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Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use

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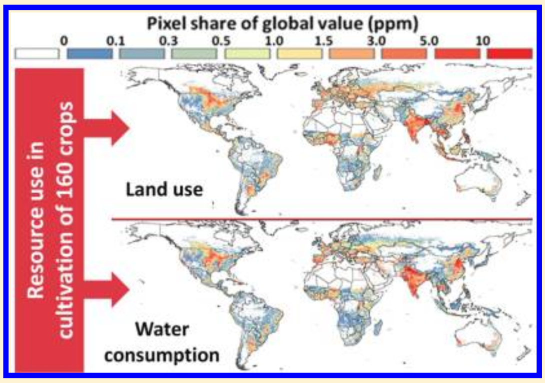
S *Supporting Information*

ABSTRACT: Global crop production is causing pressure on water and land resources in many places. In addition to local resource management, the related environmental impacts of commodities traded along international supply chains need to be considered and managed accordingly. For this purpose, we calculate the specific water consumption and land use for the production of 160 crops and crop groups, covering most harvested mass on global cropland. We quantify indicators for land and water scarcity with high geospatial resolution. This facilitates spatially explicit crop-specific resource management and regionalized life cycle assessment of processed products. The vast cultivation of irrigated wheat, rice, cotton, maize, and sugar cane, which are major sources of food, bioenergy, and fiber, drives worldwide water scarcity. According to globally averaged production, substituting biofuel for crude oil would have a lower impact on water resources than substituting cotton for polyester. For some crops, water scarcity impacts are inversely related to land resource stress, illustrating that water consumption is often at odds with land use. On global average, maize performs better than rice and wheat in the combined land/water assessment. High spatial variability of water and land use related impacts underlines the importance of appropriate site selection for agricultural activities.



INTRODUCTION

Almost 40% of the world population and many ecosystems are suffering from water scarcity.[1] Global stress on water and land resources is increasing as a consequence of population growth and increased per-capita protein and food-energy demand.[2] Agricultural production is currently responsible for the vast majority of global consumptive freshwater use (for 85% according to Shiklomanov[3]) and it is projected to double by 2050.[4] Global production of biologically derived energy and material sources (e.g., biofuels and biological textiles) is expanding and will most likely lead to a substantial increase in agricultural production in the future.[5] As a result of these pressures, water scarcity and land degradation rival climate change as major environmental concern in many regions of the world. Hence, there is a strong need for accurate estimates of water and land use and linked environmental impacts, and for relating these to agricultural commodities.

The environmental impacts of water consumption and water stress are manifold. Aquatic organisms may be directly affected by water depletion, while groundwater-dependent terrestrial ecosystems downstream of the location of water use may also suffer from reduced water availability.[6−8] Water scarcity decreases crop yields, and people, especially in the developing world, may suffer from malnutrition.[9] Fossil groundwater resources, reservoirs, and lakes are already being depleted in many regions.[2] All these environmental impacts are heavily dependent on spatial conditions. One liter of water consumed in the Nile watershed, for instance, does not compare to one liter of water from the Mississippi, because water is much scarcer in the Nile watershed. Therefore, it is necessary to characterize water consumption according to the environmental impact at the specific location. From a "polluter pays" perspective it is highly relevant to associate environmental consequences with products.[10] Depending on the crop type, the production system and the environmental conditions, large differences regarding water and land use are observed. Environmental assessment metrics are required to compare cultivation of alternative crops and in different locations. The resulting insights are equally relevant for guiding producer or consumer decisions, especially in the field of product-based life cycle assessments (LCA)[11] and the emerging water-footprint analysis,[12−16] which focus on life cycles of products and services, encompassing the entire value chain.

Environmental impacts from using land and water, which are limiting resources in agriculture, show trade-offs: Yield

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maximization reduces the pressure on land, but can coincide with lower water-use efficiencies.[2,17] Rainfed agriculture in semiarid regions, in contrast, occupies more land than irrigated cultivation. Generally, agriculture can either expand to areas with productive natural ecosystems in humid areas or on irrigated marginal lands.[4] A combined assessment of land-use and water-consumption associated impacts of global crop production on high spatial resolution has been lacking so far in the literature.

In this paper, we model global water consumption and land use in the cultivation phase of 160 crops (Supporting Information (SI) Table S1) with a high spatial resolution of 5 arc-minutes. For assessing the environmental relevance of water consumption, we characterize the irrigation water volume with a spatially explicit water-stress index (WSI) ranging from 0 to 1.[9] In order to contrast the estimated water-use impacts with those related to land use, the area and time of land occupied is modeled and characterized with a land-stress index (LSI). Using the scarcity indicators proposed, we assess the impact to land and water resources of global crop-cultivation and discuss the related trade-offs. Both, different crops and production locations are compared. To include the socio-economic perspective of the agricultural sector, crops are also evaluated with respect to their economic value. Finally, the case of textile and biofuel production is investigated to demonstrate the relevance of freshwater use and its interrelation with climate change and land use. This example is selected, as biobased-fiber and bioenergy production compete for the limited natural resources by replacing fossil resources.

MATERIALS AND METHODS

Quantifying Water Consumption and Land Use. Spatial distributions of yield and production volumes of each crop are provided from analysis of remote sensing and statistical data.[18,19] From these studies, land use per agricultural output can be directly quantified on high spatial resolution.

Water consumption refers to the amount of water that is not released back to the watershed from which it has been withdrawn, that is, due to evapotranspiration or plant uptake. We estimated water consumption applying the "green" and "blue" water concept:[6] Green water denotes water available from precipitation and soil moisture, whereas blue water represents ground and surface water. Total water consumption (TW) in this study includes green and blue water consumption, while blue water consumption (BW) only accounts for irrigation water and direct groundwater uptake by deep roots (e.g., by sorghum or sunflower[20]).

Full-Irrigation Water Consumption. Crop water requirements per crop period (CWR; mm) are calculated for each crop on a monthly basis (index i) as defined in the CROPWAT model:[21]

$$\mathrm{CWR} = \sum_i \mathrm{ET}_{c,i} = \sum_i (K_{c,i} \times \mathrm{ET}_{0,i}) \qquad (1)$$

where for each month i and crop c, $\mathrm{ET}_{c,i}$ (mm) is the specific evapotranspiration, $K_{c,i}$ (−) is the specific crop coefficient, and $\mathrm{ET}_{0,i}$ (mm) is the reference evapotranspiration as reported by FAO.[22]

K_c-values, the starting date and durations of the growing phases are provided for all crops for six global climate zones in Chapagain et al.[23] Based on this data, we calculate daily K_c-values and averaged them for each month of the growing period to derive monthly $K_{c,i}$ values. Full-irrigation total water consumption including both blue and green water ($\mathrm{TW}_{\mathrm{CROPWAT}}$; m^3 Mg^{-1}) is computed applying yield values ($Mg\ ha^{-1}$) which are available for each crop on a 5 arc-minute grid for the year 2000:[18]

$$\mathrm{TW}_{\mathrm{CROPWAT}} = \frac{\mathrm{CWR} \times 10}{\mathrm{yield}} \qquad (2)$$

Irrigation water requirements (IWR) per crop period are calculated by summing the monthly irrigation requirements ($\mathrm{IWR}_{\mathrm{monthly}}$), which were quantified for each grid cell according to CROPWAT:[21]

$$\mathrm{IWR}_{\mathrm{monthly},i} = \begin{cases} \mathrm{ET}_{c,i} - \mathrm{P}_{\mathrm{e,monthly},i} & \text{for } \mathrm{ET}_{c,i} > \mathrm{P}_{\mathrm{e,monthly},i} \\ 0 & \text{for } \mathrm{ET}_{c,i} \le \mathrm{P}_{\mathrm{e,monthly},i} \end{cases} \qquad (3)$$

where $\mathrm{IWR}_{\mathrm{monthly},i}$ is the IWR in month i (mm) and $\mathrm{P}_{\mathrm{e,monthly},i}$ is effective precipitation in month i (mm). Effective precipitation denotes the precipitation share actually available to crops. To increase robustness of the results, we used the average IWR resulting from applying two different approaches to calculate $\mathrm{P}_{\mathrm{e,monthly},i}$ (Supporting Information).

The full-irrigation blue water consumption ($\mathrm{BW}_{\mathrm{CROPWAT}}$; m^3 Mg^{-1}) is derived from IWR and related yield values ($Mg\ ha^{-1}$):

$$\mathrm{BW}_{\mathrm{CROPWAT}} = \frac{\mathrm{IWR}}{\mathrm{yield}} \times 10 \qquad (4)$$

Deficit Water Consumption. CWR and IWR calculations are based on full-irrigation water consumption under optimal irrigation. In practice, less water than calculated IWR is often applied for irrigation due to lack of irrigation facilities or limited water availability.[24] Such deficit irrigation is often optimized in regions where land is not a limiting resource and water is rather scarce (e.g., Australia). In order to compute the area shares of irrigated cropland ($\mathrm{irrcropland}_{\%}$; %), we combine a global map of percentages of irrigated area ($\mathrm{IrrArea}_{\%}$; %)[25] with a global map of cropland shares ($\mathrm{cropland}_{\%}$; %).[19] Accordingly, the deficit blue water consumption of each crop ($\mathrm{BW}_{\mathrm{deficit}}$; m^3 Mg^{-1}) is obtained by

$$\mathrm{BW}_{\mathrm{deficit}} = \frac{\mathrm{irrcropland}_{\%} \times \mathrm{IWR}}{\mathrm{yield}} \times 10 \qquad (5)$$

In this calculation, we assume that all crops in each grid cell have an equal fraction of area under irrigation.

Deficit irrigation reduces total water consumption ($\mathrm{TW}_{\mathrm{deficit}}$) by the difference of $\mathrm{BW}_{\mathrm{deficit}}$ and $\mathrm{BW}_{\mathrm{CROPWAT}}$.

Expected Water Consumption. Both full-irrigation and deficit water consumption estimates rather represent boundaries than expected results. Full-irrigation blue water consumption overestimates irrigation water consumption where water deficit irrigation is practiced. Deficit blue water consumption as calculated above generally underestimates water consumption as actual irrigation might be higher than reported in available data sets.[26] We used the arithmetic mean of the full-irrigation and deficit-irrigation calculations to quantify the expected water consumption $\mathrm{TW}_{\mathrm{expected}}$ and $\mathrm{BW}_{\mathrm{expected}}$. As variation in the different model outcomes can be considerable, we calculated the variation factors (VF) as the range between maximum and minimum values normalized by the average result.

Assessing the Impact of Water Use. The competitive pressure on regionally available water due to water scarcity is a function of water use, availability and variability in precipitation, indicated by the Water Stress Index (WSI, SI Figure S1; see ref 9 for the deduction of this indicator). We call the WSI-weighted water volume consumed “RED (Relevant for Environmental Deficiency) water”. RED water is measured in m^3 water-equivalents (m^3_{eq}) and represents a surrogate indicator for the amount of water deficient to downstream human users and ecosystems. WSI is available for the major watersheds of the world (more than 11 000)[9] and is transformed to the 5 arc-minute resolution for the calculations of RED water.

The RED water consumption (m^3 Mg^{-1}) is derived by multiplying $BW_{expected}$ by the water stress index (WSI)[9] in the specific location i:

$$\text{RED water}_i = \text{BW}_{\text{expected},\,i} \times \text{WSI}_i \tag{6}$$

Land Stress. Similar to water-use related environmental impacts (RED water), the impacts due to land occupation vary regionally. Quality of land is complex, comprising intrinsic values (e.g., biodiversity) and ecosystem services (e.g., carbon sequestration potential). There is currently no consensus on one single indicator to quantify land quality.[27] We used the net primary productivity (NPP; kg C m^{-2} yr^{-1}) of the natural reference vegetation in the respective grid cell j ($NPP_{0,j}$) as a proxy for potential land quality. NPP is an ultimately scarce resource on earth and one of the major and objectively quantifiable metrics for ecosystem services.[27] Both from an ecosystem services and land scarcity perspective higher NPP values are considered valuable, although ecosystem value does not always correlate with NPP. Our approach does not give credits for the remaining land-quality attributes, for example, differences in ecological quality between different crops or farming practices such as organic production. Studies of land-use impacts have indicated that biodiversity is largely reduced in agricultural production and only a minor part of ecosystem quality is left. NPP_0 data on a 5 arc-minutes resolution[28] is acquired to calculate a land stress index (LSI), ranging from 0 to 1 (SI Figure S1):

$$\text{LSI}_j = \frac{\text{NPP}_{0,\,j}}{\text{NPP}_{0,\,\max}} \tag{7}$$

where $NPP_{0,j}$ is NPP_0 in grid cell j and $NPP_{0,max}$ is the maximal NPP_0 of natural vegetation on the earth (~1.5 kg C m^{-2} yr^{-1}).[28]

The area directly occupied for a defined time period by the production of a certain crop, i.e. the area-time equivalent (At_{growth}; m^2 yr kg^{-1}) is specified by the yield (Mg ha^{-1}) and the crop period (t_c; yr). For perennial crops t_c is 1 year as the yield is reported per year even if the cultivation period differs. Crops are usually cultivated in the most productive period of the year, and between two crop rotations some period of fallow is generally required due to soil or temperature limitations. We therefore relate the duration of land occupation to the length of the growth period (LGP; yr),[29] that is, the share of the year when temperature and soil moisture permit crop growth:

$$\text{At}_{\text{occupation}} = \begin{cases} t_c/\text{LGP} \times 10/\text{yield}_j & \text{for } t_c < \text{LGP} \\ 10/\text{yield}_j & \text{for } t_c \geq \text{LGP} \end{cases} \tag{8}$$

The land stress related to crops, measured in m^2 yr land-equivalents (m^2 yr_{eq} kg^{-1}), quantifies loss of natural, productive land in equivalents of the globally most productive areas and is calculated for each grid cell j as

$$\text{land stress}_j = \text{LSI}_j \times \text{At}_{\text{occupation},\,j} \tag{9}$$

Economic Values of Crops. While for the comparison of different grains the impact per weight is an appropriate reference to evaluate alternatives from a nutritional point of view, this is not meaningful for comparing grains with other crops for food, fiber or biofuel production, such as tomatoes, vanilla or sugar cane. Hence, the results are related to economic values of the crops. These are estimated based on producer prices (prices receivable by farmers at the farm gate or first point of sale, excluding VAT and transport charges) in the five most populated countries as reported in PRICESTAT[30] for 121 crops and the years 2000−2006: China, India, U.S., Indonesia and Brazil. These countries are main producers of agricultural goods, cover different climatic regions, and include 48% of global population.[31] Further details are described in the SI.

Biomass vs Fossil Fuels. We analyzed the life cycle cumulative energy demand of cotton fiber and biofuels from five feedstocks, and calculated the net difference to polyester and fossil fuels they would offset, respectively. Further details are described in the SI.

RESULTS

Global Distribution and Hotspots of Agricultural Water and Land Use. Total water consumption ($TW_{expected}$) per tonne (Mg) of harvested crop depends only weakly on climatic conditions. Thus, the global distribution of total water consumption reflects almost directly the degree of agricultural activity (SI Figure S2). A similar regional distribution of intensity is obtained for land and water stress (SI Figure S3). However, for example, in Pakistan there is mainly pressure on water resources and almost no land-use impacts; in Indonesia we find the opposite case. The results for RED water may shift some hotspots of water consumption, as the site-dependent impact is taken into account with this indicator. For example, in China, critical regions now include the Northwest,

Product-Related Analysis. For product-related assessments, the RED water and the land stress were quantified per crop. Our analysis shows that wheat, rice, cotton, maize (excluding forage), and sugar cane, account for 49% of the RED water and 42% of land resource stress caused by worldwide crop production (SI Figure S4). Three of these crops, namely wheat, rice, and maize, provide about 60% of the current global food calorific content and contribute in total between 37% and 38% to global RED water and land stress. In addition to their use as foodstuffs, maize and sugar cane are also major sources of biofuel feedstock, whereas cotton supplies about 40% of global textile fibers.[32]

Spatial variability of RED water varies largely as both irrigation intensity and water stress fluctuate substantially among different climatic regions. Figure 1 depicts the spatially explicit RED water per tonne for wheat, rice, and maize. Wheat production in central and northern Europe, for instance, is mostly rainfed and therefore has almost no blue and RED water consumption, whereas large environmental impacts may result from wheat production in arid regions, such as Texas or northern India. Similarly, rice, which is almost irrigation-free in South-East Asia, features high

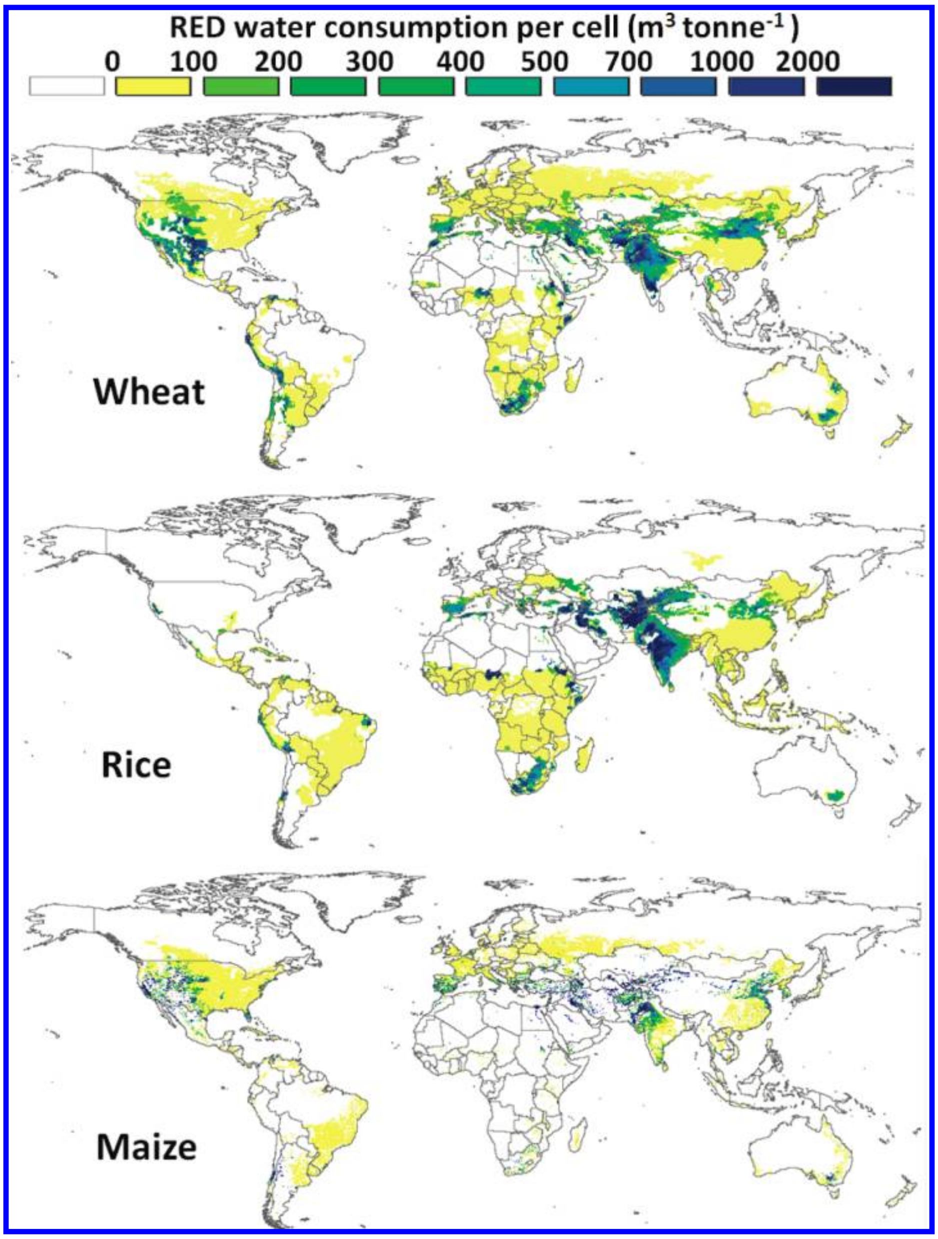

Figure 1. Specific RED water consumption of the globally most important crops: wheat, rice, and maize.

RED water in central Asia. Spatial variability is not bound to country boundaries, but rather to climatic and hydrological conditions. In fact, for many crops the coefficient of variation (CV) of RED water consumption is higher within countries than the global CV of the same crops (SI Table S8).

Comparison of median and 25%-percentiles of country average RED water values for ten major crops with the respective worldwide production-weighted average (SI Figure S5) indicates that a large production share is situated in areas with water scarcity: The global production-weighted average is higher for the considered crops than the median values and for cotton, sugar cane and groundnuts, even above the quartiles.

The average RED water per US Dollar ($) economic turnover for 121 considered crops is 0.97 m^3_{eq} $\$^{-1}$. Most crops (83%) feature a value between 0 and 2.00 m^3_{eq} $\$^{-1}$ but there are also exceptions: Oil crops grown mainly in developing countries, such as castor and safflower, have the highest values (15.8 and 9.8 m^3_{eq} $\$^{-1}$, respectively), which reflects high water consumption for low value crops. The land stress of global agricultural turnover is 4.11 m^2yr_{eq} $\$^{-1}$. Highest values of more than 20 m^2yr_{eq} $\$^{-1}$ are attributed to production of low-yielding crops such as millet, sorghum and coconut, while vegetables and fruits feature lowest values.

Land/Water Trade-off. Comparing current global average land stress and RED water of the different cereal types with the overall average of all grains reveals four compartments of relative environmental performance (Figure 2A): While maize and rice perform better than average regarding both, land and water impacts (++), wheat has higher impacts in both dimensions (−−). Oats, rye, and barley are typically grown in temperate, productive climates without irrigation and feature higher relative land than water pressures (−+). These results need to be qualified by their large variability in blue water consumption and yields (blue ovals in Figure 2A) and care should be taken in

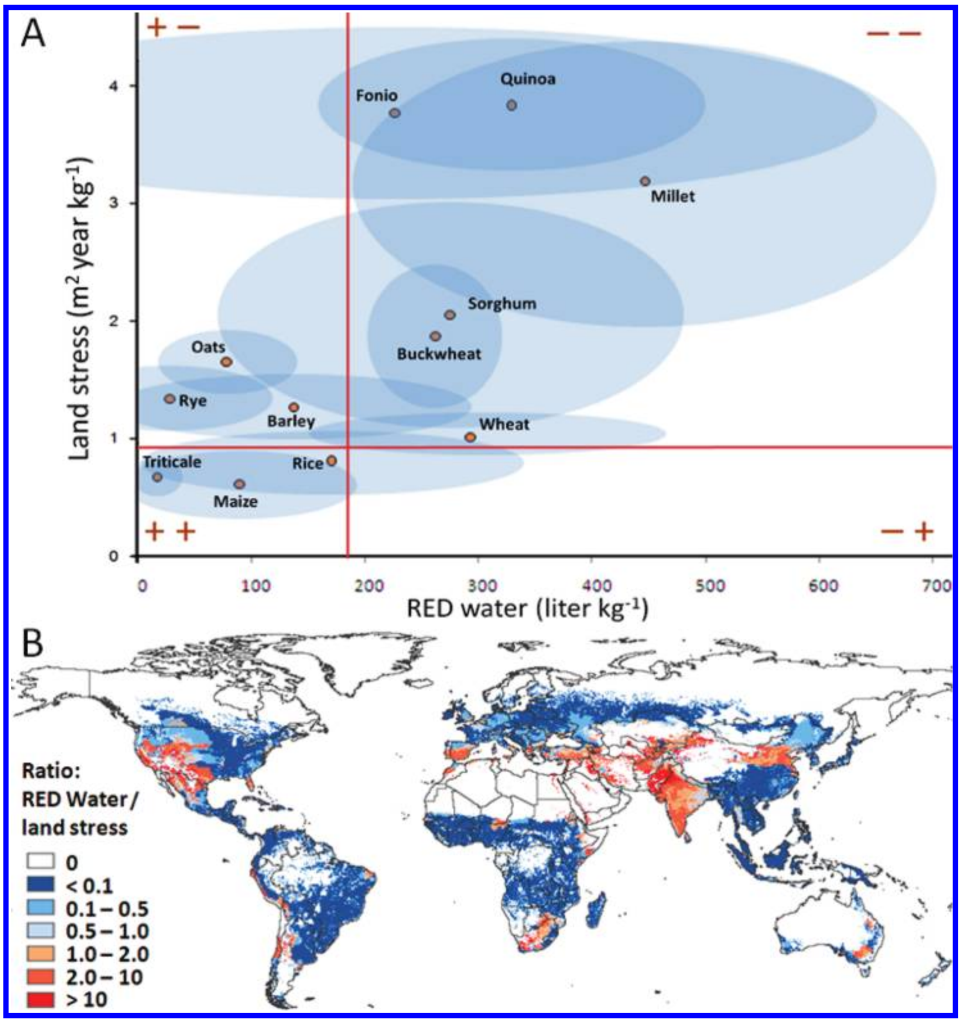

Figure 2. Land/water trade-off: global average RED water and land stress of the most relevant grains with ±0.5 SD described by blue ovals (A). We split the chart in four compartments by the average values for total grain production: 0.927 $m^2 yr_{eq}$ kg^{-1} and 182 L_{eq} kg^{-1}. Considering total global crop production, the ratio of water to land impacts maps high relevance of water use in red areas (B).

using these results for generalized crop evaluations. For instance, millet performs rather badly with regard to both dimensions in the graph. This is due to very low yields as millet is often cultivated with low intensity and in unfavorable climatic conditions where high-performance crops might not grow at all and water scarcity is high. The land/water trade-off is therefore more a question of location of the cultivations than of crop characteristics. Figure 2B indicates the areas where the pressure on water resources is relatively more important than land use or vice versa. Water use is generally more relevant in arid and semiarid areas, but also in relatively humid areas in India and northeastern China, where intensive irrigation and population pressure leads to high water impacts.

Production of Fibers vs Biofuels. Cotton needs more than twice the amount of RED water per MJ of fossil fuel saved compared to rapeseed, the highest value for biofuel feedstock (Table 1). Considering current global crop production, palm oil biodiesel is the best option concerning water consumption for reducing fossil fuel use. Yet, palm oil globally has higher impacts on land than sugar cane and would be less favorable regarding ecosystem damage and greenhouse gas emissions if tropical forests are replaced.[33]

DISCUSSION

Appropriateness of Water-Use/Land-Use Data and Resource Indicators. Uncertainties of the input data applied in our model are high but not quantified as we use unique data sets for assessing 160 crops on high spatial resolution and global coverage. The most critical data sets are crop distribution and related yields[18] for land and water use as well as applied irrigation[25] for water use. Additionally, model assumptions add considerable uncertainty, namely the calculation of effective precipitation and evapotranspiration. The results must be considered under these aspects. Nevertheless, using state-of-the-art data sets results in the most reliable outcome attainable today.

The deviations between agricultural water consumption and general water stress (compare SI Figure S3) illustrate that total and blue water consumption are often not sufficient indicators of stress on water resources. Therefore, an additional characterization is needed for meaningful product assessments and comparisons of water footprints. While for global analysis of water consumption the total water use-to-availability ratio has been established as an indicator of water stress,[34] for single product-related information RED water is a suitable choice.[15] RED water

Table 1. RED Water and Land Stress Impacts per Fossil Fuel Offset by Various Bioenergy Crops and for Cotton Fiber

feedstock	feedstock origin	net fossil fuel offset of crops[a] (GJ Mg^{-1})	RED water per fossil fuel offset (m^3_{eq} GJ^{-1})	land stress per fossil fuel offset (m^2yr_{eq} GJ^{-1})
cotton	global mix	15.6	84[a]	101[a]
maize	U.S.	4.1	10	83
	global mix		22[b]	151[b]
sugar cane	Brazil	2.0	1	45
	global mix		17[b]	40[b]
palm oil	Malaysia	10.6	0	37
	global mix		0[b]	51[b]
soy bean	U.S.	7.0	13	158
	global mix		20[b]	160[b]
rape-seed	Switzerland	11.2	1	102
	global mix		36[b]	159[b]

[a] Results are based on net fossil fuel offset by biobased goods compared to conventional fuels and polyester, respectively. The figures also account for life-cycle energy demand and energy content of feedstock for polyester. [b] Calculated based on energy offset of specified countries and global average RED water and land stress of feedstock.

accounts for crop- and location-specific irrigation water consumption and characterizes it with cumulated water use and availability in the respective region. These are relevant factors when it comes to the resource-related impact of water consumption. One limitation of this indicator is that it does not account for socio-economic aspects or vulnerability of the natural ecosystem, which are aspects addressed in other approaches described in refs 9 and 16. Also, WSI is not based on consumption-to-availability but on the use-to-availability ratio, which indirectly includes also degradative use, such us thermal and chemical pollution. RED water is therefore not a purely water-scarcity driven metric and might therefore overestimate scarcity in industrialized countries with large nonconsumptive water use and proper wastewater treatment.

Compared to conventional total or blue-water footprints,[23] the RED water indicator thus includes more information that helps to differentiate products according to their environmental relevance. For instance, tropical crops like coffee, cacao or palm oil become less relevant in RED water assessments compared to their total and blue water assessment, while crops mainly grown in areas with high water scarcity, such as cotton, remain of high relevance. Concerning land use, a simplified indicator for land scarcity was defined in order to be able to apply it globally. Although this indicator does not capture all major effects of land use, such as biodiversity loss or carbon sequestration by soils, it is a feasible and useful first step to quantitatively account for land scarcity and efficiently capture one of the crucial aspects of land quality. Intensity of land use and effects of crop rotations are, however, not included.

Due to the dependence of both NPP and water scarcity on water availability, LSI and WSI share a common input variable. As they are negatively correlated, the land-water trade-off is amplified by the chosen metrics.

Comparison to Previous Studies. Previous studies extrapolated global estimates of water use only from a limited set of agricultural crops[35−37] or on a country-based spatial resolution.[23] In comparison with these studies, our global total water consumption results are in the lower range (5519 km^3 yr^{-1} compared to 5500−8000 km^3 yr^{-1}), while the global blue water ($BW_{expected}$) estimate is rather high (1772 km^3 yr^{-1}, compared to 929−1870 km^3 yr^{-1}). The relatively low total water ($TW_{expected}$) reflects deficit irrigation (supply below full crop-water requirement) practiced in many regions of the world. The presented blue water consumption values are rather high as they are based on effective yields, which are often much lower than modeled yields, and also implicitly include rainwater harvesting techniques and plant groundwater uptake. The difference between $BW_{expected}$ and $BW_{deficit}$, (SI Figure S2, Tables S6−S7) may serve as a quantitative measure of the uncertainty in this context, as $BW_{deficit}$ can be considered to represent the lower margin of irrigation-water demand. Especially in Africa and tropical regions, where irrigation is often absent, these low estimates might be more appropriate, although not conservative regarding environmental impact. Under this consideration, millet and quinoa which feature the highest RED water among grains become less critical.

The main benefits of our study are the combined land/water assessment based on common sources and the provision of regionally explicit water consumption values for a large range of individual crops, covering most of worldwide agricultural output. Within countries, large variations in water consumption and environmental impacts exist (Figure 1 and SI Figure S3). Country average information, as practiced in many previous studies, therefore does not allow for a proper analysis, in particular not for countries such as China, India, and the U.S. The current study hence allows for more detailed and precise assessments.

Land−Water Trade-off. Global agricultural production shows a clear spatial trade-off between water and land resource pressure (Figure 2B). Temperate regions with relatively low natural NPP and high water availability are performing best in the combined land/water assessment. However, these regions are already occupied and future expansion of agricultural production needs further evaluation of potential impacts. Here, the combined land/water assessment illustrates the need for a multi-dimensional assessment, including further potential indicators.

To test the theoretical plant-specific differences in land use and water consumption, we modeled irrigation water demands for maize and wheat applying theoretically attainable yields from FAO on generally suitable areas for cereal production:[33] No significant difference in yield and irrigation requirements is observed between maize and wheat in these simulations. The current differences in land and water use between crops (Figure 2A) may thus be due to additional properties of the crops (e.g., drought resistance) or economic profitability, resulting in cash crops to be grown with priority at suitable production sites. They also illustrate the role of miss-harvest and poorly managed agriculture as drivers for overuse of natural resources. As we used data on actual yields and irrigation in our study such effects are included and add to the spatial variability and further indicate priorities to take action. Thus, Figure 2A should be understood as a description of the status quo of current global average impacts of grain production on land and water resources, with limited usefulness for decision-making on crop choices.

The example of millet illustrates some of the limitations of our assessment: High land and water impacts are most likely because millet is drought resistant and therefore often grown with minimal irrigation on marginal lands with low productivities, resulting in low yields. While reduced water consumption can be estimated by applying $BW_{deficit}$ as discussed above, the low LSI of such regions does not account for potentially lower impacts on ecosystems in low-intensity agriculture. This issue should especially be considered if pastures, where large areas of relatively low intensities are used, are included in the assessment.

Biomaterials. To minimize water stress per unit of fossil fuel depletion avoided, our findings suggest that driving with biofuels is currently preferable over dressing in cotton. Equivalent calculations for land use show less total variability among crops, and cotton performs within the range of an average biofuel. Although cotton textiles are widely used, their application should be reconsidered. However, environmental impacts of biofuels are also substantial and fossil fuel consumption should be rather limited by reducing energy demand and using renewable energy sources other than biofuels.

Application of Results. The presented results allow us to enhance life-cycle based product information such as ecolabels of food products, biofules and textiles, which currently often only address climate-change impacts ("carbon footprinting"[38]). Although the presented indicators are rather coarse and based on many simplifications, their use is important to account for impacts on land and water resources in decision-making of various stakeholders, in addition to commonly assessed impacts. There is a large demand for such environmental product information by consumers and particularly by retailers and food processing companies. They use this information in sourcing their products and, in the process, may induce a reduction of demand for high-impact commodities. For broader applications, the water consumption and land use data represent a rich source of inventory data on high spatial resolution for most crops. Our results are hence closing an important data gap for assessing products using biomass as feedstock. Also, the information may be employed as a screening device to identify products that require a more detailed assessment on farm level, potentially leading to revised regional water- or land-resource management strategies to address scarcity of water or land.

Moreover, the information on spatially resolved impacts may be used as a basis for integrating compensatory mechanisms or offsetting programs to the assessment of impacts. This would (a) make relatively harmful products more expensive, thus lowering demand, and (b) provide a means of financing ecosystem service or biodiversity conservation programs, complementing similar efforts to reduce and compensate for greenhouse gas emissions. On a country level, per-capita land stress and RED water consumption can be used to identify economies with high reduction potentials (SI Figures S6−7).

Outlook. The combination of the local and global assessments will help to compare the environmental impacts of intensification and expansion scenarios in the future and to decide upon where investment in agriculture could be most reasonably allocated. This study provides the basis for a global comparison regarding water and land use. In addition, inclusion of trade data may allow connecting the location and severity of environmental impacts to the goods consumed for implementing the polluter pays mechanisms. This ultimately supports the development of less water-intensive economies and investments in sustainable local water resource management. The paper can also be used as a basis for assessing the water and land-use impact of global dairy and meat production and different livestock management options. In this case, the data on feed production could be taken from our study, but would need to be enhanced with data on pastures. Furthermore, our results allow the inclusion of water and land use impacts in LCA, by providing detailed inventory data with global coverage, and also enhance the applicability of water footprints.

ASSOCIATED CONTENT

S Supporting Information. Additional results and method descriptions. This material is available free of charge via the Internet at http://pubs.acs.org.

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