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Short communication

More food with less water – Optimizing agricultural water use

Mikhail Smilovic[a,*], Tom Gleeson[b], Jan Adamowski[c], Colin Langhorn[d]

[a] Water Program, IIASA, Schloßplatz 1, A-2361 Laxenburg, Austria
[b] Civil Engineering, University of Victoria, PO Box 3055, EOW 206, 3800 Finnerty Road, Victoria, British Columbia V8P 5C2, Canada
[c] Bioresource Engineering, McGill University, Macdonald Stewart Building, 21111 Lakeshore Road, Ste. Anne de Bellevue, Québec H9X 3V9, Canada
[d] Department of Geography, University of Lethbridge, 4401 University Drive, Lethbridge, Alberta T1K 3M4, Canada

Global food demand is projected double by 2050 (Gerland et al., 2014; United Nations 2015; Godfray et al., 2010; Foley, 2015; Licker et al., 2010) significantly increasing freshwater consumption (Bruinsma, 2009; Wada and Bierkens, 2014), a pivotal sustainability challenge directly related to the UN sustainable development goals of zero hunger, clean water and sanitation, life below water, and life on land (UN, 2015). Optimally using irrigation water within a watershed could support both food and water security by increasing water productivity or ‘crop per drop’ (Brauman et al., 2013; Oweis and Hachum, 2012) which will help to close ‘yield gaps’ (Mueller et al., 2012). Optimizing water use of an agricultural region involves managing both the timing and spatial distribution of water – this is the first study to evaluate optimizing water use with both on-farm timing of irrigation and the spatial distribution of water between farms within a region or watershed. Here we develop a broadly-applicable tool to evaluate the potential of optimizing the spatial and temporal distribution of irrigation water and show impressive results when demonstrated for wheat across a large watershed in western Canada. Wheat production can be maintained while reducing water use by ~77%, or production can increase by ~27% without increasing irrigation water use. The results support the management of irrigation water at watershed-scale to maximize water productivity, and supports optimizing irrigation water and creating the management infrastructure to buffer potential crop failures and losses that will be exacerbated by increasing climate variability (Stocker et al., 2013; Field et al., 2014). In regions of severe water scarcity, optimally managing water is a critical initiative to increase food and water security (Rockström and Falkenmark, 2015). We anticipate the tool, which can be applied to any crop and region with sufficient data to calibrate a crop model, will be of interest to governments, water-managers, agriculturalists, and industry evaluating sustainable initiatives to grow more food with less water.

Optimizing irrigation water implies maximizing agricultural production for a given quantity of water, namely, maximizing the “crop per drop” defined as irrigation (or blue) water productivity. This study evaluates the potential of optimizing irrigation over a watershed by allowing water to be distributed where and when it generates the most increases. Previous efforts related to water productivity have evaluated the potential increases in water productivity without explicitly considering specific practices (Brauman et al., 2013), as well by explicitly evaluating the increases from improving irrigation efficiency (Jägermeyr et al., 2015), practicing water harvesting (Jägermeyr et al., 2016), and optimizing crop distribution (Davis et al., 2017). This is the first study to determine the potential increases from optimally determining the timing of irrigation and spatial distribution of water use. Embedded in this approach is the possibility that farms receiving water may not necessarily be allocated sufficient water as to completely avoid water stress. Therefore, the timing of this water stress, or the timing of irrigation, are necessary investigations in optimizing water-limited irrigation. The practice of irrigating with limited water is generally called supplemental irrigation, as compared to full irrigation where crops ideally do not experience water stress. Supplemental irrigation has been shown to improve water productivity in semi-arid and dry regions globally (Oweis and Hachum, 2012), but has yet to be evaluated beyond field-scale. Supplemental irrigation has been suggested and demonstrated as an effective option to support non-irrigated agriculture, which is currently responsible for 70% of global food production (Oweis and Hachum, 2012; Siebert and Döll, 2010; Wada et al., 2014). Increasing crop water productivity globally has been estimated to be of potentially significant impact (Brauman et al., 2013). The rainfed water gap, defined as the ratio of actual yield and estimated yield without water stress for rainfed agriculture, is averaged globally at 29% (Jägermeyr et al., 2016) (Fig. 1). In other words, the rainfed water gap is the ratio of yields resulting exclusively from green water use, namely consumption derived from precipitation, and yields from also using blue water to meet potential water use, namely consumption of the water withdrawn from rivers, lakes, reservoirs, and aquifers (Aldaya et al., 2012). Optimizing irrigation reduces the rainfed water gap by more optimally using blue water.

However, there has yet to be a tool to evaluate independently the impact of implementing supplemental irrigation, and further, the potential of completely optimizing the spatiotemporal distribution of irrigation, across multiple spatiotemporal scales. *Water productivity* is the amount of crop yield produced per unit of water and of specific interest for this study, *irrigation water productivity* is the ratio between the yield derived from irrigation, namely the total yield minus the yield under non-irrigated conditions, and the seasonal irrigation water use. In other words, irrigation water productivity evaluates the amount of irrigation-

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[*] Corresponding author.
E-mail address: smilovic@iiasa.ac.at (M. Smilovic).

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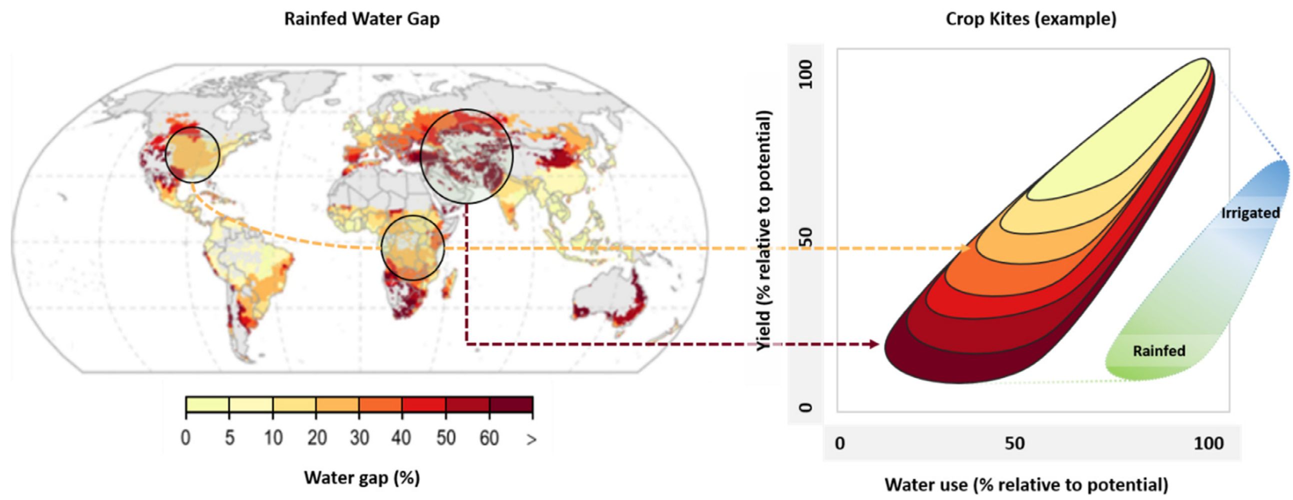

Fig. 1. The global rainfed water gap map (Jägermeyr et al., 2016) illustrates the regional potential of optimizing irrigation. The height of the associated crop kites, the space of potential water use and yield relationships, are related to the magnitude of the water gap. For each crop kite, the results with higher yields and water productivity result from increasing blue water consumption, namely irrigation water – the bottom left of each crop kite represents the yield exclusively from green water consumption, namely rainfed agriculture. The space between these two points is the entire crop kite. The benefits of optimizing irrigation are emphasized for regions with significant water gaps.

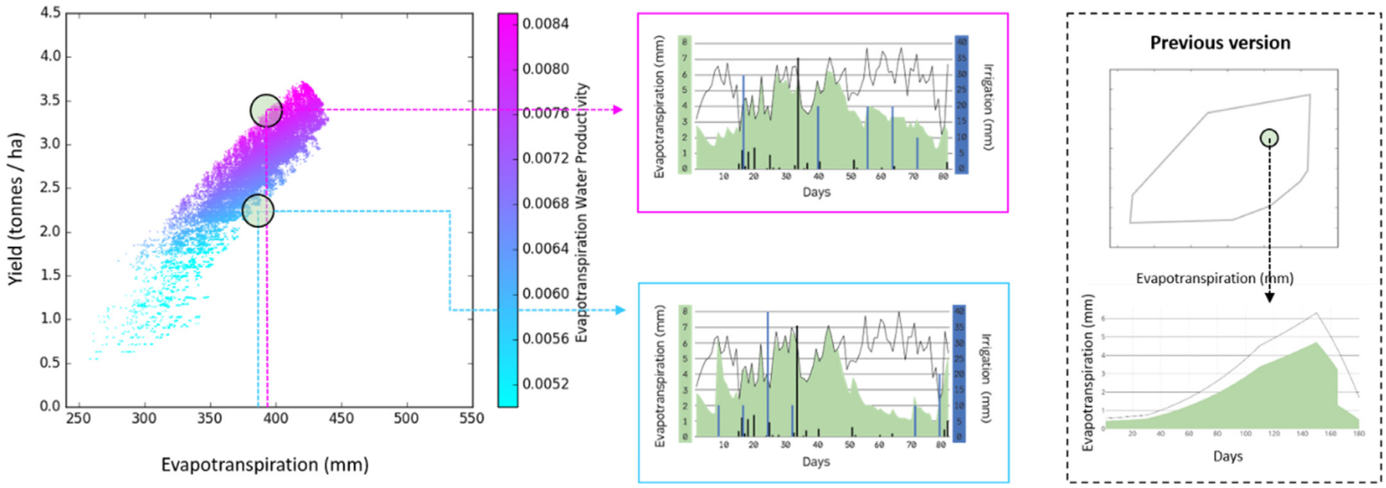

Fig. 2. Crop kite: each point represents the results of simulating a different irrigation schedule, holding all other agroclimatic variables constant. Two simulations are highlighted: both are provided 100 mm of irrigation (distributed differently, represented by the vertical blue bars) and result in similar actual evapotranspiration (represented temporally by the filled in green space) – note that both share the same precipitation (vertical black bars) and potential evapotranspiration (upper black line). However, the two irrigation schedules result in significantly different yields. The box on the right displays the previous version of crop kites, including both the simpler estimated crop kite outline, as well as the simplified ET-day function. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

derived yield per drop of irrigation water consumed. This study presents for the first time, a tool to evaluate the regional potential of optimizing the spatiotemporal distribution of irrigation water.

The study further expands on the concept of crop kites (Smilovic et al., 2016), constructing the space of crop water use and yield relationships as resulting from the outcomes of adopting different irrigation schedules. The resulting geometry of the crop kite is then used to derive optimal solutions. The improvements to the methodology allow us to determine crop kites at a significantly finer spatiotemporal resolution by incorporating more specific agroclimatic data, as well as a more complex and process-based crop simulation model. Crop kites are the space of points relating crop water use and crop yield, where each point represents the results of an irrigation schedule (Figs. 1 and 2). Simulating sufficiently many and distributed irrigation schedules allow one to determine the envelope in which all possible simulation outcomes will occur. Using this crop kite envelope, one can determine the optimal relationship between water use and crop yield, as well as the suggested schedule(s) that result at or near the optimal point.

Water productivity can be determined at multiple and nested spatial scales. Supplemental irrigation can be used to limit irrigation on fully-irrigated crops and introduce limited irrigation on non-irrigated crops, and the balance between the two has been shown to increase water productivity (Oweis and Hachum, 2012; Oweis, 1997). This study takes a system's approach by determining the maximum historical irrigation water productivities for a watershed made theoretically possible by adopting an optimized practice of supplemental irrigation throughout the watershed. Inherent in the optimization, water withdrawn within the watershed is used when and where it is most productive within the watershed, and the optimal timing and distribution of water are decided accordingly. This follows the suggested breaking of the current separation of irrigated and non-irrigated agriculture (Rockström et al., 2010) and evaluates the maximum productivity potential of the already abstracted water, not necessarily subject to water abstraction rights determined in less-optimized ways. The tool determines the year-specific potential decreases in water use while maintaining production, as well as potential increases in production while not increasing water use.

The tool derives the relationship between irrigation water use and optimal yield, defined as an optimized crop-water production function (Geerts and Raes, 2009). Crop yield is dynamically related to both the availability and temporal distribution of soil moisture – under soil moisture deficit scenarios, crop growth and yield will both be affected non-linearly (Doorenbos and Kassam, 1979; Steduto et al., 2012), and thus deriving the relationship between crop-water use and yield is challenging. Previous efforts have attempted to determine this relationship with field experiment or theoretical construct, but are necessarily limited with observations and field data of at most a few years, limiting and potentially biasing the temporal distributions of water use investigated, as summarized by Smilovic et al. (2016). The methodology introduced in this study constructs the solution space of possible irrigation-water use and crop yield relationships, defined here as a *crop kite*, with the use of a crop growth and water use simulation model: the model is used to determine the outcome of adopting *any possible* irrigation schedule, and maps each irrigation schedule to its associated point on the crop kite relating irrigation water use and crop yield.

Crop kites for preliminary regional evaluations with limited available data and not considering irrigation scheduling is presented in Smilovic et al. (2016). The previous version introduced crop kites as the space of water use and crop yield, but did not develop the necessary methodology or to be used for the practical purposes of estimating the potential of optimizing irrigation. This version takes the introduced concept of crop kites and develops a tool for its actual application. The current version improves upon previous efforts in the following ways: first, it investigates determining the effect of adopting *any* irrigation schedule, and derives from all the potential schedules the optimal irrigation schedule maximizing yield for each amount of irrigation water, and is not limited or biased in its choice of irrigation schedules to evaluate; second, it provides the capacity to evaluate over a wide range of agroclimatic variables, assuming appropriate calibrations, greatly facilitating the evaluation of supplemental irrigation at larger spatiotemporal scales; and third, it partitions water consumption into its precipitation and irrigation contributions, allowing for the determination of irrigation water productivity. The methodology is a fundamental conceptual shift from the current general approach to understanding crop-water production functions, and this is expressed in its capacity to evaluate quantitatively the potential benefits of optimizing irrigation, something not before estimated. The previous rendition of the crop kite is presented alongside the current version in Fig. 2.

This study employs the crop-water model Aquacrop (Andarzian et al., 2011; Mehraban, 2014; Salemi et al., 2011; Ghanbbari and Tavassoli, 2013; Rezaverdinejad et al., 2014; Erkossa et al., 2011; Guendouz et al., 2014; Soddu et al., 2013; Iqbal et al., 2014; Jin et al., 2014; Zhang et al., 2013b; Sarangi et al., 2016; Kumar et al., 2014; Singh et al., 2013; Raes et al., 2009), however, the methodology is not dependent on Aquacrop and can be used with any sufficiently good crop-water model with local calibration. The tool is broadly-applicable for different crops and regions, and the necessary data to employ the tool for a different region or crop are generally available, including daily precipitation, minimum and maximum temperature, soil profiles and characteristics, planting and harvest dates, and sufficient time series of crop-specific yields and areas sown and harvested. If sufficient data on crop yields are not available uniformly across the entire study region, we introduce the development of agroclimatic zones discussed in the supplementary information (Text S3). This study demonstrates the application for different regions and crops by determining different sub-regions within the watershed related to specific agroclimatic conditions with potentially different crop varieties.

Mkhabela and Bullock (2012) calibrated and evaluated Aquacrop for wheat varieties in the Canadian prairies, and provided the necessary initial calibrations for this study. The methodology is demonstrated for spring wheat production in the Oldman River watershed of western Canada (Fig. 3). The region was chosen as it is generally representative of semi-arid regions with both irrigated and non-irrigated fields, and presents ranging climate and soil characteristics. Wheat was chosen as it covers more land surface globally than any other cultivated crop (Curtis et al., 2002) and is the third largest produced in terms of weight (Steduto et al., 2012). Wheat has been studied extensively for use with supplemental irrigation (Salemi et al., 2011; Iqbal et al., 2014; Jin et al., 2014; Oweis et al., 1998; Tavakkoli and Oweis, 2004; Ilbeyi et al., 2006; Tafteh et al., 2013; Zhang et al., 2013a; Rezaverdinejad et al., 2014; Mahmood et al., 2015) and modelled extensively with Aquacrop. The cell- and year-specific crop kites are constructed at 10-km resolution, where each cell is represented by its local weather and soil data. The crop kite shape is dependent upon local agroclimatic conditions and thus shifts significantly between the years and among different areas – the simulated crop kites for a relatively dry (year 2000) and a relatively wet year (year 2009) for two different agroclimatic zones are illustrated in Fig. 3.

The year- and cell-specific optimized crop-water production functions are derived and arranged to determine the potential of optimizing irrigation at watershed-scale. An average of 77% less irrigation water is sufficient to maintain annual spring wheat production (Fig. 3b), statistically significant with a *t*-value of −5.24 and coefficient of variation of 24%. Isolating for the effect of exclusively redistributing irrigation water within the watershed, and remaining subject to the separation of fully irrigated and non-irrigated areas, an average of 19% less irrigation water is sufficient to maintain annual spring wheat production, with a coefficient of variation of 11%. Notably, the significant potential of optimizing irrigation water results from integrating both the spatial and temporal optimal distributions of irrigation water.

An average of a 27% increase in spring wheat production is possible while maintaining annual irrigation water use (Fig. 3c), statistically significant with a *t*-value of −5.24 and a coefficient of variation of 15%. This is presented in Fig. 3(c) alongside the time series of the actual production, estimated production if all areas sown with spring wheat are irrigated, and estimated production assuming all areas are non-irrigated. Isolating for the effect of exclusively redistributing irrigation water within the watershed, an average of a 16% increase in spring wheat production is possible while maintaining annual irrigation water use, with a coefficient of variation of 13%.

The results show the estimated maximum potential increases in irrigation water productivity resulting from optimally managing irrigation water are significant. These estimates were determined using historical data, and we were thus with the retrospective advantage of determining optimal irrigation schedules while understanding the weather conditions of the entire growing season. However, these optimized estimates are still appropriate to frame potential changes, and can significantly support watersheds in evaluating the benefits of improving water productivity, including decreased water use and increased agricultural production, resulting from adopting these initiatives. The potential changes to the distribution network to allow for such irrigation water redistribution, the necessary investments in infrastructure, as well as community support and learning, are costs that can then be appropriately weighed against the benefits, tailoring the evaluation for different socioeconomic, cultural, and political contexts. The model assumed the use of sprinklers, the most commonly used technology of the region, which is represented in Aquacrop by assuming that 100% of the soil surface is wet by irrigation, and thus susceptible to evaporation – this is customizable for the region being evaluated. We assumed no increases in irrigation efficiency under our simulated scenarios to isolate for the increases from optimizing the spatiotemporal management, but

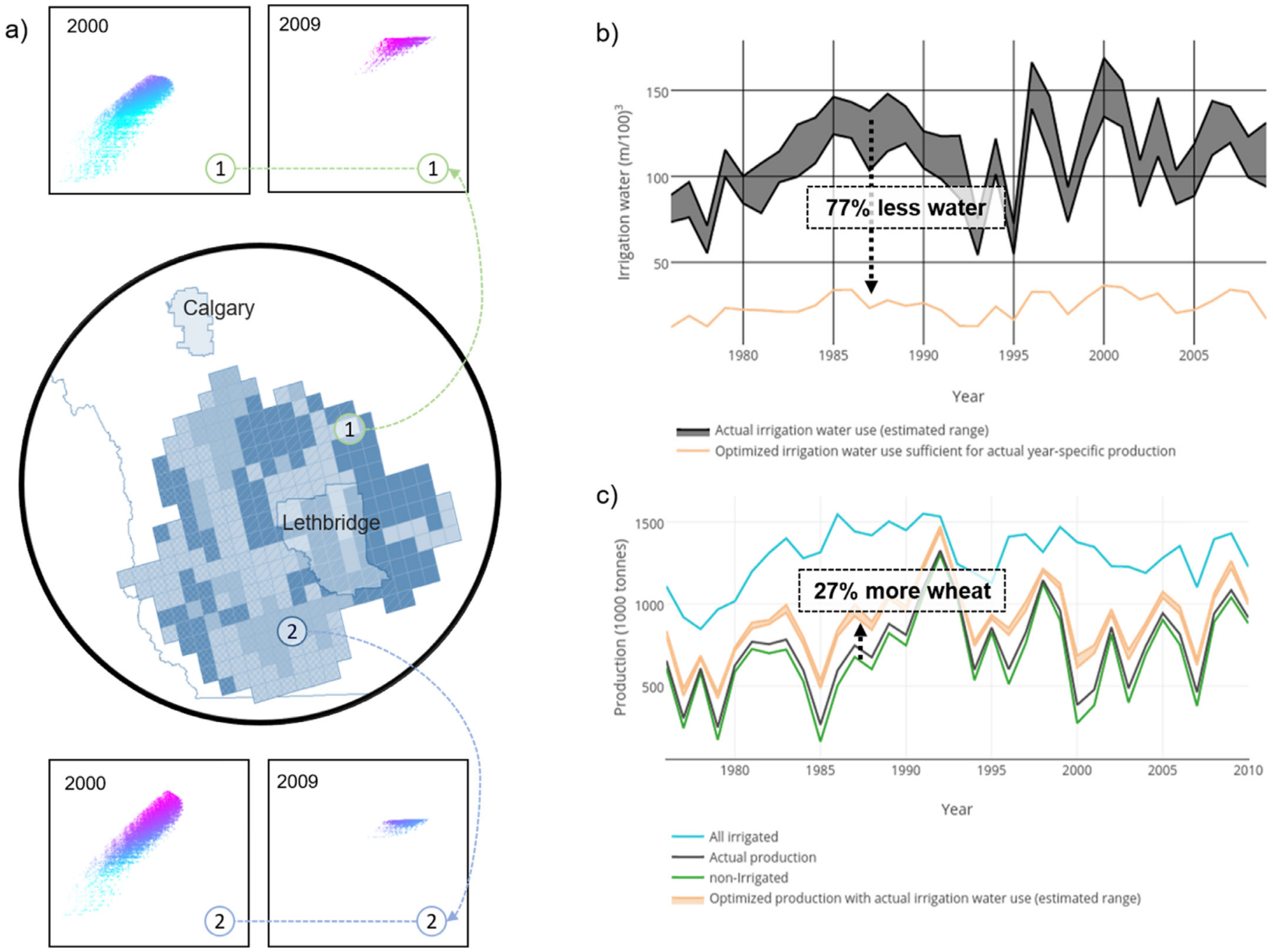

Fig. 3. (a) The crop kites for two different agroclimatic zones for two different years – the axes, scale, and colors for the crop kites are the same as for Fig. 2. The watershed is positioned in the southwest corner of Alberta, Canada, and the cities of Calgary and Lethbridge are highlighted. The gridded watershed represents the different agroclimatic zones with shades and textures, detailed in the supplemental information (b) The estimated range of actual irrigation water use and the minimum water use sufficient to maintain year-specific spring wheat production. (c) Spring wheat production under various irrigation scenarios: Full irrigation on all areas sown, the optimized distribution of simulated actual year-specific irrigation water use, actual production, and no irrigation on all areas sown.

any increases in irrigation efficiency would further improve the results. In regions sowing multiple crops in a single field, the solution could optimize towards a weighted sum of the different normalized yields, weighted depending on the relative chosen value of each crop. Actual irrigation water use was simulated as reliable and accurate observations on water use were unavailable. To account for this, we emphasized the use of Aquacrop for this study as the crop-water model that had been appropriately calibrated for the region and in general has been strongly referenced to accurately simulate crop water use (S3.4). We did not discuss the important issue of water quality, but our results show that yields can be maintained while significantly reducing the water use derived from irrigation, and allow for this *extra allocated* water to no longer be abstracted but stay for the benefit of the water system and associated ecosystems. Importantly, the over application of irrigation water is a direct cause of nutrient runoff into nearby waterbodies and aquifers, and the limited application of irrigation may reduce nutrient runoff and soil erosion.

This study developed for the first time, a broadly applicable tool to evaluate the potential of optimizing irrigation water with supplemental irrigation and the spatial redistribution of irrigation water. The results provide strong evidence that using irrigation water when and where it is most beneficial provides a clear opportunity to both reduce water consumption and increase agricultural productivity, particularly valuable for water-limited regions. The methods introduced in this study construct crop kites with a calibrated crop-water model and derive optimized crop-water production functions, liberating optimized and supplemental irrigation evaluations to larger-scales and embracing multiple agroclimatic conditions. The methodology is broadly applicable for different crops and regions for which a sufficiently calibrated crop simulation model exists. Demonstrated for a large watershed in western Canada, the average potential savings in irrigation water use while maintaining year-specific production was 77%, and alternatively, the average potential increase in spring wheat production while maintaining year-specific irrigation water use was 27%. The increase in water productivity resulting in the decrease of water consumption liberates water for other critical purposes, including potable water supply and higher flows and levels for the associated ecosystems, supporting the sustainable development goals of clean water and sanitation, life on land, and life below water. Increasing water productivity to increase food production supports the sustainable development goal of zero hunger. The balance of objectives to decrease water consumption or increase food production will depend on the socioeconomic, political, cultural, and environmental contexts of the region, though in all cases, optimizing irrigation offers a sustainable management option to increase water productivity. This research demonstrates the potential of optimizing irrigation water from a watershed perspective, and given the global gaps in water productivity and yields, will be instrumental in achieving both food- and water-related sustainable development goals (Fig. 1). We anticipate the methods will be of interest to water managers, agricultural practitioners, governments, and researchers evaluating initiatives to increase agricultural and water productivities.

1. Methods

The methodology is demonstrated for spring wheat in the Oldman River watershed of southern Alberta, with a drainage area of 26,700 km^2 (Fig. 3a) – the example should act as a template for the application to other crops and regions.

The crop-specific distribution of area sown at 5 arc-minute resolution representative of around the year 2000, including the crop-specific ratio of areas equipped for irrigation and that not equipped for irrigation, was derived from MIRCA2000 (Portmann et al., 2010) using the data containing monthly irrigated and non-irrigated growing areas. Our study integrates data on year-specific areas sown with spring wheat as determined from statistics compiled by the Canadian and Albertan governments, but assumes the *distribution* of spring wheat as determined by MIRCA2000 is adequately representative for the historical period of interest given the relative stability of the area sown with spring wheat: the mean area planted with spring wheat from 1976 to 2010 is ~400,000 hectares with a mean coefficient of variation of 13% with no significant increasing or decreasing trend. If the crop-specific distribution of area sown around the year 2000 is not appropriately representative of the historical period of interest, another dataset or available time series of crop distribution should be used. For the procedures used to determine the year- and cell-specific areas sown with irrigated and non-irrigated spring wheat, we refer the reader towards the supplementary information (Texts S1 and S2).

Previous efforts have attempted to determine the optimized crop-water production function from field-based data which are necessarily limited spatiotemporally and significantly limited to investigating but a few temporal distributions of the irrigation water throughout the growing season. A calibrated crop-water model, however, is not similarly limited in the number of temporal distributions it can investigate. Instead, by constructing the crop kite by simulating a sufficiently representative subset of the set of all possible irrigation schedules, one can determine the entire space of crop yield-water use relationships, as well as both the maximum water productivity associated with each amount of irrigation water.

Irrigation can potentially occur on any day within the growing season, leading to a technically infeasible number of simulations. To mitigate this, it is necessary to determine a sufficient number of and appropriately distributed simulations as to determine with confidence the upper boundary of the crop kite. Explicitly, for each cell and year, the following three variables must be determined as to find a suitable subset: a sufficient number of potential irrigation days evenly distributed throughout the growing season (*Irr days*), a sufficient irrigation depth interval (*Irr depth*), and a sufficient maximum total irrigation water use (*Irr max*), after which there are no increases in yield. Increasing *Irr days* and *Irr max*, and decreasing *Irr depth* all necessarily increase the number of simulations.

Given the length of the growing season, |*growing season*|, irrigation potentially occurs on the days within the growing season determined as follows:

$$\frac{|growing\ season|}{Irr\ days} \cdot i, \qquad 1 \leq i \in \mathbb{N} \leq Irr\ days \tag{1}$$

An irrigation schedule with a total amount of irrigation water use equal to *Irr* can be interpreted as a sequence, defined as $(x)_{i=1}^{Irr\ days}$ such that x_i is a non−negative multiple of *Irr depth* and

$$\sum_i x_i = Irr \tag{2}$$

In words, each individual irrigation application may range from 0 to *Irr* in *Irr depth* intervals, and the sum over all applications throughout the growing season must equal *Irr*.

In a circular fashion, each of *Irr depth, Irr days*, and *Irr max* are determined by fixing the other two and determining the sufficient value of the variable in question. Sufficiency is determined as the value at which there are no longer significant changes in the top boundary of the crop kite (root mean squared error) from refining the value further, such as increasing *Irr days* and *Irr max* or decreasing *Irr depth*. It was determined for this study that in all cells and all years, an *Irr depth* of 30 mm (Fig. S3a; Table S3), *Irr days* equal to 11 (Fig. S3b; Table S4), and *Irr max* equal to 210 mm were sufficient as to determine the top boundaries of the associated crop kites – a total of ~30,000 simulations were thus completed for each cell- and year-specific crop kite.

The top boundary of the constructed crop kites are exactly the optimized crop-water production functions, and these top boundaries are derived from a collection of crop kites representing both the agronomic and climatic variability of the study region. Finally, these top boundaries are fragmented and glued together in order of decreasing irrigation water productivity to form a watershed-scale optimized crop-water production function. The algorithm for this process is included in the supplementary information (Text S3). Estimates on year-specific actual production and actual-water use (as determined in Text S2) are used to demonstrate quantitative estimates of potential to reduce irrigation water consumption or increase crop production.

2. Author contributions

M. S. was the lead creator and investigator on all accounts and wrote the manuscript.

T. G. collaborated on the original idea development, research objectives, and supervised and supported the project along its execution, including the editing of several drafts.

C. L. collaborated on the development of agroclimatic zones and calibration of the crop-water model for the nine agroclimatic zones, and organized the data.

J. A. similarly supported the project along its execution, including the editing of several drafts.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2018.09.016.

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