Improvements in crop water productivity increase water sustainability and food security—a global analysis

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Abstract
Irrigation consumes more water than any other human activity, and thus the challenges of water sustainability and food security are closely linked. To evaluate how water resources are used for food production, we examined global patterns of water productivity—food produced (kcal) per unit of water (l) consumed. We document considerable variability in crop water productivity globally, not only across different climatic zones but also within climatic zones. The least water productive systems are disproportionate freshwater consumers. On precipitation-limited croplands, we found that \( \sim 40\% \) of water consumption goes to production of just 20\% of food calories. Because in many cases crop water productivity is well below optimal levels, in many cases farmers have substantial opportunities to improve water productivity. To demonstrate the potential impact of management interventions, we calculated that raising crop water productivity in precipitation-limited regions to the 20th percentile of productivity would increase annual production on rainfed cropland by enough to provide food for an estimated 110 million people, and water consumption on irrigated cropland would be reduced enough to meet the annual domestic water demands of nearly 1.4 billion people.

Keywords: water productivity, food security, irrigation, global hydrology, sustainability

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1. Introduction

The world is facing twin challenges of water stress and food insecurity—challenges that are already pressing and are projected to grow \([1–3]\). Because crop production is the largest global consumer of freshwater, and because water is a key resource in food production, neither of these challenges can be addressed in isolation \([4, 5]\). Producing more food for each drop of water will be a crucial strategy to address both challenges \([6]\).

Issues of global water availability and scarcity have been considered in a variety of ways, including identifying areas of water availability \([7]\), water stress, \([8–10]\), impacts of water use \([11]\), and projections of future water scarcity \([2, 12]\). Many recent studies have tied water scarcity to agricultural water consumption \([13–15]\). For the most part, however, these studies have considered water consumption in relation to generic or country-level measures of crop production. However, a number of recent papers have highlighted the wide variability in crop yields worldwide, and located systems where yield improvements are possible \([3, 16, 17]\). Studies
that link agricultural water consumption with detailed yield data tend to be strongly place-based [14, 18–20]. These studies provide key information about specific interventions to improve yields and reduce water use. Global-scale analysis can augment these studies by facilitating learning among systems that are geographically and culturally dispersed. Recognizing that, several reviews have consolidated and analysed field studies of crop water productivity [21, 22]. This study draws on both modelled and empirical data to analyse the global range of crop water productivity, providing insight into the magnitude and location of potential levers of change.

When water is scarce, understanding the magnitude of water consumption is important. In most cases, however, evaluation for decision-making requires information about efficiency—when water is being used, is it being used wisely? With new water consumption [23] and crop production data [17], we can quantitatively assess the range of crop water productivity worldwide. Locating the low end of this range is additionally useful because efficiency improvements tend to be easiest where efficiency is low [24, 25]. Finally, global data allow inference making about drivers of variation in crop water productivity.

Here we assess global-scale patterns of crop water productivity for 16 major food crops using spatially distributed, crop-specific water consumption and yield data. We quantify the tradeoffs between water consumption and food production, evaluate the extent to which factors other than climate limit crop water productivity, and illustrate potential benefits of improved water productivity worldwide.

2. Methods

We analysed crop production, water use, and crop water productivity for 16 staple food crops: wheat, maize, rice, barley, rye, millet, sorghum, soybean, sunflower, potato, cassava, sugarcane, sugar beet, oil palm, rapeseed (canola), and groundnut (peanut). These crops constitute 56% of global crop production by tonnage [26], account for 65% of crop water consumption [23], and cover 68% of all cropland [17]. Crop water productivity is defined here as food (edible) kilocalories produced per litre of water saved were the water productivity of any crop below its 20th percentile value. We then calculated the calories that could be added or saved where crop water productivity for each crop was less than its 20th percentile value for each climatic zone where P<br>100 000 ha (irrigated) or >50 000 ha (rainfed) in a given climatic zone. Further detail on methods is provided in the supplementary information (SI, available at stacks.iop.org/ERL/8/024030/mmedia).

We calculated the Generalized inequality index (Gini) [32] to quantitatively compare inequalities in water productivity among crops and across regions. Cumulative water consumption and cumulative kilocalorie production for each crop at 5 arc minute resolution were ordered by water productivity; the ‘curves’ in figure 3(b) are compilations of these points.

2.2. Water productivity gap

For each crop, we calculated the production-weighted 20th percentile value for each climatic zone where P < PET. In each climatic zone, we identified all cropland where water productivity for each crop was less than its 20th percentile value. We then calculated the calories that could be added or water saved were the water productivity of any crop below its 20th percentile value increased to that value (SI table 1 available at stacks.iop.org/ERL/8/024030/mmedia). Because improvements for each crop are measured against its own 20th percentile value in the same climatic zone, improvements are scaled to the range of variability for each crop.
Figure 1. Annual water consumption across climatic zones. Rainwater (left of centre line) and irrigation water (right of centre line) consumption by all crops, including those (in greys) that are not included in this analysis. For the 16 food crops analysed, the majority (83%) of water originates as rainfall on cropland. Climatic zones, most arid at the bottom and most humid at the top, are based on \( P/PET \) and are evenly distributed in climate space. Cropland in climatic zones in which \( P/PET > 1.9 \) are compressed into a single zone.

3. Results

3.1. Variation in crop water consumption and productivity

Water consumption by crops varies substantially across the globe (SI figure 2 available at stacks.iop.org/ERL/8/024030/mmedia), reflecting differences in cropping density, crop choice, soil characteristics, irrigation availability, and agricultural management as well as climatic drivers of evapotranspiration. The distribution of crop water consumption among climatic zones (figure 1) illustrates the crops likely to contribute substantially where water resources are scarce. In arid climates (\( P/PET < 0.2 \)), rainwater consumption is dominated by millet and sorghum while irrigation water is mainly used for wheat and rice. In semi-arid and dry-sub-humid climates (\( 0.2 < P/PET < 0.7 \)), rainwater consumption is dominated by wheat, rice, and maize while irrigation water use is dominated by wheat, rice, sugarcane, and maize. For the 16 crops studied, 52% of rainwater consumption (by irrigated and rainfed crops) and 82% of irrigation water consumption occur in regions where precipitation is potentially limiting (\( P < PET \)).

We found a large range in crop water productivity. For example, in large parts of Sub-Saharan Africa maize water productivity was below 1 kcal l\(^{-1} \) (0.3 kg m\(^{-3} \)) while the highest water productivities of maize (>6 kcal l\(^{-1} /1.7 \) kg m\(^{-3} \)) were computed for the US corn belt and Northern China (figure 2). Field-based studies (such as those surveyed in [21, 22, 33]) document a similar range of water productivities; our analysis extends their insights to a broader set of climates, locations, and crops.

Variation in water productivity causes water consumption in certain areas to be disproportionately large. On the least water productive rainfed cropland in precipitation-limited regions, ~46% of water was consumed in the production of just 20% of maize calories. Irrigated crops consume both rain and irrigation water—for those low productivity irrigated croplands in precipitation-limited regions where irrigation water provides at least 50% of total water, ~44% of irrigation water consumption by maize went to 20% of food production.

Crop water productivity is not evenly distributed (figure 3). For example, for irrigated wheat in precipitation-limited areas, the USA has a national-level water productivity (2.9 kcal l\(^{-1} /0.9 \) kg m\(^{-3} \)) that is close to the world average (2.8 kcal l\(^{-1} /0.9 \) kg m\(^{-3} \)), but water productivity is unevenly distributed (Gini of 0.32) compared to, for example, China, where irrigated wheat water productivity is uniformly high (4.3 kcal l\(^{-1} /1.3 \) kg m\(^{-3} \)) and evenly distributed (Gini of 0.09).

Variation in crop water productivity is not solely a function of climate. While each crop we analysed has its highest water productivity in specific climatic zones, water
Figure 2. Maize water productivity in precipitation-limited regions. Data for both (a) rainfed and (b) irrigated systems are centred at 3.5 kcal l\(^{-1}\)/1.0 kg m\(^{-3}\), close to the median production-weighted water productivity for rainfed (3.2 kcal l\(^{-1}\)/0.9 kg m\(^{-3}\)) and irrigated (3.5 kcal l\(^{-1}\)/1.0 kg m\(^{-3}\)) maize where P < PET, so that areas of relatively low water productivity are shown in orange and areas of relatively high water productivity are shown in blue.

productivity varied within each climatic zone (SI figures 3 and 4 available at stacks.iop.org/ERL/8/024030/mmedia). For most crops, we see as much variability in water productivity resulting from non-climate drivers as from climate (figure 4).

For irrigated crops, we evaluated water productivity based on combined evapotranspiration of rain and irrigation water. Water productivity of only irrigation (blue) water is a function of both fraction of overall water originating as irrigation water and total crop water productivity. The fraction of irrigation water is strongly correlated with aridity (Pearson’s \(r^2\) is 0.96 for wheat, 0.85 for maize, and 0.99 for rice), while water productivity of irrigated crops is not (SI figure 4 available at stacks.iop.org/ERL/8/024030/mmedia).

We therefore focus on overall water productivity of irrigated crops. Though the full impact of increasing water productivity of irrigated crops would not be gained in irrigation savings, it would result in a lower irrigation water requirement, particularly in more arid climates.

3.2. A water productivity gap

If water productivity on only the least productive, precipitation-limited croplands were increased, the impact would be substantial. For illustrative purposes, we assume all rainfed improvements go towards production and all irrigated improvements go to water savings. On rainfed
cropland in precipitation-limited regions, increasing water productivity to the 20th percentile could increase production by \(\sim 120\) trillion kilocalories per year while holding water consumption constant (figure 5(a)). This amounts to a \(\sim 30\%\) increase over current production in these areas and would provide food for \(\sim 110\) million people annually (assuming an average food requirement of 3000 kcal d\(^{-1}\) cap\(^{-1}\) [34]).

On irrigated croplands, increasing the lowest water productivity in precipitation-limited regions could save \(\sim 77\) km\(^3\) yr\(^{-1}\) of water without reducing food production (figure 5(b)). This water savings amounts to more than one quarter of current water consumption on low water productivity irrigated cropland and would be enough to meet the annual domestic water demand of \(\sim 1.4\) billion people (assuming a demand of 150 l d\(^{-1}\) cap\(^{-1}\) [35]).

To identify countries where water savings on irrigated cropland would be most beneficial, we analysed irrigation water consumption on cropland with the lowest 20% of water productivity in precipitation-limited climates (figure 6). India accounts for more than 40% of total irrigation water consumption in these areas, 67 km\(^3\) yr\(^{-1}\), primarily in wheat and rice cultivation. Because India has so much cropland in these areas, however, irrigation intensity (consumption per hectare) is \(\sim 520\) mm yr\(^{-1}\), close to the median value.
of irrigation intensity on all precipitation-limited, low water productivity cropland (~500 mm yr\(^{-1}\)). By contrast, in similar climates in Uzbekistan, food crops consume only ~3 km\(^3\) yr\(^{-1}\). However, irrigation intensity (~1400 mm yr\(^{-1}\)) is nearly three times greater. Because of low total water consumption, improving irrigation efficiency of food crops in Uzbekistan is unlikely to alleviate basin-wide water shortages, though on-farm impacts may be dramatic. In India, by contrast, small but widespread improvements in irrigation intensity could have a substantial impact. Assessments should not assume that high irrigation consumption is linked to high irrigation intensity.

4. Discussion

4.1. Implications of findings

We sought to quantify the range of tradeoffs between crop water use and production to explore, first, the feasibility of interventions to increase food production and reduce water consumption by improving crop water productivity, and, second, to quantify the potential magnitude of this type of intervention. The extensive variability in crop water productivity within climatic zones indicates that there are many non-climate related drivers of low crop water productivity, and these can potentially be managed. Even when limitations are due to soil or slopes, management techniques such as nutrient addition and terracing or furrowing can improve yields [36]. Water productivity is a ratio, and in many cases low water productivity is likely a function of low yield, so interventions to increase water productivity may focus more on improving yield than on decreasing water consumption.

Specific management strategies to increase crop water productivity must be tailored to local contexts; studies in Nigeria, Sudan, and Niger, for example, have shown that nitrogen and phosphorus limitation restrict millet and
sorghum yields [37]. Water productivity could be increased by increasing yields via improved soil nutrient conditions and reduced wind-driven erosion. Examples of other interventions that have demonstrated improvements in water productivity include: rainwater harvesting and local water storage, applying drip or deficit irrigation, adjusting planting dates, and modifying tillage practices to reduce evaporation [21, 25, 33, 38–40]. In many cases, techniques for increasing water productivity, especially when it is low, require little or no additional water [41].

Any improvement in crop water productivity will have a positive effect on either food production or water savings. We demonstrate the magnitude of increasing low water productivity to the 20th percentile because this is a plausible level of increase. Allocative efficiency demonstrates that it is easier to increase resource use efficiency when resources are used inefficiently; improving the very lowest performing systems therefore should take less effort than improvements in high-performing systems [24, 25]. Implications of crop water productivity improvements to other levels are discussed in the SI (available at stacks.iop.org/ERL/8/024030/mmedia).

4.2. Limitations

By limiting our analysis to 16 crops, our study does not provide a complete picture of all global crop water use or food production. Further, due to data limitations, we are unable to assess water requirements to prevent salinization or for non-beneficial irrigation. Our analysis thus underestimates the volume of water required for irrigated agriculture, particularly in arid regions where irrigation water is often the primary source of water for irrigated crops. In addition, we assume all irrigation demand is met and that irrigation is not limited by water supply. These issues loom large in local and regional management, and we hope to address them at the global scale in the future. We also do not assess production losses due to spoilage, animal feed, or post-consumer waste. The end points of food production provide important context in decision-making about water allocation but are outside the scope of the current research.

We address limitations of methodology in the SI (available at stacks.iop.org/ERL/8/024030/mmedia) in detail.

5. Conclusions

By reducing the amount of water required for crop production, increasing crop water productivity is a key strategy for achieving food security and water sustainability in a world with growing demands for both. If, for example, low water productivity in precipitation-limited regions were raised to the 20th percentile, the total rainfed food production in Africa could be increased by more than 10% without exploiting additional cropland. Similar improvements in water productivity on irrigated cropland could reduce total water consumption by \(\sim 8–15\%\) in precipitation-limited regions of Africa, Asia, Europe, and South America.

The estimated effects of changing management on water productivity are close to the mean water productivity observed for each crop, demonstrating that in many low-productivity systems on-farm interventions can be a leverage point for increasing water productivity. Global analyses like the one presented here can help generalize findings from field-level or regional agronomic studies. However, appropriate management activities to increase crop water productivity will vary regionally and even locally.

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