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Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production

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ABSTRACT

Irrigation is the dominant human activity leading to water stress, with environmental consequences on the local and global level. The relevance of spatial resolution to the assessment of water consumption and to impacts related to crop production has been acknowledged in previous research on water footprint. The temporal aspects of crop cultivation and the related impacts, however, have been neglected in analyses with global coverage. Such aspects are important since different crop options can shift irrigation water consumption within a year, increasing or decreasing the related water stress. Additionally, in some regions, temporal aspects are crucial due to the high variability of water availability. Consequently, an annual assessment might be misleading regarding crop choices within and among different regions. A temporal resolution is therefore essential for proper life cycle assessment (LCA) or water footprint of crop production. For this purpose we develop a water stress index (WSI) on a monthly basis for more than 11,000 watersheds with global coverage. The median and average watershed area are 1327 and19591 km^2, respectively. The WSI ranges from 0.01 (least water scarcity) to 1 (maximal water scarcity), and quantifies the fraction of water consumed of which other users are potentially deprived of. Moreover, irrigation water consumption for 160 crop groups is calculated on a monthly basis and on a high spatial resolution (<10 km). Crop water footprints (WFP) are calculated by multiplying monthly WSI with monthly crop irrigation water consumption and by summing the result over the cultivation period. With these results we facilitate a new level of detail for WFP analysis.

We estimate global irrigation water consumption in the year 2000 at $1.21*10^{12}$ m^3/a, with an average WSI of 0.44. The regional pattern changes considerably with higher temporal resolution and therefore in many regions it is relevant to consider monthly WSI. Changes are also shown to be sensitive to crop types due to different growth patterns, which might lead to increasing or decreasing water footprint. Additionally, we examine the role of different conceptual assumptions for the definition of water footprint characterization factors, which can be expressed as marginal and average figures. WSI is a marginal characterization factor. However, a practitioner may favor an alternative average factor to match impact assessment with the given goal and scope of the study. An average characterization factor allows for calculating WFP of a whole region as well as the global annual WFP of agriculture, which is estimated at $3.5*10^{11}$ m^3-equivalents. This number can be interpreted as water consumed in an extremely water-stressed situation and therefore highly depriving others of its use.

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1. Introduction

Irrigation is the dominant human activity leading to water stress, with environmental consequences on the local and global level. Agriculture is responsible for ~85% of total global water consumption and ~70% of water withdrawal (Shiklomanov, 2003). Water consumption is not uniformly distributed, and varies spatially depending on many factors such as cultivated crops, irrigation techniques, soil type, and water availability. Another main determinant for the total annual water consumption in agriculture is the climate, which, commonly, has a temporal variability and influences growing seasons. This high variability is not common in industrial water use such as power production, which is the other major water consuming economic sector (Pfister et al., 2011a; Mekonnen and Hoekstra, 2011a). Therefore, in global analyses the water consumption of crops is mostly calculated on a monthly basis (Pfister

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et al., 2011b; Mekonnen and Hoekstra, 2011b). In these analyses, irrigation water consumption is referred to as "blue" water consumption (BW). This is in contrast to "green" water consumption, which refers to natural water supply by soil moisture/precipitation.

Global water consumption can be assessed in different ways [e.g. 1,4,5], and one of the most established ones is the water footprint (WFP). However, the WFP is not well specified, and its definition has even led to confusion in the past. While the original suggestion was calculating WFP by plain aggregation of water consumption volumes (e.g. (Mekonnen and Hoekstra, 2011b)), this is not anymore considered a full WFP (ISO, 2013). The main shortcoming of this approach is that water consumption is entirely equated to environmental damage, without accounting for regional vulnerabilities. On the other hand, for reporting water scarcity issues related to products and services, the WFP was defined in-line with carbon footprint and life cycle assessment (LCA) (Pfister and Hellweg, 2009; Ridoutt and Pfister, 2012, 2010). A recent UNEP resource panel report compared the different available water-related assessment procedures and revealed their similarities as well as the deficiencies of the plain volumetric approach (McGlade et al., 2012). Calculation of water consumption related impacts is optimally done based on specific regional characteristics (including socio-economic analysis). For an efficient analysis of processes in the supply chain, related impacts need to be integrated in a spatially explicit model. These processes are often major contributors to the overall WFP and require coupled water stress and consumption assessment to avoid the loss of spatial detail (Feng et al., 2011).

The framework of LCA is standardized by ISO (ISO, 2006a; ISO, 2006b) and its use has been established in industry over the last decade. LCA consists of four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. It is an iterative process and one purpose of the interpretation step is to advise how to improve the analysis when first or preliminary results are available. Sensitive factors, relevant processes and parameters, system boundaries and modeling procedures are identified and may need to be critically reviewed or further developed. In fact, water footprint analysis follows the same strategy (McGlade et al., 2012), and impacts of consumptive water use are also embedded as an impact category in LCA (Frischknecht et al., 2008; Bayart et al., 2010). In general, impacts in LCA can be addressed on midpoint and endpoint level (Jolliet et al., 2004). Midpoint assessments are based on characterization factors (CF) that quantify environmental consequences within impact categories caused by specific emissions or resource consumption (e.g. CO_2-emission contributing to global warming potential). Some CF account for effects on endpoint level which consider potential damage to areas of protection (mainly Human Health, Ecosystem Quality and Resources). Typically, impacts on midpoint-level are further modeled along the cause-effect chain to arrive at a few endpoints, which for instance indicate loss of human life (typically measured as disability-adjusted life years (DALY) (WHO, 2013)) or loss of ecosystem quality caused by emission of CO_2–equivalents (Goedkoop et al., 2009) for the case of global warming potential.

Various impact assessment methods to assess the water footprint co-exist for the different impact levels (Kounina et al., 2013). The methods available for global scale analysis have a limited spatial or temporal resolution. This is due to the lack of data, and to limit the computational effort and method complexity. However, to capture the highly variable impact of irrigation on a regional scale, a fine spatial resolution is necessary, accounting for hydraulic conditions (e.g. in different watersheds), climate, and crop cultivation. Temporal variability is affected mainly by climate and seasonal growing. Still, most impact assessment methods provide annual CF, and only one is available on a monthly basis, but on the expense of a coarse spatial resolution and lack of global coverage (Mekonnen and Hoekstra, 2011c). One main contribution of the present work is to introduce monthly midpoint CF with global coverage and high spatial resolution (>11,000 watersheds). We enhance the most commonly used CF "water stress index" (WSI, (Pfister et al., 2009)) for monthly assessment. The WSI serves as a characterization factor in LCA and ranges from 0.01 to 1.00 following a logistic function. The WSI can be interpreted as the water deprivation proportion caused by water consumption, that is, how much of the water consumed is considered to be taken away from downstream users (humans and/or ecosystems). While this cause-effect assessment is mainly of conceptual nature, it is useful for identifying hotspots of water consumption impacts in an LCA or WFP study (Kounina et al., 2013), or for analyzing future scenarios (Chiu et al., 2012; Pfister et al., 2011c). However, to address impacts of water consumption in higher detail, local, site-specific analysis might be necessary, especially if crop production is the foreground system in the analysis, such as concluded for the WFP of wine production in New Zealand (Herath et al., 2013). The distinction of foreground and background (e.g. supply chain) processes is a question of the level of detail in an LCA or WFP study and should be defined in its scope definition.

With our study we facilitate a new level of detail for WFP analysis. However, the improved temporal resolution is not the only focus: we also examine the role of different conceptual assumptions for the definition of WFP characterization factors. The objectives of this work thus are (a) improvement of monthly estimates on crop water consumption, (b) evaluation of monthly vs. annual crop water footprints on a high spatial resolution (c) analysis of marginal vs. average approach in water stress characterization (WSI) and (d) analysis of total water footprint caused by agriculture. In the following sections), the calculation methods for irrigation water consumption, annual and monthly CF, as well as average and marginal CF are presented. Global variability of irrigated water consumption is subsequently assessed by averaging of estimates from different calculation procedures. This is followed by a comparison between results for marginal and average CF, and finally the benefit from improved temporal resolution is elaborated. The new assessment methodology is applied to 160 crops irrigated in global agriculture.

2. Material and methods

2.1. Crop irrigation water consumption

Irrigation water consumption of 160 crops and crop groups is modeled on a spatial resolution of 5 arc minutes (~10 km) and on a monthly basis based on CROPWAT (FAO4.3 ed., 1999). To account for the fact there are different standard methods available to calculate crucial hydrological parameters such as evapotranspiration and effective precipitation, each arising from different conceptual assumptions, we average the results from different methods, to obtain more robust estimates. This approach also accounts for the fact that even high resolution data on crop cultivation or hydrology may be inaccurate, not up-to-date or incomplete. Often irrigation is not well reported, and this may be considered in the calculation by including an estimated proportion of irrigated area. As described in detail in our previous work (Pfister et al., 2011b), we distinguish four different procedures to quantify irrigation water consumption, or blue water: we used the two methods integrated into CROPWAT to calculate effective precipitation and applied each of these to the equations assuming (a) full irrigation ($BW_{CROPWAT}$) and (b) deficit irrigation ($BW_{deficit}$). $BW_{deficit}$ is calculated by multiplying $BW_{CROPWAT}$ with the reported proportion of irrigation (Siebert et al., 2007). The four derived results are combined to determine a range with lower ($BW_{deficit}$) and upper ($BW_{CROPWAT}$) bound, and the arithmetic mean has previously been taken as the best estimate of the expected value (BW_{arith}) (Pfister et al., 2011b). As an alternative, here the geometric

mean, BW_i, is chosen. The geometric mean is considered more suitable since it represents the expected value of a lognormal distribution, and places the emphasis on smaller values and on conditions where irrigated land proportion is expected to be relatively small. For each crop i it is derived by

$$BW_i = \begin{cases} \sqrt{\left(BW_{i,\text{deficit}} * BW_{i,\text{CROPWAT}}\right)} & \text{for } BW_{i,\text{deficit}} > 0 \\ 0.05 * BW_{i,\text{CROPWAT}} & \text{for } BW_{i,\text{deficit}} = 0 \end{cases} \quad (1)$$

The lower limit, $BW_{deficit}$ accounts for the reported proportion of irrigated area (Siebert et al., 2007). If no irrigation is reported, this lower limit is 0. The resulting geometric mean also becomes 0, even if the upper range indicates that a crop requires significant irrigation, which in turn reveals a lack of accuracy in the maps reporting proportions of irrigated area or rainwater harvesting techniques (which is also considered as blue water consumption). As a slight modification, to put less weight on the lower limit under such conditions, we attributed 5% of the $BW_{CROPWAT}$ to the expected value of BW_i. This is based on the assumption that 0.25% of cropland area is irrigated even if no irrigation is reported (this proportion is exceeded in 97% of all 6703 country/crop BW estimates larger than zero).

2.2. Monthly water stress index (WSI)

Monthly resolution of water consumption in agriculture is essential in order to account for the growing seasons of crops. A major improvement of the revised WFP presented here is, that not only water consumption but also induced water stress is expressed by time-dependent measures. This means that the life cycle impact assessment step is carried out using a monthly WSI (WSI_{mon}). The concept of monthly factors was originally discussed at the LCA Food Conference 2012 (Pfister and Baumann, 2012) and is adopted here as follows: The original, annual WSI by Pfister et al. (Pfister et al., 2009), WSI_{year}, does not ignore temporal variability, but this is not computed by time discretization. Instead, calculation of WSI_{year} includes a fixed variation factor (*VF*) reflecting monthly and annual temporal variability of water availability in order to account for increased scarcity in watersheds with irregular water supply for each watershed h:

$$WSI_{year}(h) = \frac{1}{1 + e^{-6.4 \cdot WTA^{*}_{year}(h)}\left(\frac{1}{0.01} - 1\right)} \quad (2)$$

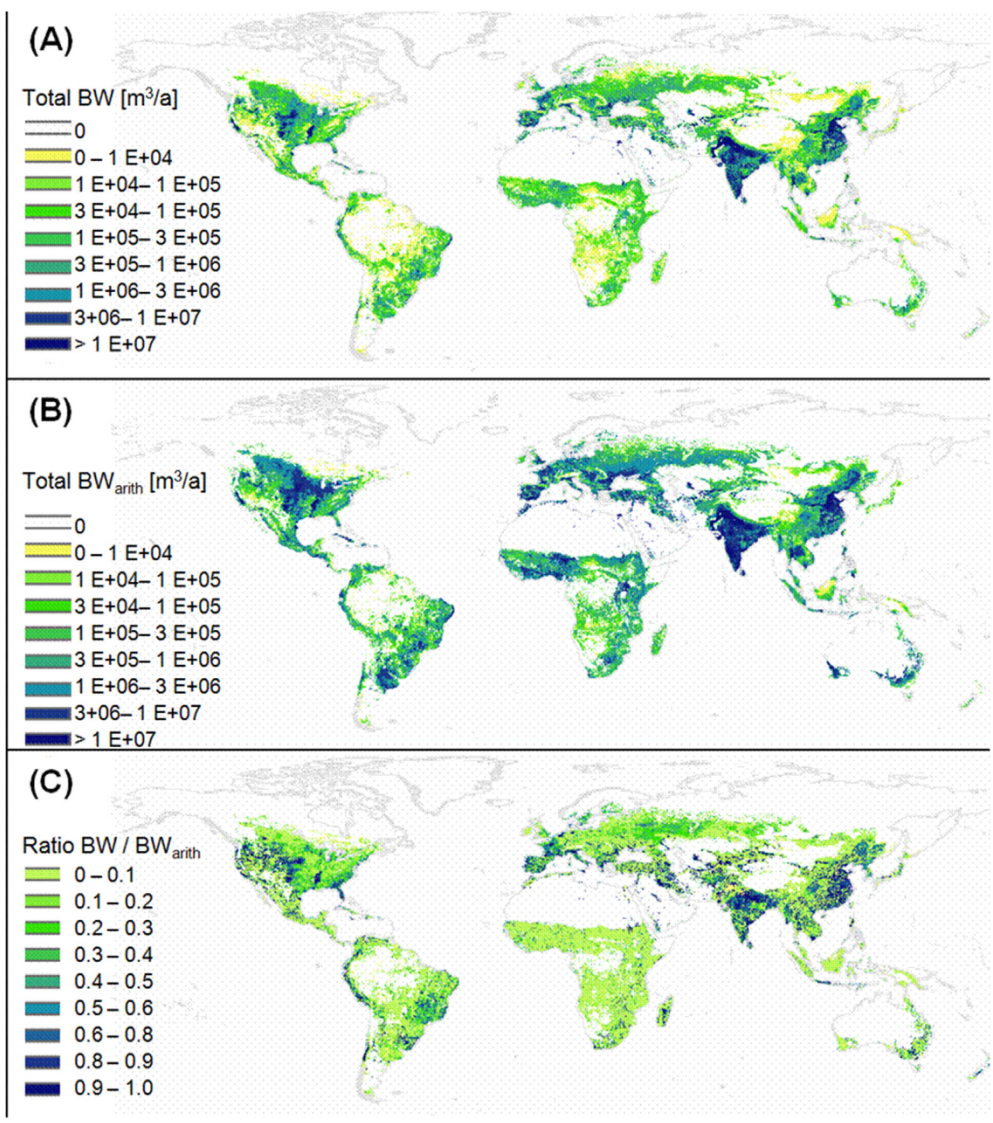

Fig. 1. Comparison of crop irrigation water consumption using the geometric mean (A) or arithmetic mean (B) of the four different modeling approaches. Map (C) presents the ratio of geometric to arithmetic mean.

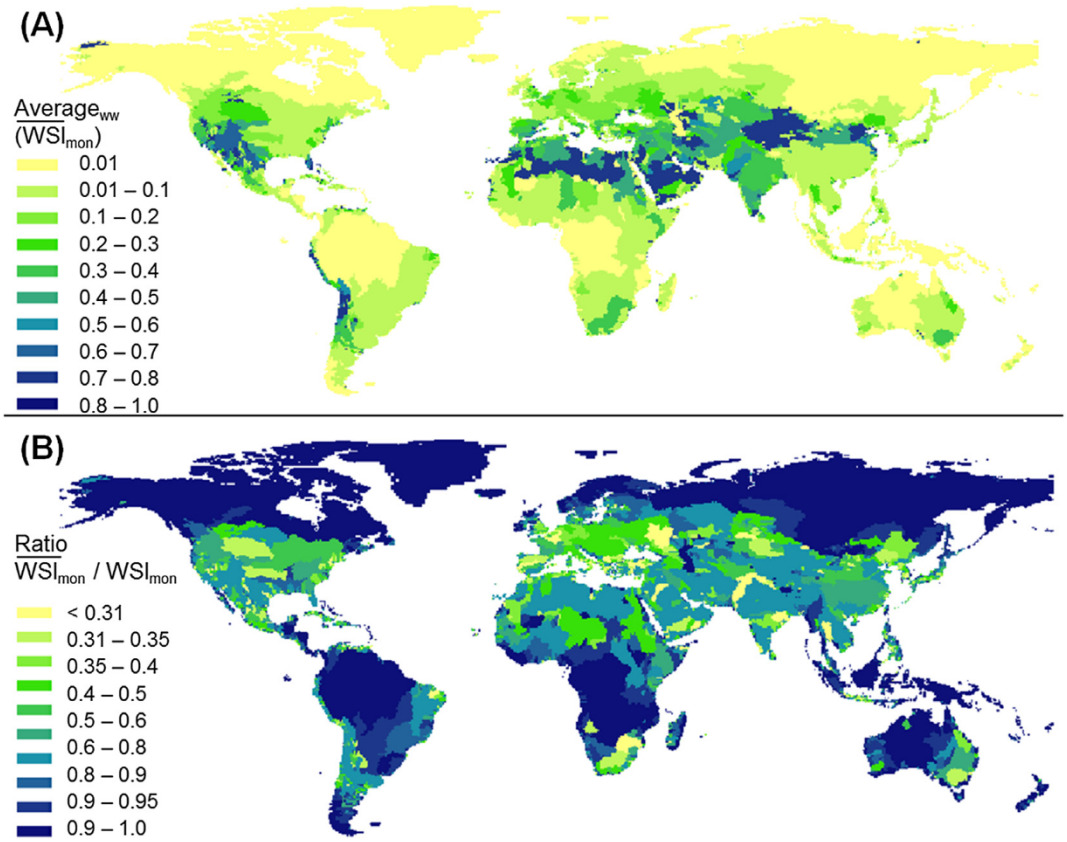

Fig. 2. (A) Distribution of the annual average $\overline{WSI}_{mon}$ (average$_{ww}$ ($\overline{WSI}_{mon}$)) in worldwide watersheds, (B) ratio between results from the average and marginal approaches, average$_{ww}$ ($\overline{WSI}_{mon}$)/average$_{ww}$ (WSI_{mon}); yellow areas indicate the highest discrepancy. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where

$$WTA^*_{year}(h) = VF\ (h) \cdot WTA_{year}(h) \tag{3}$$

By discrete time-stepping, a monthly resolved WSI_{mon} with better resolution is derived. This replaces the component of the fixed VF to reflect monthly fluctuations, and the value of the factor is modified to reflect only inter-annual variability. This is expressed by the geometric standard deviation, s^*_{year}, of annual precipitation during the "climate normal period" (1961–1990). In comparison to the computation of the original WSI_{year}, the VF is consequently smaller. The factor's value reduces from 1.8 to 1.17 and hence the logistic function is adjusted for each watershed h by replacing the factor "6.4" in the annual WSI_{year} (Eq. (2)) with "9.8" in the monthly assessment:

$$WSI_{mon}(h) = \frac{1}{1 + e^{-9.8 \cdot WTA^*_{mon}(h)}\left(\frac{1}{0.01} - 1\right)} \tag{4}$$

where

$$WTA^*_{mon}(h) = s^*_{year}\ (h) \cdot WTA_{mon}(h) \tag{5}$$

WTA_{mon} is the withdrawal-to-availability ratio, which is used to calculate a modified, variation based WTA^*_{mon} by applying s^*_{year}. The watershed dependent, monthly WTA_{mon} is based on the annual withdrawal-to-availability ratio WTA_{year}, taken from WaterGAP (Alcamo et al., 2003) and used in (Pfister et al., 2009), by:

$$WTA_{mon}(h) = a_{mon}(h) \cdot WTA_{year}(h) \tag{6}$$

The monthly factor, a_{mon}, is derived for each month as WTA_{mon}/WTA_{year}, based on data with 0.5 arc-degree resolution published by Fekete et al. (Fekete et al., 2002). These monthly $a_{mon}(i)$ factors on the 0.5 arc-degree level are aggregated to watershed level $a_{mon}(h)$ by weighting $a_{mon}(i)$ by the withdrawal of the respective grid cells i.

2.3. Marginal vs. average characterization factors (CF)

CF in LCA can either assess a marginal or an average impact caused by an environmental interaction through resource use or emissions. While marginal effects consider the effect of an additional activity, the average approach attributes the damage evenly to all emissions or resource consumption, i.e. anthropogenic water consumption in our case. Often, impact assessment methodologies report only marginal CF, without permitting a choice between the two options. Huijbregts et al. (Huijbregts et al., 2011) suggests the final choice between

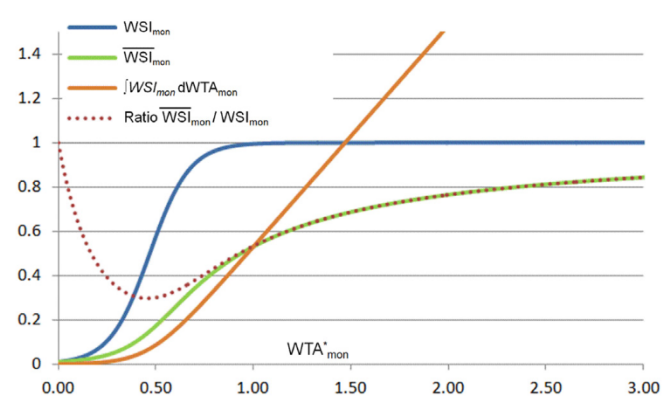

Fig. 3. Different WSI functions (Y-axis) in relation to WTA* for the monthly assessment.

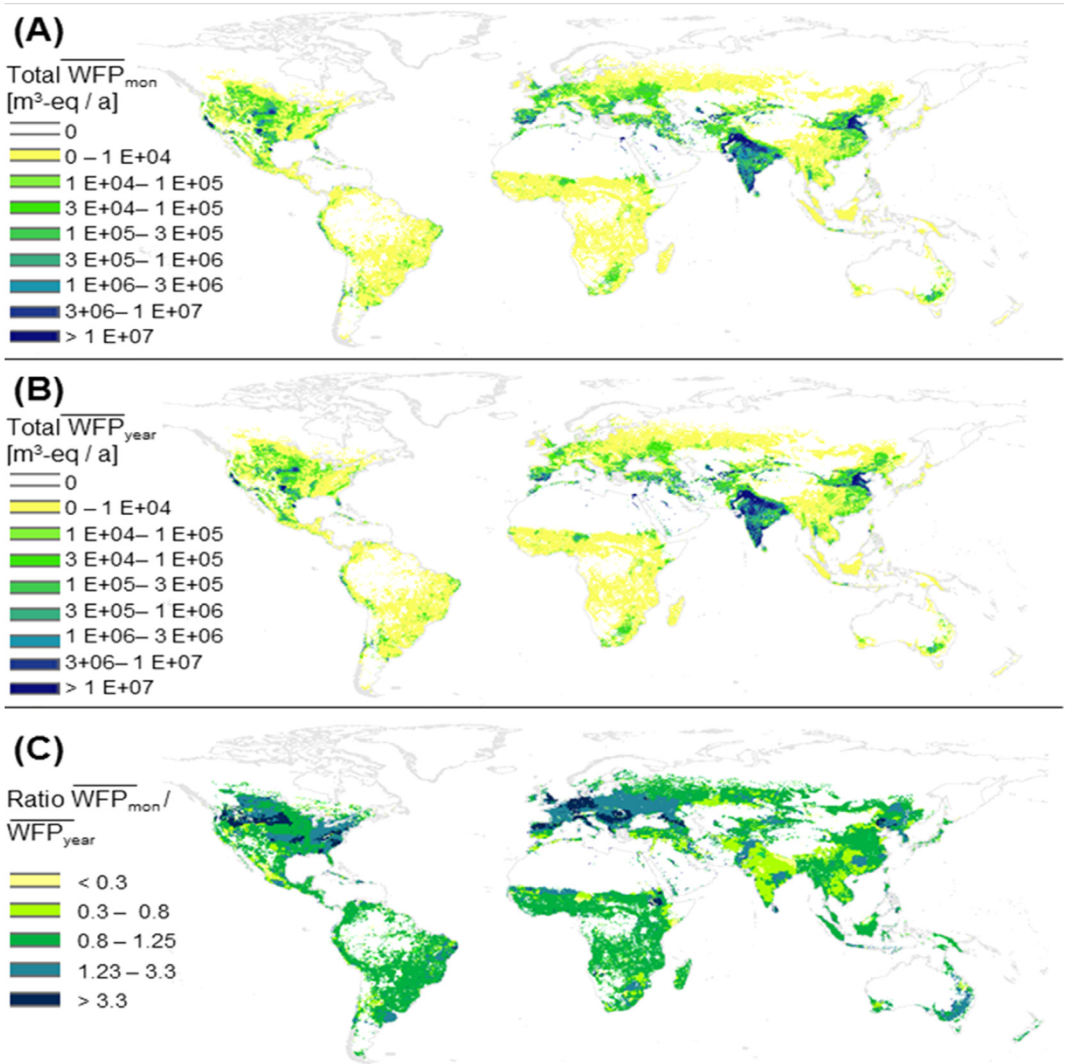

Fig. 4. Consumptive Water footprint of crop production using the geometric mean for irrigation water consumption and the average WSI based on a monthly assessment (average$_{ww}$ ($\overline{WSI}_{mon}$), A) and on an annual assessment (WSI_{year}, B). (C) shows the ratio of monthly over annual consumptive water footprint in each grid cell (WFP_{mon}/WFP_{year}).

marginal or average CF should depend on the purpose of the study and emphasizes that average CF should be given much more attention for assessing environmental impacts in LCA.

The WSI_{mon} (and WSI_{year}) represents a marginal midpoint CF for water consumption in LCA (Pfister et al., 2009) and consequently for characterization in water footprinting. This is because it denotes the proportion of water of which downstream users are deprived of as a function of the current withdrawals and therefore current stress level. However, this is a pessimistic perspective. The path to the current stress level commonly starts with a minor effect (of the first user) that increases to the marginal value (see the orange curve of the integrated WSI in Fig. 3). In other words, the first water user is typically exposed to a stress level smaller than the marginal one and therefore it is not appropriate to assess the total amount of water consumed by the marginal CF. An average CF concept, on the other hand, is capable of tracing this path. We therefore first integrate the WSI_{mon} function, (Eq. (4)), from zero to the current WTA_{mon} to get the total damage in terms of WSI_{mon}*WTA_{mon}. Then this total damage is divided by the current WTA_{mon} to get the average WSI, $\overline{WSI}_{mon}$. As we assume a constant consumptive use proportion in the watershed, and since availability is also considered constant, withdrawal and WTA are different from consumption only by these constant factors. Therefore integrating WSI over WTA and water consumption results in the same $\overline{WSI}_{mon}$. Likewise, the watershed-specific $\overline{WSI}_{mon}$ (h) represents the consumption weighted average CF:

$$\overline{WSI}_{mon}(h) = \frac{1}{WTA_{mon}(h)} \int_0^{WTA_{mon}(h)} WSI_{mon}(h)\,dWTA_{mon}(h) = \frac{\frac{1}{9.8}\ln\left(e^{9.8\cdot WTA_{mon}(h)} + 99\right) - \ln(e^0 + 99)}{WTA_{mon}(h)} \tag{7}$$

In comparison, the annual average, $\overline{WSI}_{year}$, is obtained by

$$\overline{WSI}_{year}(h) = \frac{1}{WTA_{year}(h)} \int_0^{WTA_{year}(h)} WSI_{year}(h)\,dWTA_{year}(h) = \frac{\frac{1}{6.4}\ln\left(e^{6.4\cdot WTA_{year}(h)} + 99\right) - \ln(e^0 + 99)}{WTA_{year}(h)} \tag{8}$$

In the following sections, annual and monthly resolution of water stress index, as well as marginal and average values are compared for the purpose of analyzing water consumption in global agriculture.

3. Results and discussion

3.1. Crop irrigation water consumption

One of the main updates to the existing quantification of crop irrigation water consumption is that the arithmetic mean is replaced by the geometric mean in the process of averaging estimates obtained by four different calculation procedures. The revised, geometric mean based calculation for expected global annual water consumption for crop production yields a total value for all crops of $1.21*10^{12}$ m^3/a, which is 68% of the original arithmetic value of $1.77*10^{12}$ m^3/a (Pfister et al., 2011b). Such discrepancies due to conceptual model assumptions and parameter uncertainties are similarly recognized and discussed by Pfister et al. (Pfister et al., 2011b) for water consumption modeling. They reported a range of global irrigation water consumption from $6.01*10^{11}$ to $3.32*10^{12}$ m^3/a. These minima and maxima do not seem realistic compared to results from other studies ranging between $9.29*10^{11}$ to $1.87*10^{12}$ m^3/a (Pfister et al., 2011b). The values presented here using the geometric mean match these previously reported numbers better than the values based on the arithmetic mean. This suggests that the geometric mean is a more appropriate choice and yields plausible estimates.

The difference between updated geometric and original arithmetic global values is especially relevant for crops grown in humid and tropical regions such as cocoa, coffee, oats, oil palm, plantain, vanilla and fodder crops (see Appendix B). For these crops, revised values are less than half of the original arithmetic mean values. The averaged four procedures differ with respect to hydrological parameters (two crop water availability models) and each is used once including reports of irrigated land proportions and once assuming full irrigation. Often no irrigation is performed even though plant growth would be optimized. The fact that only a fraction of land is irrigated turns out to be an assumption to which the derived crop water consumption is sensitive. However, global maps estimating irrigated area are of limited accuracy, especially in developing countries and therefore no high-quality data are available on a global scale. To obtain robust results that are less prone to inaccuracies, averaging appears favorable over single calculation strategies. Values obtained by the geometric mean are more realistic than arithmetic averaging, since the geometric mean puts more emphasis on the lower values of a set, and it is those values that account for the fact that only a certain fraction of cultivated land is irrigated. This also explains the pronounced discrepancy between the mean values observed for tropical crops. In humid and tropical areas, water productivity may barely increase with irrigation. In contrast, the revised values of the crops dominating the total irrigation water consumption such as wheat, rice, maize, sugarcane, cotton are only 15–35% lower. This reflects that the irrigated land proportion of these crops is substantial, as they are relatively water intense and often grown in semi-arid regions.

Fig. 1 shows the spatial pattern of irrigation water consumption. By definition, the geometric mean provides equal or lower values than the arithmetic one, and the derived patterns differ slightly. Interestingly, this difference is smallest at hot spots of high WFP in agriculture such as India, Northeastern China, Midwestern USA and Spain. This denotes a high proportion of irrigated land, which is expected for high water-consuming areas. In contrast, in many regions with relatively low WFP, the computed difference is high. This might be an indication of overestimation of water consumption with the arithmetic mean. In such cases, the geometric mean might also overestimate the true conditions, which could best be approximated by no irrigation at all. This is revealed for some examples, for which we tried to validate the results. For instance, for cocoa production in Western Africa we checked our estimates with an organic chocolate producer and we found that our figures overestimate irrigation, since most cocoa production is not irrigated. This example demonstrates that especially tropical regions (such as in Africa) with unreliable irrigation data need

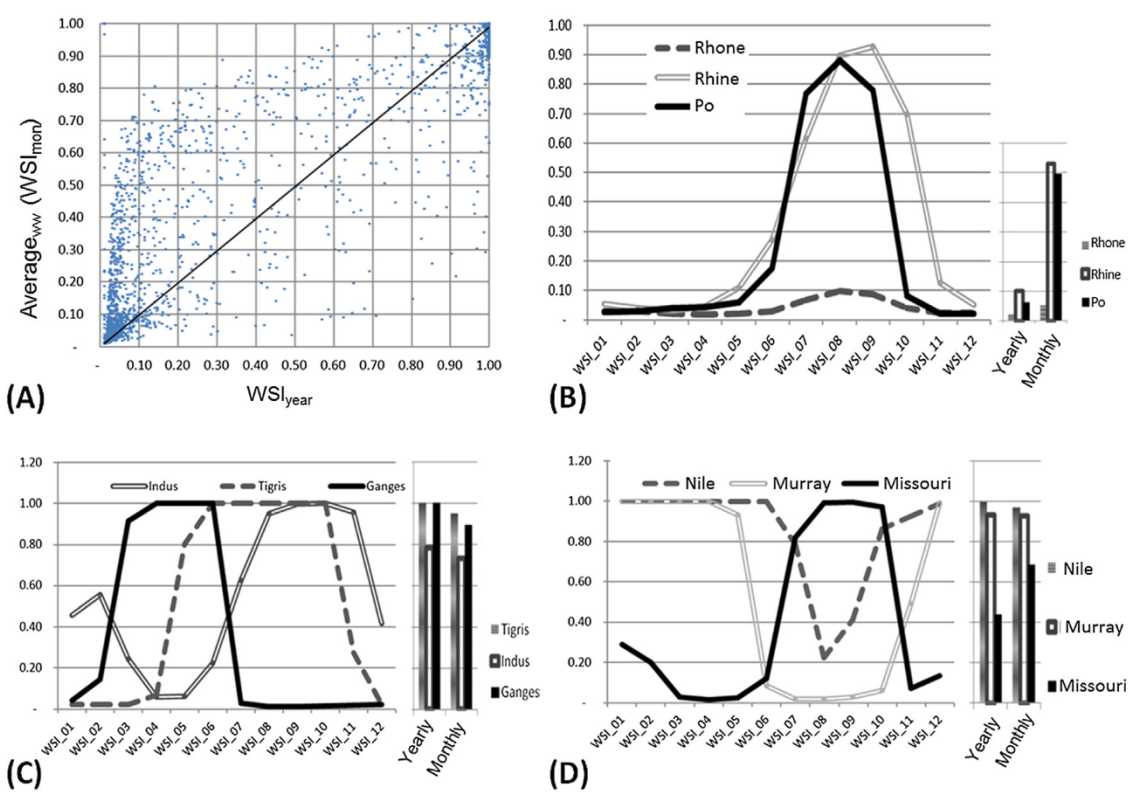

Fig. 5. The graphs show an analysis of annual WSI (WSI_{year}) versus water-use weighted annual average of WSI_{mon} ($Average_{ww}$ (WSI_{mon})). The scatter plot (A) shows all values for all watersheds. The graphs (B–C) show the monthly WSI (WSI_01 = January, etc.) and the annual values for selected rivers to illustrate the variability in major watersheds. Adopted from (Pfister and Baumann, 2012).

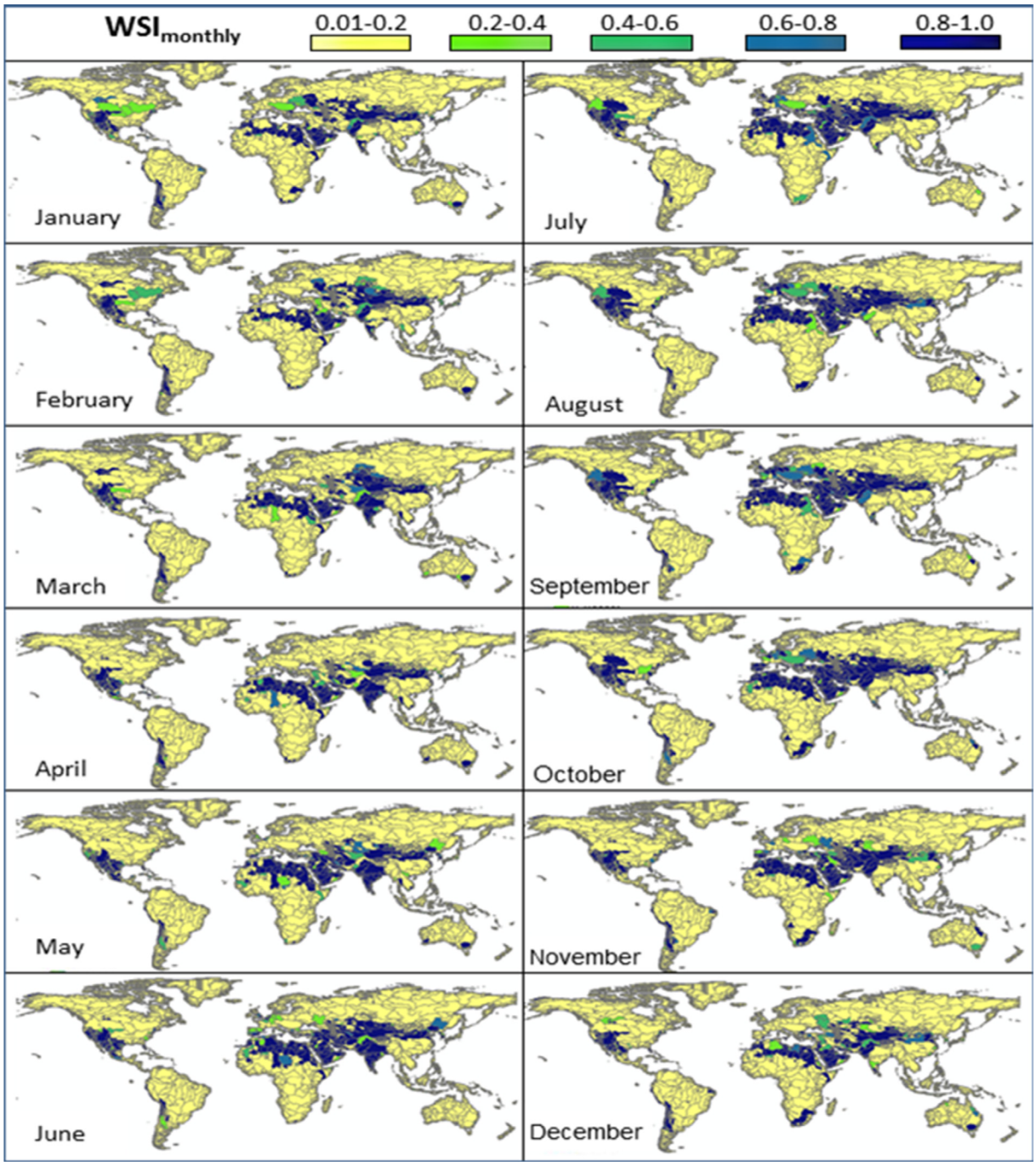

Fig. 6. These maps show the monthly WSI_{mon} for each watershed. In many areas there is no or only minor water stress while some areas consistently experience high water stress. However, some regions, such as large parts of Europe, have highly variable WSI for different months. Adopted from (Pfister and Baumann, 2012).

special attention during the interpretation of results. When applied in LCA or WFP analysis the geometric mean is suitable as an initial estimate, and minimal and maximal results from Pfister et al. (Pfister et al., 2011b) can give more insight in a sensitivity analysis.

3.2. Average characterization factor

In the following section we discuss the differences that occur when choosing an average or a marginal CF for the assessment of consumptive water use on a monthly basis. $\overline{WSI}_{mon}$ is the average CF (Eq. (7)), and the marginal CF is WSI_{mon} (Eq. (4)). A global map of the withdrawal-weighted annual average of monthly $\overline{WSI}_{mon}$ ($average_{ww}$ ($\overline{WSI}_{mon}$) is depicted in Fig. 2, showing the variability among the different watersheds.

The choice of WSI type will determine the value of the WFP, or in LCA the water consumption impact for a mass unit of crop (e.g. m^3/kg wheat). While the average WSI is suggested to assess the impact of an average produced crop or total water consumption in a region, the marginal one quantifies the impacts resulting from additional use of crops based on the currently prevailing conditions. Therefore this is a decisive choice which has to match the defined scope of a specific study. By definition, the $\overline{WSI}_{mon}$ obtained from integrating the steadily rising logistic characterization function is lower than the WSI_{mon}, which represents the upper integration limit. As shown

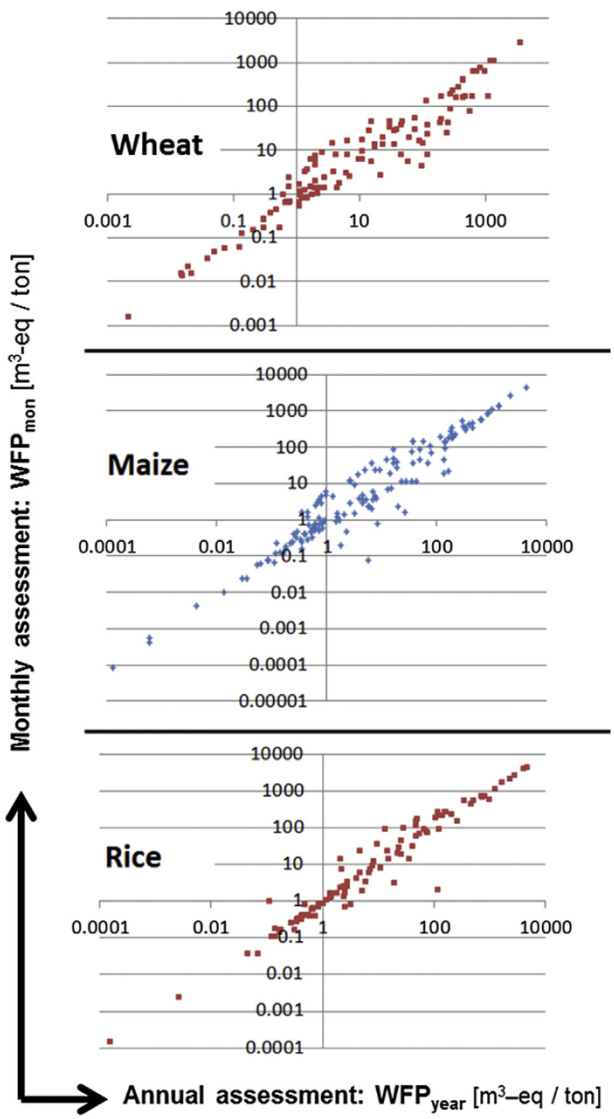

Fig. 7. Comparison of country average values of crop water footprint based on average WSI for the main staple crops wheat, maize and rice derived on annual (WFP_{year}) and monhtly (WFP_{mon}) level. These WFP are based on the marginal approach, and hence indicate the impact of an additional crop production.

in Fig. 3, the smallest ratio (1:3.4) between $\overline{WSI}_{mon}$ and WSI_{mon} is found at a WTA* of 0.46, which represents a highly stressed condition. For the total global water consumption in crop production, $\overline{WSI}_{mon}$ (=0.29) is 65% of WSI_{mon} (=0.44) using the geometric mean for irrigation water consumption. In comparison, the ratio of $\overline{WSI}_{mon}/WSI_{mon}$ for the arithmetic mean is 0.63. In comparison, in the annual assessment the ratio $\overline{WSI}_{mon}/WSI_{year}$ is 0.66.

In all cases there is a significant difference between average and marginal CF and it is therefore crucial to properly include the effects. The non-linearity of the ratio of $\overline{WSI}_{mon}/WSI_{mon}$ (Fig. 3) also changes the regional pattern and might therefore change the result of comparative LCAs. Selected results comparing WFP for the marginal and average approach are presented in Table A.1. The full table with all results per crop and country is available as Appendix B. The presented factors $\overline{WSI}_{mon}$ and WSI_{mon} are only the two most obvious results, but, in principle, average CF could also be calculated by integrating over other ranges than from zero to current WTA (Eqs. (7) and (8)). For instance, we could assume a baseline water use and start integrating from this WTA-level, or also assess non marginal changes in water consumption and therefore integrate beyond current WTA. Such CF can be calculated for specific cases using Eq. (7). This could be especially useful for sensitivity analysis. Another issue with integrating over WTA is the assumption of a linear relation between withdrawal and consumption. While it seems appropriate for regions where water use types do not largely change with increase of water use, it might not be true if we assume a baseline for domestic use and additional water consumption for agriculture. This simplification is expected to be of minor relevance, but if improved data on total water consumption become available, the average WSI can be recalculated using water consumption instead of withdrawal data.

3.3. Comparison between monthly and annual resolution of water stress index

In the following section, average stress indices calculated on annual and monthly resolution are compared. This means that the $\overline{WSI}_{year}$, which represents an annual average, is compared with the withdrawal weighted average of the values obtained on a monthly resolution, $average_{ww}$ ($\overline{WSI}_{mon}$). Both are visualized in the global maps of Fig. 4, which also exhibits a ratio map to inspect the relative differences. It can be seen that certain regions with moderate water consumption and stress but strong seasonality appear more stressed in the monthly assessment. Examples are areas in Europe and in Eastern USA. Other regions (e.g. India) have a reduced water footprint. One reason for these trends is that in stressed regions with very high $\overline{WSI}_{year}$, such as large parts of India, the most critical months cannot have significantly increased $\overline{WSI}_{mon}$ compared to $\overline{WSI}_{year}$ (see also Fig. 3). At the same time, some months of low water stress may reduce the water footprint over the whole growth period significantly, and consequently the water footprint per year decreases with a finer temporal resolution. This comparison is also true for the marginal WSI. In regions with rather low WSI on annual level, a few months with increased water consumption (such as in the Rhine basin) can heavily influence the annual average CF (Fig. 5). Maps of monthly WSI_{mon} are presented in Fig. 6 and can be downloaded in Appendix C.

An important issue is the fact that the variation factor (VF) to compute $\overline{WSI}_{year}$ only accounts for variability in availability and not in use. This is a major limitation of the annual assessment, especially for regions with high agricultural water use proportions and seasonality. By using $\overline{WSI}_{mon}$, results can be significantly improved for such regions (e.g. Spain and Northwestern China).

Fig. 7 shows the scatter plot of annual vs. monthly assessment for the main staple crops rice, wheat and maize; detailed results on crop water footprint based on the different characterization factors are presented in Appendix B. For wheat, we see that countries with high WFP on annual assessment (WFP_{year}) tend to have lower values when analyzed on a monthly basis (WFP_{mon}). This can be explained by the fact that wheat can be grown as a "winter crop" and therefore needs less irrigation in the months of highest water stress. For countries with moderately high WFP_{year} we observe mostly increased WFP_{mon}. For maize no clear trend is found, and the discrepancy between WFP_{mon} and WFP_{year} reaches 0.1–100 m^3/ton. Rice features the lowest differences, which might be explained by the fact that this crop is often cultivated in tropical or subtropical regions, where multiple crop cycles per year are feasible and therefore the water consumption varies less among seasons.

3.4. Limitations

Several limitations affect the quality of the results. One major and obvious drawback is the fact that the WFP results mainly represent crop production in the year 2000. While in many regions, agricultural patterns and technologies might not have changed dramatically, they have in many regions of emerging economies. Also, the

whole effect of biofuel production is not accounted for due to this time lag. Once better data are available, updated results should be presented. Furthermore, we did not include unproductive losses in agriculture caused by low-efficiency irrigation systems. Such losses can be up to 30% (Faist Emmenegger et al., 2011). If we consider the global agricultural water consumption, such additional water use is massive. For detailed analysis of crop WFP, this can be included in the uncertainty assessment. Another relevant uncertainty is attributed to the CF. While uncertainty for WSI_{year} has been quantified in previous work (Pfister and Hellweg, 2011), this has not been done for the adjusted factors presented here. These factors for WSI_{year} could be used as proxies also for monthly and average assessments, until better information is available. However, WSI_{mon} is considered to be of higher uncertainty, since it aims at higher temporal precision and monthly data are generally of lower quality. Additionally, the monthly factors do not explicitly account for man-made and other storages (e.g. lakes and groundwater) within a watershed. This is mainly due to the lack of global models quantifying the effect of storage processes. The temporal resolution has also effects on the proper spatial resolution: large rivers such as the Mississippi have a flow time of several months from source to sea, and consequently the monthly water scarcity is not the same in the whole watershed. Therefore higher spatial resolution, such as sub-watersheds with flow times below a month, should be considered for WSI_{mon}.

4. Conclusions

In this work we close an important gap by providing monthly CF for water consumption with global coverage and apply them to crop irrigation water consumption to derive the consumptive WFP of crops. Also, we provide two sets of factors, to address the issue of marginal vs. average impact assessment and allow the quantification of water footprints of regions by applying average $\overline{WSI}_{mon}$ to total water consumption.

Analyzing wheat and rice with monthly and annual indicators shows that the crop growing period has a considerable influence and shifting crop planting dates or crops with different calendars can help to relieve water stress. The monthly WFP therefore allows assessing more accurately the water consumption impacts and related management options such as evaluating different crop rotations as discussed in Nuñez et al. (2013).

The main limitation of the improved temporal resolution is the generally low data quality and the lack of detail in quantifying inter-monthly natural and man-made storage effects. Despite this, the produced maps and high resolution data offer generally plausible estimates. This ultimately facilitates capturing water scarcity at more appropriate temporal resolution than offered by available common water footprint concepts.

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Appendix A

Table A.1
Ratio of $\overline{WSI}_{mon}/WSI_{mon}$ of selected crops in major agricultural countries (production weighted).

	AUS Australia	CHN China	EGY Egypt	IND India	MEX Mexico	ESP Spain	TUR Turkey	USA United States	UZB Uzbekistan
All crops	**63%**	**69%**	**68%**	**69%**	**63%**	**64%**	**62%**	**62%**	**70%**
Wheat	60%	71%	70%	76%	57%	52%	53%	58%	44%
Rice	70%	62%	69%	67%	51%	68%	51%	62%	72%
Maize	67%	69%	64%	48%	61%	58%	59%	60%	74%
Sorghum	48%	67%	47%	65%	75%		75%	58%	75%
Potato	55%	69%	70%	60%	64%	58%	60%	52%	70%
Sweet potato	41%	68%	74%	57%		46%		62%	
Sugarcane	51%	50%	67%	71%	63%		67%	73%	
Sugar beet		64%	68%			64%	63%	58%	75%
Bean	67%	64%	66%	59%	62%	63%	63%	63%	
Pea	49%	72%		56%		55%	35%	35%	70%
Chick pea	48%	97%	53%	75%	69%	55%	58%		47%
Lentil	64%	70%	68%	66%	66%	63%	71%	36%	74%
Pulses		72%	74%	60%		56%	59%		69%
Cashew		40%		69%					
Almond	62%					64%	65%	69%	69%
Walnut		68%	69%		64%	51%	64%	70%	71%
Pistachio					75%		63%	71%	
Hazelnut						64%	64%	33%	73%
Soybean	62%	68%	68%	39%	69%	55%	55%	51%	73%
Peanut	77%	64%	63%	63%	57%		67%	60%	75%
Coconut		49%		65%	44%				
Oilpalm					52%				
Olive			75%		76%	68%	64%	72%	
Castor		68%		72%					
Sunflower	44%	70%	73%	56%	77%	59%	46%	45%	72%
Canola	73%	61%		66%		70%	68%	42%	

Safflower	62%	59%		55%	53%			48%	68%
Sesame		61%	69%	60%	61%		61%		75%
Cotton	56%	72%	60%	61%	71%	77%	72%	73%	75%
Linseed		68%	68%	77%		61%		45%	74%
Oilseeds				50%			44%		
Asparagus		69%			74%	63%	51%	65%	
Lettuce	34%	73%	65%	58%	51%	62%	65%	58%	
Spinach		72%	66%	75%	55%		66%	56%	
Tomato	41%	68%	77%	75%	67%	53%	58%	52%	73%
Cauliflower		69%	62%	58%	40%	66%	51%		
Pumpkins	48%	65%	70%	57%	65%		65%	68%	
Cucumber	48%	70%	63%	67%	76%		65%	70%	73%
Eggplant		69%	71%	58%	60%		64%	69%	
Onion	96%	72%	72%	65%	77%	55%	52%	63%	63%
Garlic		72%	69%	60%	57%	56%	62%	59%	65%
Green pea	66%	74%	65%	58%	77%			49%	
Carrot	51%	68%	73%	60%	59%	43%	66%	74%	48%
Okra			60%	61%	75%		77%	77%	
Banana	61%	44%	64%	68%	49%				
Orange	63%	69%	70%	66%	61%	64%	63%	74%	
Apple	65%	70%	72%	69%	67%	64%	64%	53%	69%
Pear	65%	73%	69%		46%	64%	64%	58%	69%
Apricot		57%	69%	68%		64%	64%	68%	70%
Cherry	89%	60%				64%	64%	61%	70%
Plum		70%	69%		60%	64%	65%	70%	69%
Strawberry		64%	70%		65%	60%			77%
Grape	64%	74%	62%	75%	70%	65%	64%	71%	71%
Watermelon	58%	73%	76%	69%	66%	56%	59%	70%	68%
Fig			69%		39%	63%	64%	70%	
Mango	53%	69%	69%	66%	53%			77%	
Avocado	50%	56%			46%	51%		73%	
Pineapple	53%	72%		60%	47%				
Date		58%	69%	64%	73%		67%	73%	
Kiwifruit							51%	72%	
Papaya		44%		59%	44%			77%	
Coffee		56%		72%	45%				
Cocoa				74%	42%				
Tea		68%		67%			64%		
Pimento		66%	69%	67%	64%			73%	
Vanilla					44%				
Cinnamon		48%							

Appendix B. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.11.031

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