

Monthly characterization factors for water consumption and application to temporally explicit cereals inventory

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ABSTRACT

We calculated monthly water stress indices for >11000 watersheds with global coverage. In comparison with annual assessments these indices show large differences in many locations although the general spatial distribution of water scarcity remains quite stable. 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 main limitation of the improved temporal resolution is the lack of detail in quantifying inter-monthly natural and man-made storage effects. The produced maps and data allow better capturing of water scarcity with temporal resolution, but many issues are raised and further research is required.

Keywords: temporal resolution, rice, wheat, water footprint, regionalization

1. Introduction

Water scarcity is affecting a large part of the population and will increase in future due to population growth, requiring a shift in spatial distribution of water consumption (Ridoutt and Pfister 2010a). Therefore water footprint and impact assessment of water in LCA has gained wide interest and is heavily discussed (Berger and Finkbeiner 2010), and different methods to quantify the impacts have been created and compared (Kounina et al. 2012). Relevance of spatial resolution for assessing water consumption and related impacts of plant has been highlighted in previous research (e.g. Pfister et al. 2011a). However, the temporal dimension of crop cultivation and related impacts has been neglected so far, although different crop options can shift irrigation water consumption within a year and hence lead to higher or lower water stress in the region. Furthermore, in some regions the temporal dimension is crucial, especially in cases with high variability of water use and availability. Consequently, annual assessment might be misleading in guiding crop choices within and among different regions. Temporal resolution is therefore essential for proper LCA of crop production.

The definition of a water footprint (WFP) has led to confusion as some consider and report pure aggregation of water consumption volumes to be proper WFP (e.g. Hoekstra et al. 2012), while we consider a water footprint according to carbon footprint and LCA including impact assessment as the only useful aggregated number informing about water scarcity issues related to products and services (Pfister and Hellweg 2009, Ridoutt and Pfister 2010b). This is especially relevant for processes in the supply chain, which are often major contributors to the overall WFP, as shown by Feng et al. (2011). A recent report highlighted the similarity of the approaches and revealed the shortcomings of the purely volumetric approach (UNEP 2012).

Several indicators for water scarcity have been developed recently and we focus our development based on the approach of Pfister et al. (2009). For a selection of 405 watersheds Hoekstra et al. (2012) calculated monthly water stress indicators following a different approach from the one we used.

In this work we developed water stress index (WSI) on a monthly basis for more than 11000 watersheds with global coverage. In a second step, WFP are calculated by multiplying monthly WSI ($WSI_{monthly}$) with monthly crop water consumption.

2. Methods

The original, annual WSI based on the approach of Pfister et al. (2009) includes a term for monthly variability of water availability in order to account for increased pressure in watersheds with unstable water supply over time. This factor has been excluded as it is explicitly covered by applying monthly WSI. Only the inter-annual variability is accounted for by the geometric standard deviation (s^*_{year}) of annual precipitation data during the “climate normal period” (1961-1990) within each river basin. Consequently the WSI function on monthly resolution of each watershed is adjusted to the reduced variability factor s^* by increasing the exponent factor of -6.4 to -9.8:

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$$WSI_{monthly} = \frac{1}{1 + e^{-9.8 \cdot WTA_{monthly}} \cdot \frac{1}{0.01} - 1} \quad \text{Eq. 1}$$

$$WTA_{monthly}^* = WTA_{monthly} \cdot s_{year}^* \quad \text{Eq. 2}$$

$WTA_{monthly}$ is the monthly withdrawal to availability ratio. It is determined by aggregating data from the 0.5 arc-degree model by Fekete et al. (2002) to watershed level and deriving factors of monthly WTA to annual WTA for each month. In a second step, these monthly factors are applied to the annual data from “WaterGAP” Alcamo et al. (2003) which are used in the original WSI (Pfister et al. 2009) to derive values for $WTA_{monthly}$ that are consistent with the annual factors.

The irrigation water consumption of the crops (IWR) is calculated according to Pfister et al. (2011a) and related to kg harvested crop through location-specific attainable yields (Fischer et al. 2000) in order to derive monthly WFP ($WFP_{monthly}$) and compare to the annual assessment (WFP_{annual}).

3. Results

Figure 1 shows a comparison of monthly and annual WSI, indicating large differences for some watersheds, while the general trend of spatial distribution is not changed dramatically (Figure 2). Still the variation is relevant especially due to the fact that most water is used in periods where water stress is rather high. This is also a logical consequence of the equation.

For the WFP analysis this has some additional implication, as not only the place of water use but also the timing is crucial for the assessment. This is shown by the case of wheat (Figure 3): In some areas wheat is planted as “winter wheat” and therefore has a growing phase that is prior to most other crops and consequently the average water consumption is rather in months with less water scarcity. Although the difference of annual and monthly water WFP is not changing the pattern of the global maps, it can be seen that in Southern Spain the Winter season is limiting the $WFP_{monthly}$ compared to WFP_{annual} . These effects are better shown in Figure 4, where maps of the ratio $WFP_{monthly}$ and WFP_{annual} shows that for rice and wheat the ratio can be quite different due to different growing seasons, pointing out the relevance of temporal resolution. The scatter plots (Figure 5) indicate the strong correlation but show relatively high variability in regions with average water footprints, especially for wheat.

These results and relevant data (incl. Google Earth layers) are made available on a webpage (ESD 2012).

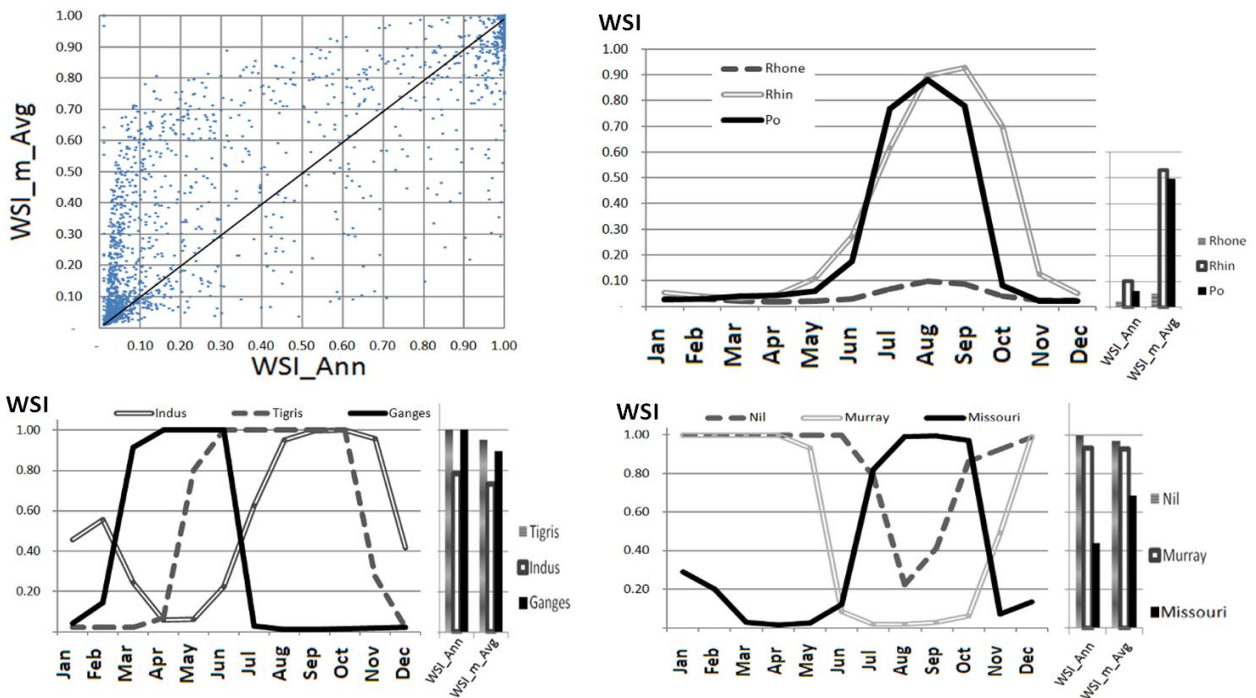


Figure 1. The graphs show an analysis of annual WSI (WSI_{Ann}) versus water-use weighted annual average of $WSI_{monthly}$ (WSI_{m_Avg}). The scatter plot shows all values for all watersheds and reveals that WSI_{m_Avg} is higher for many low WSI_{Ann} . The remaining graphs show the monthly WSI and the annual values for selected rivers for illustration of the variabilities in many watersheds.

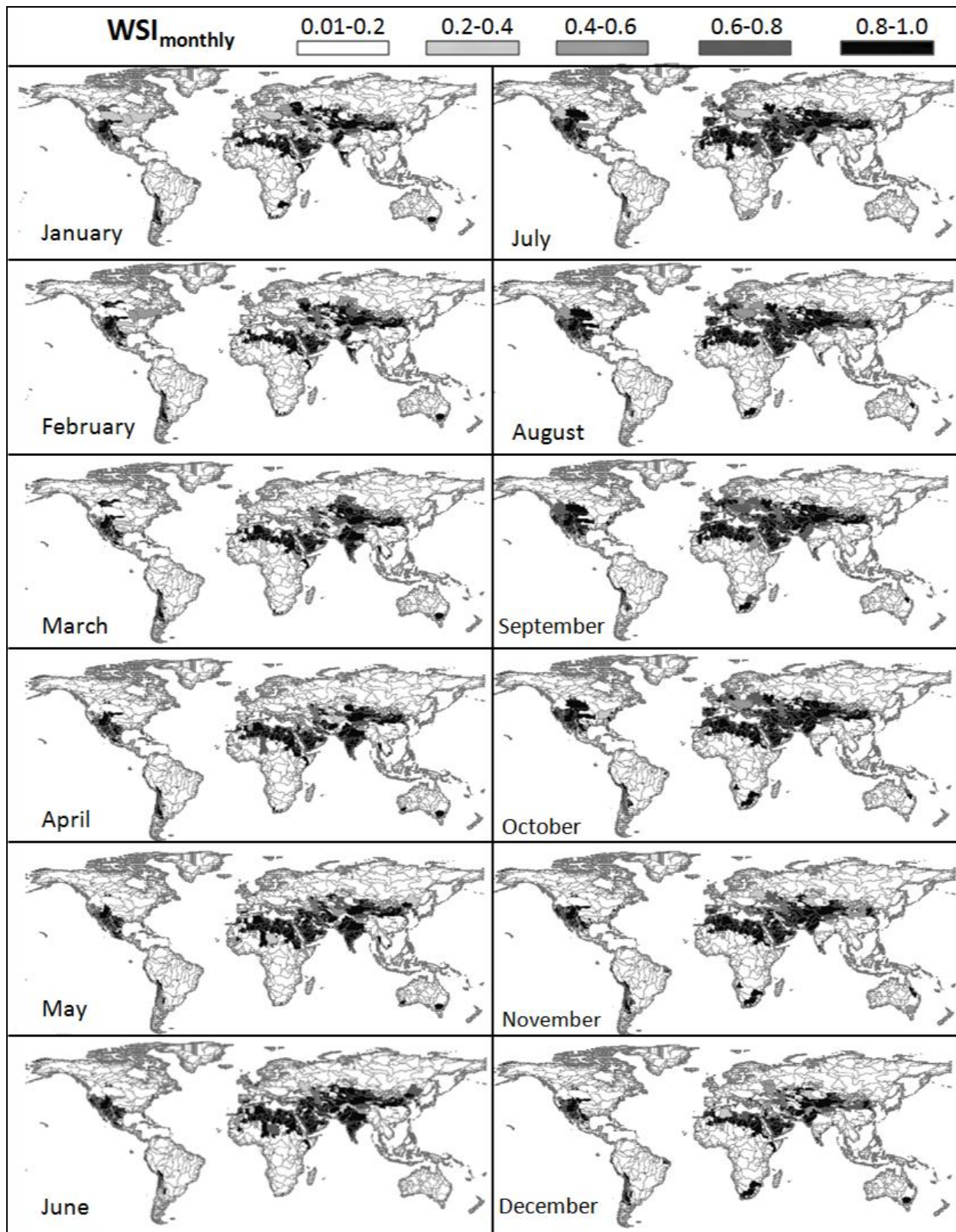


Figure 2. These maps show the monthly WSI for each watershed. In many areas there is no or only minor water stress while some areas consistently experience high water stress. However, some regions such as large parts of Europe have highly variable WSI for different months.

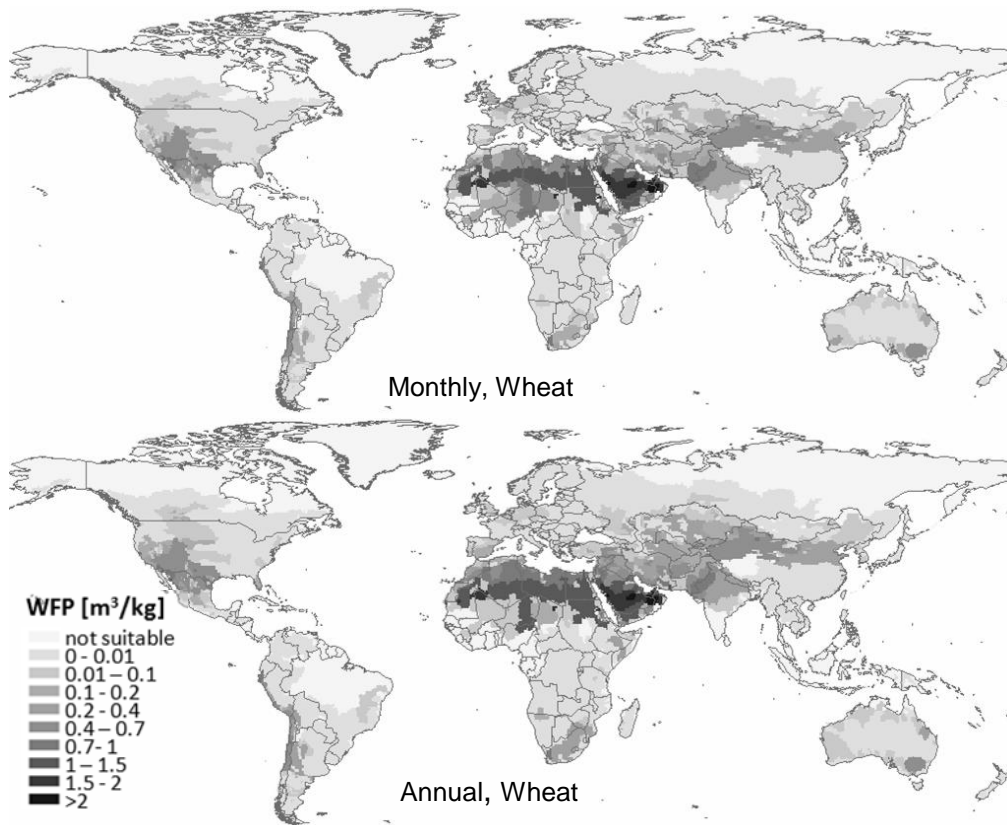


Figure 3. These maps show the water footprint (WFP) of wheat based on monthly (top) and annual (bottom) Assessment. In many areas there is no or only minor differences as the general trend is the same. However some watersheds have significantly different impacts (see figure 4).

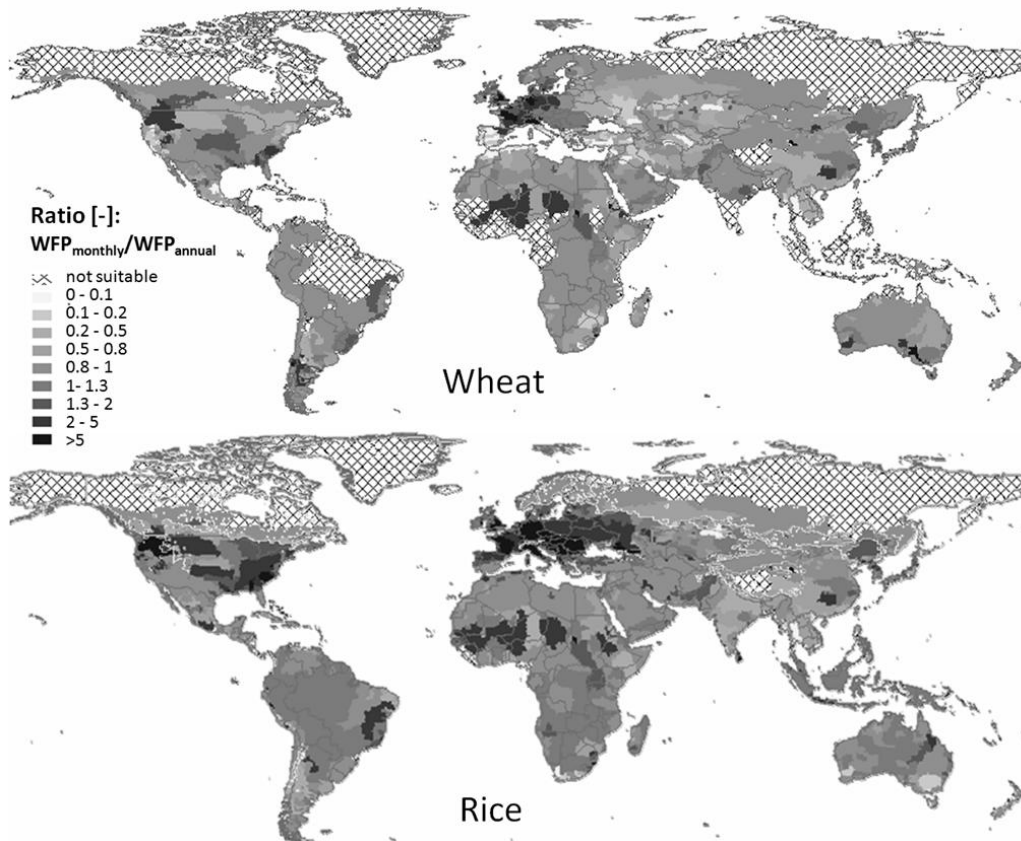


Figure 4. These maps show the ratio monthly to annual water footprint calculation of wheat top and rice (bottom). In many watersheds the impacts vary significantly. Note that although there is a similar pattern, rice and wheat differ regionally due to different growing seasons.

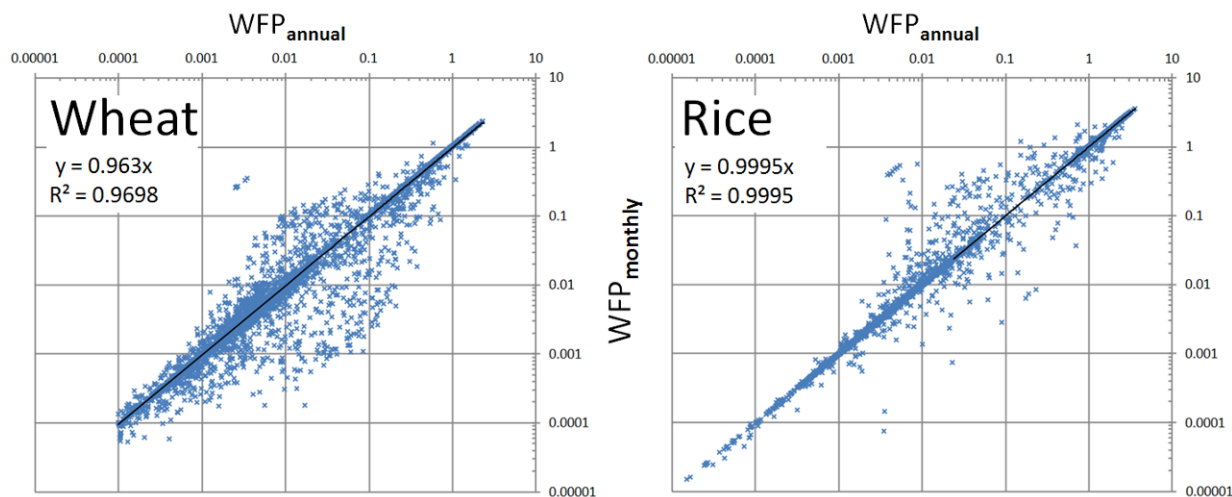


Figure 5. The scatter plots represent individual WFP values for wheat and rice production based on annual (WFP_{annual}) and monthly assessments (WFP_{monthly}) for each watershed. The linear regression indicates that monthly WFP are generally lower than WFP_{annual} for wheat, and quite consistent for rice. The high variability for the case of wheat (up to 2 orders of magnitude) reveals the importance of temporal explicit WFP.

4. Discussion

The results presented here are providing additional insights in water scarcity assessment and WFP but are having deficits. Uncertainties have shown to be extremely high in some areas (orders of magnitudes confidence intervals) even on annual WSI (Pfister and Hellweg 2011) and are assumed to be much higher for monthly factors. Additionally the inter-monthly storage needs to be accounted for and groundwater sources have to be distinguished from surface water in order to capture the relevant hydrological features. Reservoirs are also not addressed here. They could significantly change the situation of monthly availabilities, but are causing losses which can be significant as shown for dams for hydropower (Pfister et al. 2011c). All these features are also lacking in the monthly indicators for 405 watersheds by Hoekstra et al. (2012). However, those factors are based on water consumption instead of water use and therefore might capture the quantitative issue better. On the other hand also degradative water use contributes to water scarcity and therefore a mixture of water use and water consumption might be the best basis for a single water stress indicator.

The monthly WFP allows assessing more accurately the water consumption impacts and related management options such as evaluating different crop rotations as discussed in Nunez et al. (2012). The higher detail can also better analyse future crop schemes and reveal potentials for feeding the mankind in 2050. While shifting crop locations might considerably reduce water stress (Pfister et al. 2011b), shifting crop planting dates could mitigate peak water stress periods. This is an important potential as relocation of production sites might be problematic due to supply chain management of existing processing facilities as shown in Chiu et al. (2011) and reluctance of people to move their agricultural activities to completely different places. However, shifting cultivation periods might also reduce yield or increase irrigation water demand and consequently lead to higher water footprints. One limitation of the presented inventory is the exclusion of unproductive irrigation-water losses, which can lead to significant additional water consumption (Faist et al. 2011) and should be considered in future work.

Integration of water quality aspects potentially included in WFP should also consider watershed characteristics and temporal variation for impact assessment of emissions in LCA such as shown for heat emissions (Verones et al. 2011). This is a crucial step for consistently addressing the temporal dimension in LCA and aggregate monthly water footprint figures as suggested by Ridoutt and Pfister (2012). Finally the same temporal issues also concern land occupation as discussed and addressed in Pfister et al. (2010), since occupying land in winter is different than in summer. Beyond this consideration of natural growth seasons, other parameters for temporally-explicit land quality assessment are needed, especially for evaluating food products.

5. Conclusion

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 main limitation of the improved temporal resolution is the lack of detail in quantifying in-

ter-monthly natural and man-made storage effects. The produced maps and data allowing for better capturing water scarcity with temporal resolution, although further improvement is required.

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