files (Steduto et al., 2011) and local specific growing conditions. AquaCrop simulated maize yields in the UK in the range of 9.5 to 13 t ha^{-1} for different soil types and hydrological years, which is in agreement to the maize yield 9 to 11 t ha^{-1} reported in literature (Marsh, 2017).

References:

FAO-aquastat: FAO: On-line database, United Kingdom irrigated crop calendar report. Food and Agricultrue Organization of the United Nations, http://www.fao.org/nr/water/aquastat/countries_regions/GBR/GBR-CC_eng.pdf, last access: March, 2017.

Marsh, S. P.: Crimped maize grain for finishing beef cattle report for 2010. Animal Science Research Center, http://beefandlamb.ahdb.org.uk/wp/wp-content/uploads/2013/04/crimpedmaizegrainproductionstudy_16.09.10-Final-Report-Production-Study.pdf, last access: March, 2017.

Statistics-GOV.UK: On-line database, Area of crops grown for bioenergy in England and the UK: 2008 - 2014. Department for Environment Food & Rural Affairs, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/483812/nonfood-statsnotice2014-10dec15.pdf, last access: March, 2017a.

Statistics-GOV.UK: On-line database, Farming statistics final crop areas, yields, livestock populations and agricultural workforce at June 2016. Department for Environmen Food & Rural Affairs, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/579402/structure-jun2016final-uk-20dec16.pdf, last access: March, 2017b.

Steduto, P., Hsiao, T., Raes, D., Fereres, E., Izzi, G., Heng, L., and Hoogeveen, J.: Performance review of AquaCrop– The FAO crop-water productivity model, ICID 21st International Congress on Irrigation and Drainage, 2011, 15-23,

Reply to Anonymous Referee #3

We thank Referee #3 for the comments; below we give the reply to the comments.

Comment

The authors discuss an important topic about a modelling approach rather than expert based approach to deriving marginal cost curves for irrigated agriculture. Their paper has a lot of data and detailed analysis and the method they offer seems to be relevant and to work. It involves a lot of data and assumptions and would seem to be laborious in any actual application, although one could envision a software package that would make the computations easier, assuming the data could be obtained.

The authors published a paper on the same general topic in this journal, and this work would seem to be an extension of it. I have no detailed comments on the methodology, which seems to be straightforward and mainly to use a software package to simulate a lot of scenarios and then plot the resulting cost curves. I judge the work to be of publication quality.

I think the article merits publication. My suggestion is to add some text to explain how this work can be used. Who will use it and for which decisions? Is it simply a model exercise meant for the research literature or can the work be translated into action programs?

Reply: the current study indeed extends our previous work on green and blue WF reduction of irrigated crops (Chukalla et al., 2015). The modelling approach in deriving marginal cost curves relates to the yield response to field management, water stress and local conditions. The consideration of a large number of combined management options led us to use modelling to assess effects of field scale measures and their interaction, as field experiments are limited in covering such combinations; here we draw from Chukalla et al (2015). The calculation of marginal costs of WF reductions is methodologically straightforward. The derivation of plausible WF reduction pathways requires insight in the agronomic plausibility of successive implementation of field scale measures. Next, the derivation of the marginal cost curve for WF reduction again is in itself straightforward but still uncommon in the WF literature.

The previous paper estimated the WF reduction of different measures and combinations of measures. The current paper, through the MCC, shows the cost-effectiveness of measures and combinations of measures. Therefore, the current paper gives important information for decision making on WF reductions by farmers, using both the cost and physical effect to rank measures. As the referee suggests, it is important to show how the work can be used, who can use it, and for which decisions it can be used; this is explained in the paper in section 3.4: the application of the marginal cost curve.

In reaction to a similar comment of referee #2 we will address in the revised paper the relevance of the work for farmers, companies in the food and beverage sector and water managers. The MCCs presented in the paper are of interest to farmers who are seeking to or incentified to reduce crop water footprints in their production practice. They are of interest of companies in the food and beverage sector that increasing formulate water efficiency targets for their supply chain and that are seeking to stimulate farmers to reduce their WF. Finally, the MCCs are of interest to water managers responsible for water allocation and supply to irrigation farming, providing them with information on the costs to farmers if they reduce WF permits to farmers.

References:

Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrol. Earth Syst. Sci., 19, 4877-4891, 10.5194/hess-19-4877-2015, 2015.

Reply to Anonymous Referee #4

We thank Referee #4 for the comments; below we give the reply to the comments.

Comment

The paper tries to derive marginal costs curves for water footprint reductions. In summary, the paper calculates costs and savings of standard practices using the standard tool Aquacrop for 3 european locations plus Israel. The concept is straightforward and therefore of limited originality. The author claim to be the first doing this type of analysis, while later in the paper they admit it has been done previously in the same context but slightly different condition. The difference is relation to water footprint, which is in this context very specifically defined (and only late in the paper). The definition deviates from international standards and should be introduced early in the paper (acknowledge the different definitions and provide rationale for the chosen approach). Additionally, the scope is very narrow (selecting 4 locations) but not having actual case study data and thus being theoretically. However, the topic as such is not novel and might be suitable for an irrigation journal.

Reply:

We agree with the referee comment that the definition of water footprint (WF) is introduced later in the paper. In the introduction part of the revised paper, we will add the WF definition and the rationale on the chosen approach: "*Reducing the non-beneficial consumptive water loss is a means of demand management to increase water use efficiency and thus reduce water scarcity (Mekonnen and Hoekstra, 2016). In crop production, reducing the non-beneficial consumptive water use is possible by decreasing the ratio of evapotranspiration (ET) over the growing period to the crop yield (Y) or increasing the inverse ratio (Y to ET). The first ratio is called the water footprint of crop production (Hoekstra et al., 2011); the inverse ratio is called water productivity (Molden et al., 2010).*"

There are model-driven and expert-based approaches to develop the MCC; the two approaches have been applied extensively in *carbon footprint* reduction. In the area of WF reduction, the expert-based approach has been applied only once, in a case for the industrial sector (Tata-Group, 2013). The current paper pioneers by introducing a *model-driven MCC* in the area of WF reduction and by applying a MCC for water footprint reduction in *irrigated agriculture*. In addition to MCCs, we show the plausible WF reduction pathways, which requires insight in the agronomic plausibility of successive implementation of field scale measures. The approach is highly original and much needed, filling the gap of existing literature on water footprint 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 referee is right we did not use field measured data for validating the simulated result. This limitation puts a disclaimer to the simulated results of our study, but we believe that the results of this study provide a useful reference for similar future studies with other models. Basically we develop an advanced method to develop MCCs and WF reduction pathways for irrigated agriculture.

Comment

All regions are high income countries and therefore this needs to be stressed in the title (add in high income regions). Also cost data is partially only representative of EU conditions.

Reply:

We will add the description of the case study areas in the abstract and introduction section of the revised version of the paper.

Comment

One major flaw in the analysis is the lack of accounting of important costs such as fertilizer and land, which is completely omitted but highly important, since land is typically limited and therefore deficit irrigation has a yield reduction (which is a land cost increase). The results are therefore to be reconsidered.

Reply:

The study is not a full cost benefit analysis of crop production. The study is a cost-effectiveness study to achieve a certain water footprint reduction. We include marginal costs and benefits associated with changing different components in the overall management practice. Costs of fertilizers are a highly relevant element of cost for a farmer, but we don't change fertilizer application practice, so there are no changes in this respect. The costs of land are also relevant, but we consider a fixed field, which means no change in land costs. Moving from full irrigation to deficit irrigation indeed involves yield reduction, but in our study yield reduction from deficit irrigation is kept under 2%.

Comment

L 14 The authors write about water footprint permit per hectare, which needs to have a rationale

Reply:

With the overall increasing demand for water and effect of climate on water availability (Hanjra and Qureshi, 2010), there is fierce competition among various water using sectors. The rationale behind a WF permit per hectare is that the water availability per catchment is limited to runoff minus environmental flow requirement. 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 hectare of cropland. This could be translated in water allocation policy into a max WF permit per hectare. This is just one way of promoting water footprint 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. The MCCs we develop can be used for analysing cost-effective WF reduction given either a target level for WF per unit of crop or a target level for WF per hectare.

Comment

Introduction in general: The authors mainly cite their own work, while it is important to give a broader overview, especially in a diverse field such as water footprint, where many different water footprint concepts have been published and the reader needs to be informed what is done here and how this relates to other work.

Reply:

We are aware as there are debates on water footprint concepts and methodological assessment phases between the life cycle assessment (LCA) and water footprint assessment (WFA) approaches (Chenoweth et al., 2014;Pfister et al., 2017;Hoekstra, 2016). The two approaches differ in their impact/sustainability assessment stage, not in the way they account water consumption in their inventory/accounting stage (Boulay et al., 2013). The current study focuses on cost-effective reduction of water consumption from a field, whereby it does not make a difference on whether we take a WFA or LCA perspective.

Comment

L100: here it is important to talk about land use costs too

Reply:

The study is on MCC for reducing WF per hectare, which informs us about cost of saving water per ha, and on MCC for reducing WF per tonne, which informs us about cost of increasing water use efficiency. We do not aim to represent an agro-economic cost-benefit analysis with inclusion of the costs of all input factors and all revenues. We make sure that yields remain within 2% of the max yield, so that is why we left out reduced revenue at the cost side. We will better highlight this in the paper (now this remark is hidden in method section 2.2).

Comment

Section 2.2 is basically directly summarizing Aquacrop and might be moved to Appendix as it does not provide important additional information (at least it can be summarized).

Reply:

In Section 2.2 we don’t really summarize Aquacrop, but highlight the way we implement the different measures in Aquacrop, just to be fully transparent about our analysis.

Comment

L188ff: The authors talk about green water and differentiating it form blue water. However, there is no way this can be properly done nor is there any hydrological definition of green waster vs. blue water. However, if the concept is used, literature refers to green water as soil moisture (see Falkenmark et al) and thus this is in conflict with previous research. I suggest to omit as it does not add meaningful information.

Reply:

We follow the broadly agreed interpretation that blue water in the soil refers to irrigation water (derived from groundwater or surface water) and that green water in the soil stems from rainwater (Falkenmark and Rockström (2006). 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).

Comment

L204-206: What about fertilizer use? Is this assumed to be optimal? What are the cost related to it?

Reply:

Yes, we assumed optimal fertilizer. The cost of fertilizer is not considered as it is not required to develop the objective of the paper, developing MCCs for reducing WF.

Comment

L208. The authors define water footprint cutting supply chain (which is commonly included even by the author's own references on water footprint). E.g. seedling and fertilizer water use should at least be mentioned.

Reply:

The WF of a *product* is equal to the WF of the *processes* to produce the product, considering all processes over the supply chain (Hoekstra et al., 2011). In the current study we just focus on the process of crop growing, hence we just look at the WF at field level, not the WF of inputs to the process. We will highlight that in the paper.

Comment

Section 2.4. Since major aspects (land and fertilizer costs) are omitted the analysis is very theroetical and not covering the full picture. Additionally the author mix data form global sources and European, while it is used for the European context. Adjustments to price levels needs to be discussed. Some data is really old (1992)

Reply:

Using up-to-date cost data that reflect the market value of the technologies would have been our interest, but we notice that getting such data is difficult. For our purpose, showing a method rather than evaluate a specific case, the data we used suffice. We will advise readers to use the paper as a guide to develop MCCs for WF reduction rather than take all data for granted. Each specific case will require its own data.

Comment

L260. Where is the StDev presented?

Reply:

We indicate the uncertainty around the cost using whiskers in Fig. 3, 4, 7 and 8.

Comment

L293: the scope of the study (locations etx) should be presented at the beginning,
since up to this point the reader supposes it is a globally relevant study.

Reply:

We will add the location of the study both in the abstract and introduction section of the revised paper.

Comment

Results: the results must be revised after inclusion of the additional costs. Also they should report uncertainties. this also applies to the discussion. **Especially the main finding that deficit irrigation is useful (even win-win based on this study) the authors should also discuss why there is still potential for it and why it has not been done already (what are the constraints etc).**

Reply:

We will reflect on the cost uncertainties and why deficit is not practiced yet in the discussion and conclusion section of the revised version of the paper.

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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.

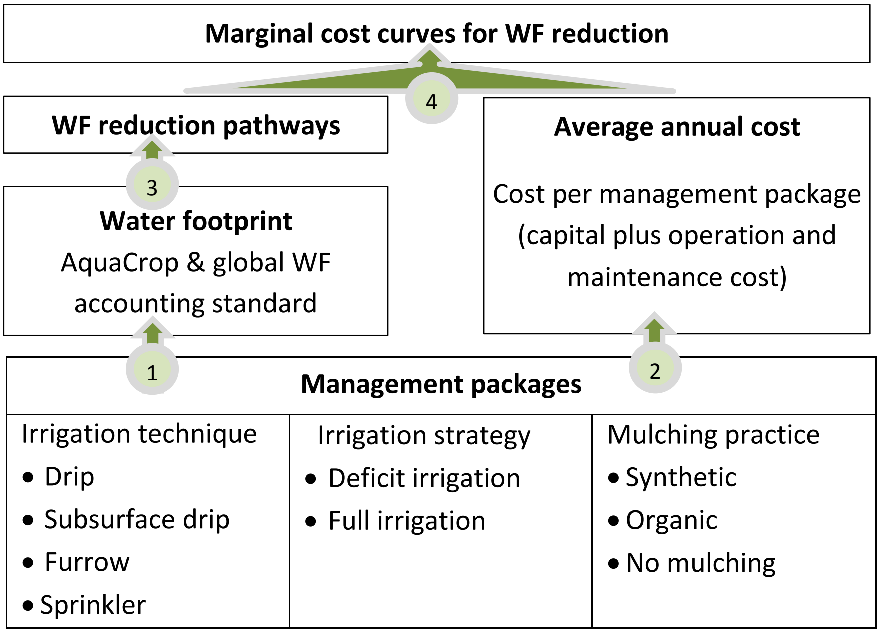

Figure 1. Flow chart for developing marginal cost curves for crop production

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:

$$CF = (1 - f_m \times mc) \quad (1)$$

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.

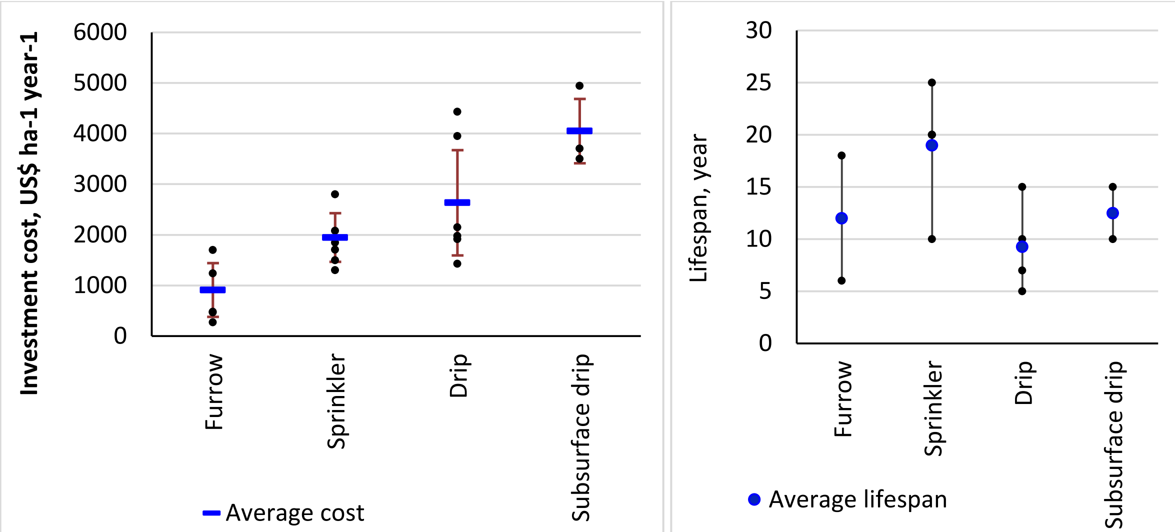

Figure 2. Annual investment cost and lifespan for irrigation techniques

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:

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

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 ^oN, 11.53 ^oE; 19m amsl), Badajoz in Spain (38.88 ^oN, -6.83 ^oE; 185m amsl), and Eilat in Israel (29.33 ^oN, 34.57 ^oE; 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 $1 \times 1 km^2$ 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.

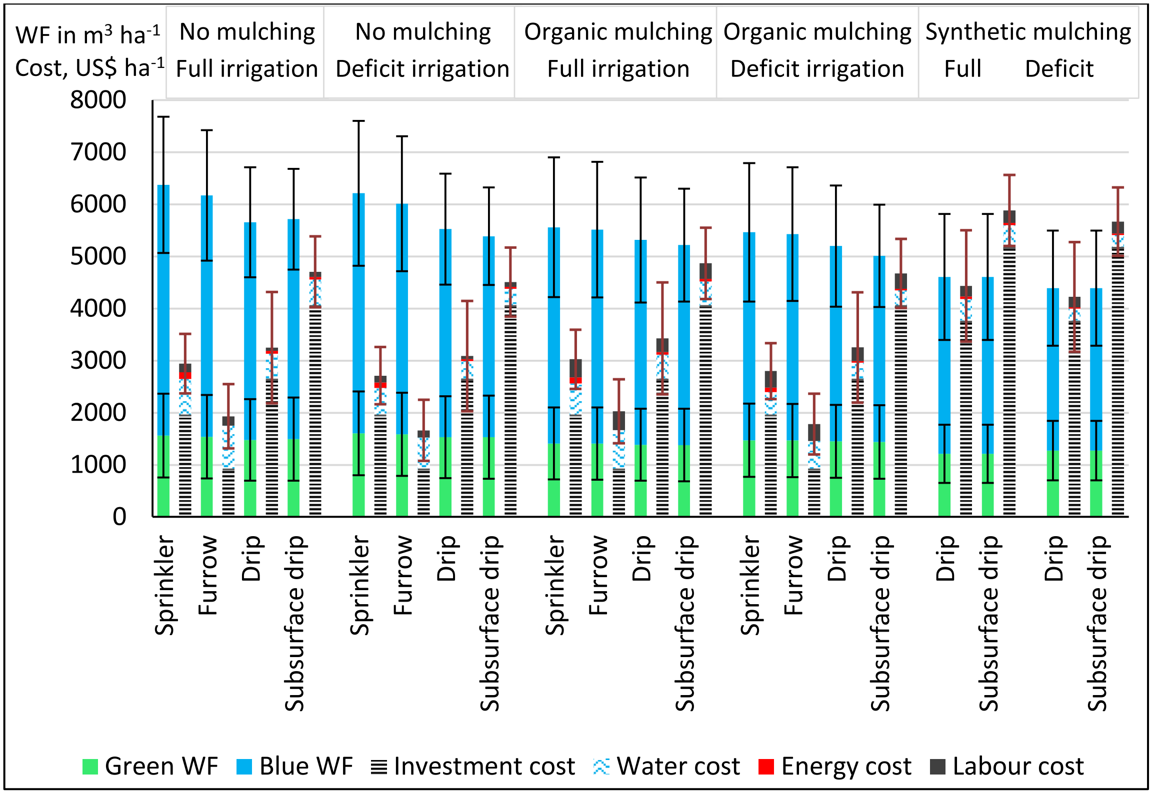

Figure 3: Average WF per area (m^3 ha^{-1}) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers around cost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

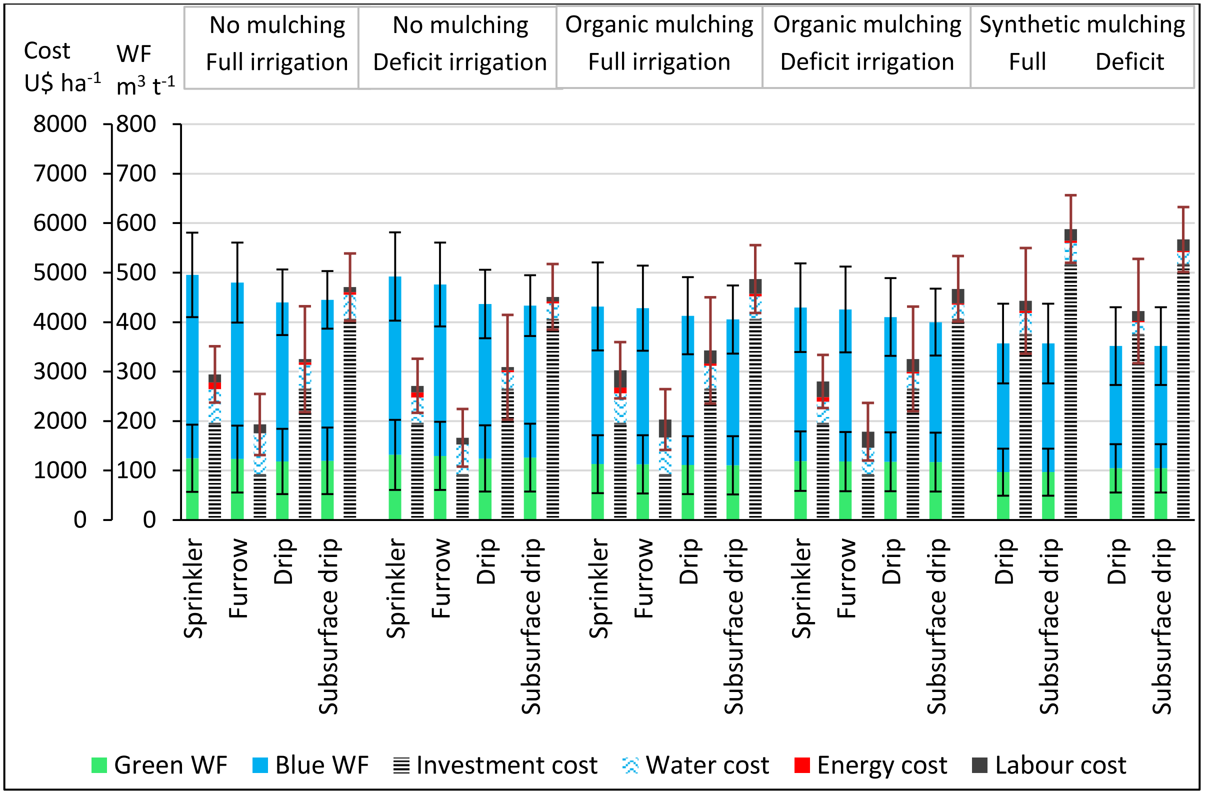

Figure 4: Average WF per product unit ($m^3\ t^{-1}$) for maize production and average annual costs associated with 20 management packages. The whiskers around the WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers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

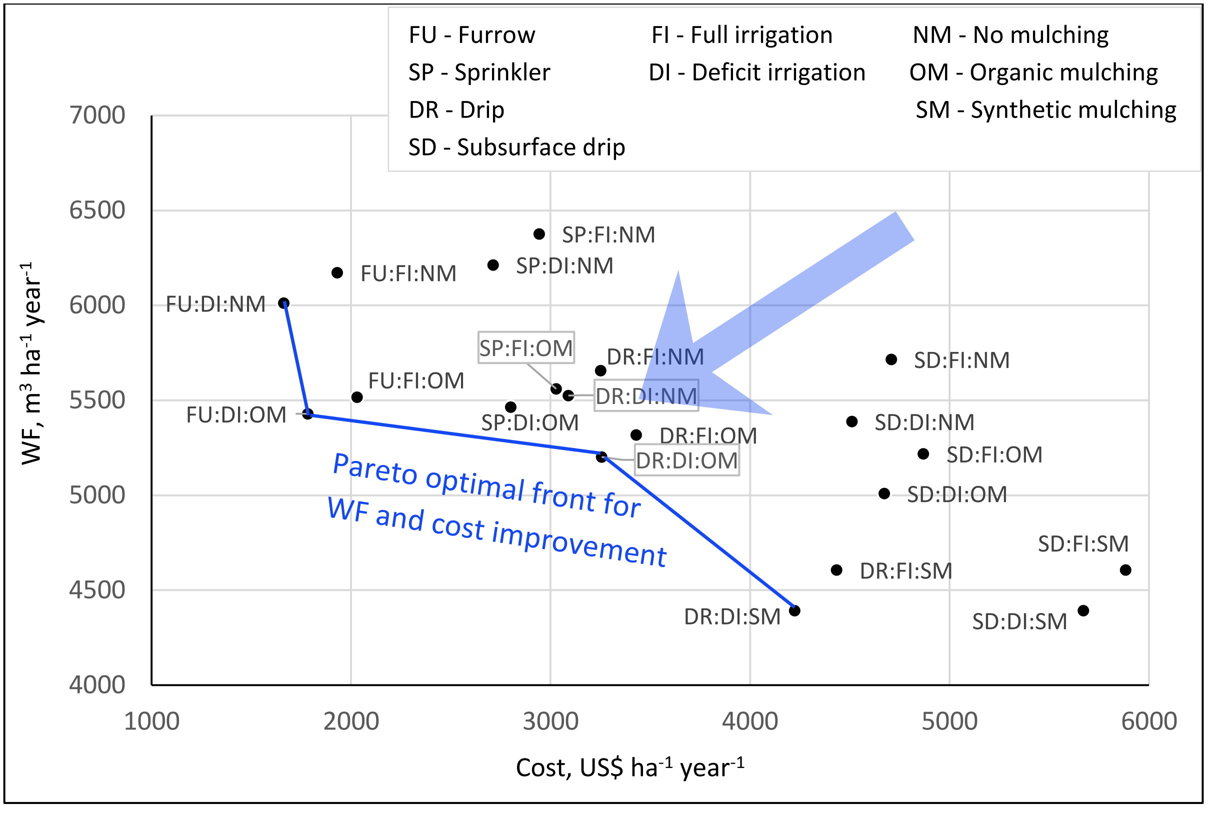

Figure 5: Pareto optimal front for WF and cost reduction in irrigated crop production. The dots represent the annual cost of maize production and the WF per area for twenty management packages. The line connects the Pareto optimal management packages.

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.

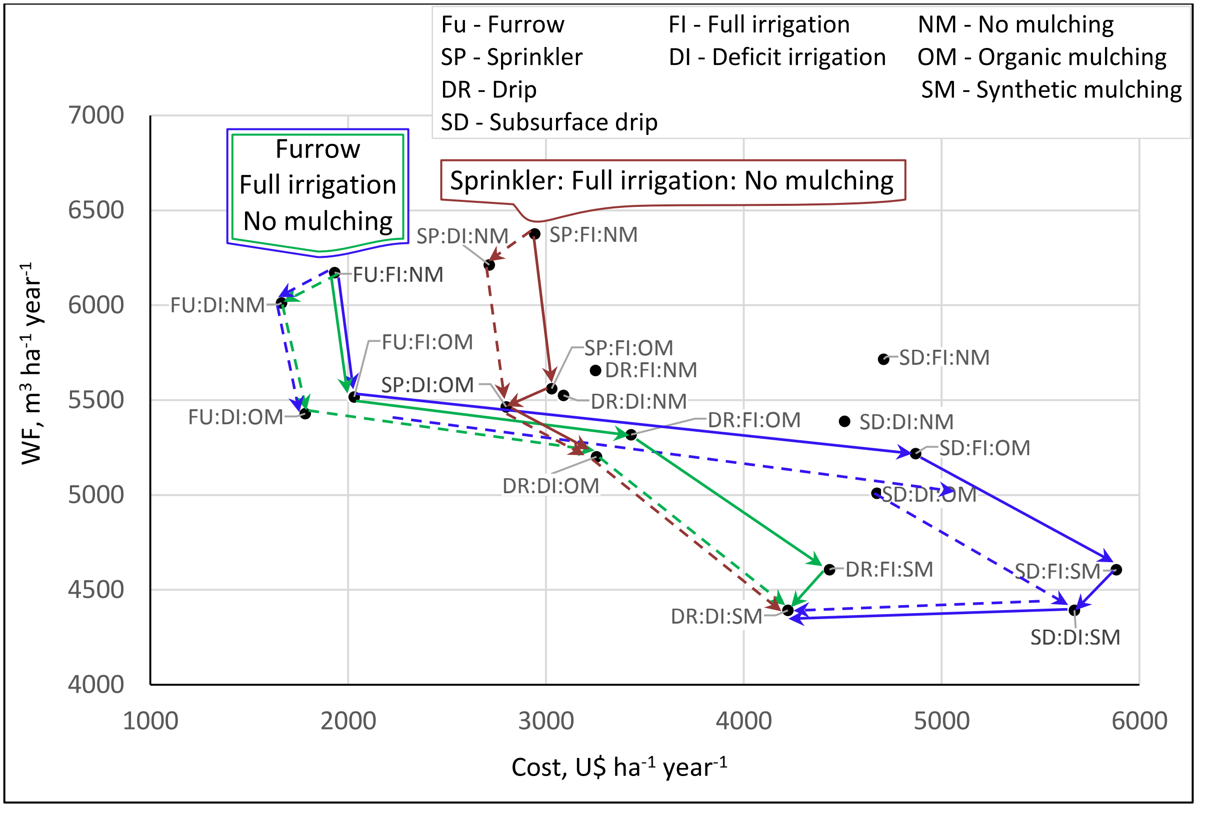

Figure 6: WF reduction pathways for maize from two baseline management packages: full irrigation and no mulching with either furrow or sprinkler irrigation.

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.

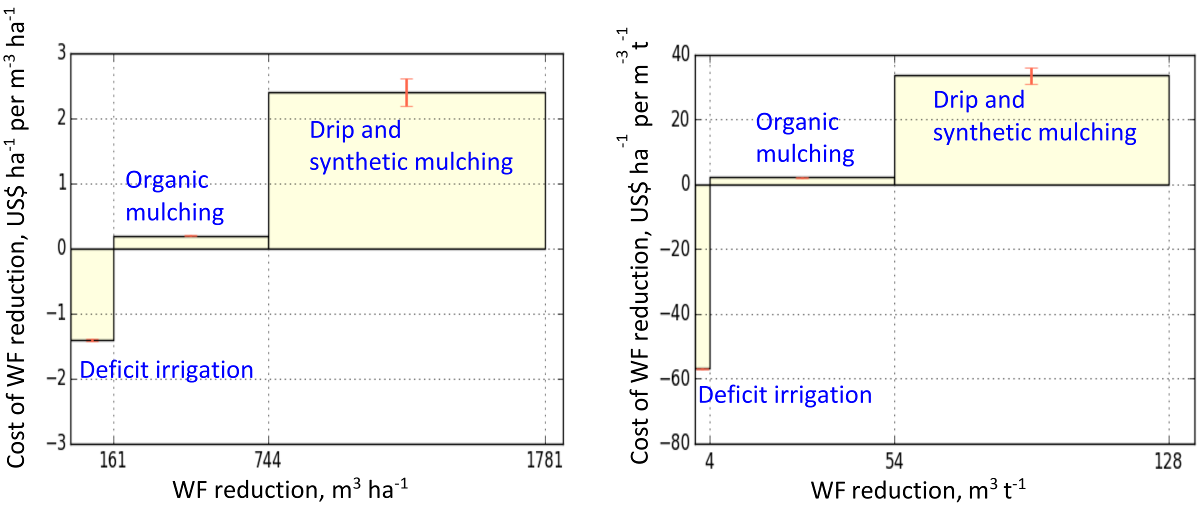

Figure 7: Marginal cost curves for WF reduction for maize for the baseline of furrow irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.

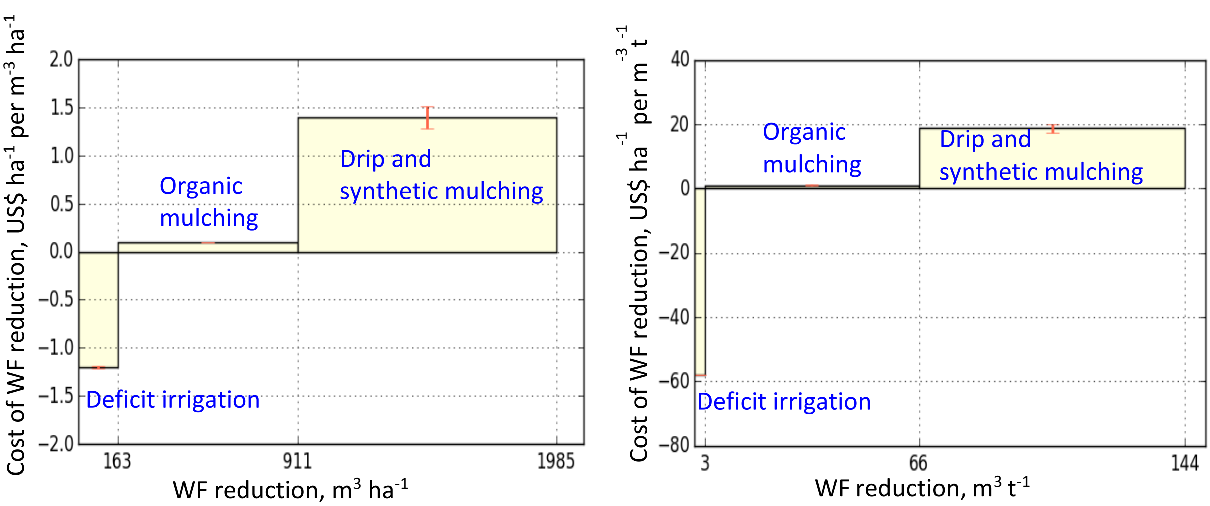

Figure 8: Marginal cost curve for WF reduction of maize for the baseline of sprinkler irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.

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.

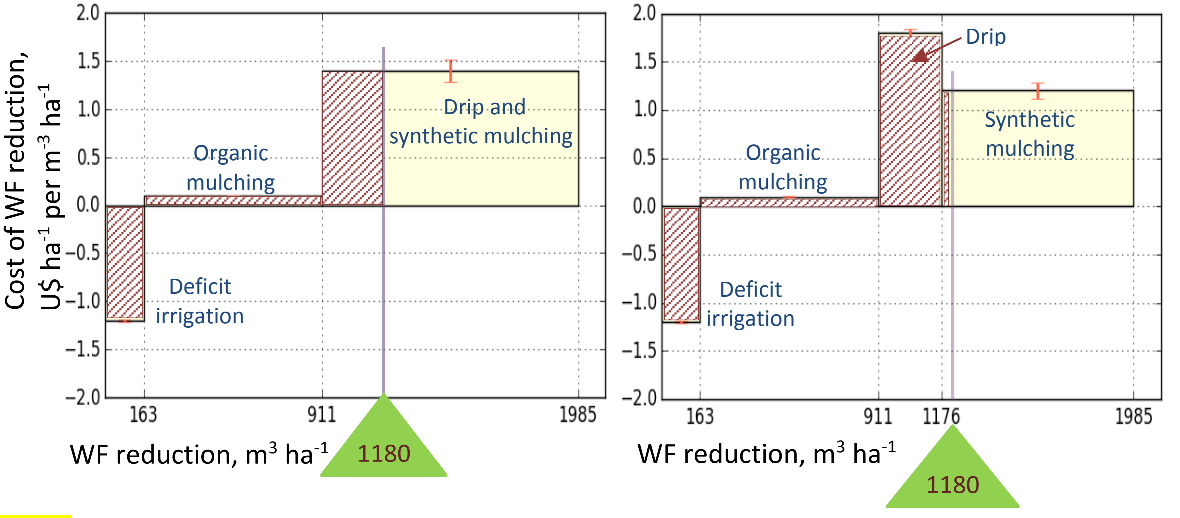

Figure 9: Application of the MCC in an example where the WF of maize production needs to be reduced. The baseline is sprinkler, full irrigation and no mulching with a WF of 6380 m^3 ha^{-1}. This needs to be reduced by 1180 m^3 ha^{-1} in order to meet a given local WF permit. Left: in the third step, 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} per m^3 ha^{-1}	US$ ha^{-1} per m^3 t^{-1}	m^3 ha^{-1}	m^3 t^{-1}	US$ ha^{-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} per m^3 ha^{-1}	US$ ha^{-1} per m^3 t^{-1}	m^3 ha^{-1}	m^3 t^{-1}	US$ ha^{-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 $\text{US\$ ha}^{-1}$
	$\text{US\$ ha}^{-1}$ per m^{-3} ha^{-1}	$\text{US\$ ha}^{-1}$ 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.

<table>
<tr><td rowspan="2">Measures</td><td colspan="2">Marginal cost</td><td colspan="2">WF reduction</td><td rowspan="2">Total cost $\text{US\$ ha}^{-1}$</td></tr>
<tr><td>$\text{US\$ ha}^{-1}$ per m^{-3} ha^{-1}</td><td>$\text{US\$ ha}^{-1}$ per m^{-3} t^{-1}</td><td>m^{-3} ha^{-1}</td><td>m^{-3} t^{-1}</td></tr>
<tr><td>Deficit irrigation</td><td>-0.4</td><td>-275.5</td><td>840</td><td>1</td><td>-323</td></tr>
<tr><td>Organic mulching</td><td>0.1</td><td>7.4</td><td>1045</td><td>10</td><td>73</td></tr>
<tr><td>Drip irrigation</td><td rowspan="2">1.4</td><td>143.2</td><td rowspan="2">1086</td><td>4</td><td>502</td></tr>
<tr><td>Synthetic mulching</td><td>153.7</td><td>6</td><td>983</td></tr>
</table>

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 $\text{US\$ ha}^{-1}$
	$\text{US\$ ha}^{-1}$ per m^{3} ha^{-1}	$\text{US\$ ha}^{-1}$ 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 $\text{US\$ ha}^{-1}$
	$\text{US\$ ha}^{-1}$ per m^{3} ha^{-1}	$\text{US\$ ha}^{-1}$ 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