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LETTER

A Fast Track approach to deal with the temporal dimension of crop water footprint

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Abstract

Population growth, socio-economic development and climate changes are placing increasing pressure on water resources. Crop water footprint is a key indicator in the quantification of such pressure. It is determined by crop evapotranspiration and crop yield, which can be highly variable in space and time. While the spatial variability of crop water footprint has been the objective of several investigations, the temporal variability remains poorly studied. In particular, some studies approached this issue by associating the time variability of crop water footprint only to yield changes, while considering evapotranspiration patterns as marginal. Validation of this Fast Track approach has yet to be provided. In this Letter we demonstrate its feasibility through a comprehensive validation, an assessment of its uncertainty, and an example of application. Our results show that the water footprint changes are mainly driven by yield trends, while evapotranspiration plays a minor role. The error due to considering constant evapotranspiration is three times smaller than the uncertainty of the model used to compute the crop water footprint. These results confirm the suitability of the Fast Track approach and enable a simple, yet appropriate, evaluation of time-varying crop water footprint.

1. Introduction

Global food demand and rising living standard increased the global water use by 6–8 times from 1900 to 2010 [1, 2], highlighting the growing importance of each drop of water as water consumption gets closer to water availability [3].

The concept of ‘water footprint’ [4, 5] provides a useful tool to quantify the efficiency of water used for food production. The water footprint of a generic product measures the water volume required for its production; it is also known as the virtual water content of the product because it represents the water amount conceptually embedded (though not physically present) in the good [6].

In light of the fact that agriculture is the major water-consuming sector, with irrigation accounting for 70% of freshwater withdrawal [7–9], many studies have focused on the crop water footprint, *CWF*, which is quantified as the volume of water evapotranspired during the growing season divided by the crop yield [10, 5]. It has been shown that crop water footprint is highly heterogeneous in space due, e.g. to different climate and soil conditions, fertilizer application rates, and agricultural mechanization level, even at the sub-national scale [10–13].

While a great deal of attention has been devoted to the *CWF* variability in space, less attention has been paid to its variability in time even though climatic fluctuations and yield variations have been remarkable in the past decades [14–16]. To date, only local studies have evaluated a time-varying crop water footprint [17–19], with particular regard to the Chinese case [20–22].

A larger number of studies investigated the temporal evolution and dynamics of the virtual water trade (VWT) associated to the international trade of agricultural goods [23]. The VWT has been recognized for its ability to improve access to water for food production in those countries where water scarcity is a major concerning issue, i.e. through the import of water-intensive products [24, 25]. It has been shown how both the virtual water volume embedded in internationally-traded goods and the number of trade relations grew significantly between 1986 and 2010 [26, 27], mainly driven by population, GDP, and geographical distance between countries [28, 29]. These studies approached the time variability of the VWT using annual trade data of agricultural goods, i.e. available on the FAOSTAT database, and time-averaged crop water footprint, i.e. provided by Mekonnen *et al* (2010, 2011) [10]. At the same time, also some local studies dealt with the time variability of the VWT using constant *CWF* values [30, 31].

However, considering constant crop water footprints precludes analyses on the implications of climate patterns and yield trends on the virtual water content and, thus, on the virtual water trade. In order to keep pace with this issue, a number of studies have adopted a simple approach that ascribes the time variability of virtual water content only to yield trends, leaving out the effects of evapotranspiration variations [32–35]. This approach has been adopted both for global [36–38] and local [39, 40] water footprint assessments. But feasibility of this approach has yet to be proved. Can this approach capture the main *CWF* temporal variability? How big is the error arising with the assumption of constant evapotranspiration? What is the effect of *CWF* variability on the virtual water trade? This Letter addresses these questions by (i) providing a systematic validation of the method (here referred as the Fast Track method), (ii) furnishing a comprehensive assessment of the associated uncertainty, and (iii) giving an example of application to highlight its relevance.

2. Materials and methods

2.1. Fast Track approach

Recent literature on virtual water testifies a growing application of a Fast Track (FT) approach for introducing the time dependency in crop water footprint assessment, with the main objective of calculating the volumes of virtual water embedded in internationally-traded agricultural goods.

According to the FT approach, the crop water footprint of country c in year t, $CWF_{c,t}(Y)$, is only driven by crop yield variations, $Y_{c,t}$ [ton·ha^{-1}], while evapotranspiration depth, $\overline{ET}_{c,T}$ [mm], is kept constant to an average value typical of a reference year or period (T), namely

$$CWF_{c,t}(Y) = 10\frac{\overline{ET}_{c,T}}{Y_{c,t}}\left[\frac{\text{m}^3}{\text{ton}}\right], \qquad (1)$$

where, 10 is a numerical factor to convert the evapotranspiration depth from mm to m^3·ha^{-1}. With this formulation, it is implicitly assumed that the variations of crop evapotranspiration have negligible effects on the crop water footprint when compared to the effects of yield variations and thus the $\overline{ET}_{c,T}$ value can be fixed for any year t. The advantage behind equation (1) is that yield time-series data are easily available at the country scale (e.g. FAOSTAT database), and thus the *CWF* variability can be obtained without the adoption of computationally demanding models that are generally used to estimate evapotranspiration. Equation (1) has been adopted in previous studies to include time variations in the analyses of virtual water trade [32–35] for all years lacking annual ET, but without testing the suitability nor the uncertainty of the adopted methodology. Validation of the FT approach is the main purpose of this letter.

The FT approach allows one to exploit average crop water footprint estimates determined over a period T, $\overline{CWF}_{c,T}$. Literature accounts a number of *CWF* estimates at different spatial scale and averaged over different time intervals [10, 11, 13]. These time-averaged crop water footprints can be scaled with yield variations, according to

$$CWF_{c,t}(Y) = \frac{\overline{CWF}_{c,T}\cdot\overline{Y}_{c,T}}{Y_{c,t}}\left[\frac{\text{m}^3}{\text{ton}}\right], \qquad (2)$$

in order to make them time dependent. $\overline{Y}_{c,T}$ is the average crop yield over T while $Y_{c,t}$ is the yield of year t. Equation (2) has been recently applied, e.g. by Duarte *et al* (2016) [38] to compute annual virtual water flows from 1965 to 2010 for 133 products.

To date, equations (1, 2) have been applied only at the country scale. However, they can be applied at any spatial resolution, depending on the goals and data availability. Thus, symbol c can refer also to a region, a province or a cell and the time-interval T can indicate both a single year or a temporal window of two or more years length.

2.2. Validation of the Fast Track approach

Here we test and validate the assumption of constant evapotranspiration that grounds the FT approach. The aim of validation is twofold: (i) to support previous studies that have applied the method without examining in depth its feasibility and (ii) to foster its adoption to deal with temporal variability in future water footprint assessment. In order to test the method, we compare the *CWF* estimates obtained with the FT approach to the estimates accomplished through a more refined model accounting for both the inter-annual yield and evapotranspiration changes. The two different estimates are obtained as detailed in the following for wheat, rice, maize, and soybean. These crops provide more than 50% of the global caloric content of human diet [41], they contribute for more than 50% to the global water footprint [10] and they account for over 30% of the global virtual water trade of agricultural goods [28]. The validation could be accomplished for any other product, provided that data are available (see below).

2.2.1. Evaluation of the crop water footprint through the FT approach

Annual *CWF* estimates are carried out according to equation (2) applied at the country scale for the period 1961–2013. Equation (2) requires as input the time-averaged crop water footprint ($\overline{CWF}_{c,T}$), the time-averaged yield ($\overline{Y}_{c,T}$), and the annual yield from 1961 to 2013 ($Y_{c,t}$). The average crop water footprint values are provided by Tuninetti *et al* (2015) [13] for the period $T = 1996$–2005 at 5 × 5 arc minute resolution. To obtain country averages, these gridded estimates are aggregated through a production-weighted mean (see Tuninetti *et al* (2015) [13] for further details). The country yield averages $\overline{Y}_{c,T}$ are obtained by averaging the annual FAOSTAT data available for each producing-country from 1996 to 2005; finally, the annual yield values $Y_{c,t}$ are derived from the same database but with t running from 1961 to 2013.

2.2.2. Evaluation of the crop water footprint with the detailed method

The $CWF_{c,t}(Y)$ estimates obtained with the FT approach are compared with the annual water footprint estimates achieved when both the yield and the evapotranspiration changes are taken into account. To this purpose, we adapted the model proposed by Tuninetti *et al* (2015) [13] for time-fixed assessments, by introducing the time variability of both yield and evapotranspiration.

The yield- and evapotranspiration -dependent annual crop water footprint in cell i of year t belonging to the range 1961:2013, $CWF_{i,t}$ (Y, ET), reads

$$CWF_{i,t}(Y, ET) = \frac{10 \cdot ET_{i,t}}{Y_{i,t}}\left[\frac{\mathrm{m}^3}{\mathrm{ton}}\right]. \tag{3}$$

In this case, both the crop evapotranspiration, $ET_{i,t}$, and the crop yield, $Y_{i,t}$, are time dependent, differently from equations (1, 2) where the ET values are assumed constant and averaged over T.

The annual $ET_{i,t}$ value is the water depth actually evapotranspired by the crop during the growing season of year t. It is determined [42] as the product between the potential evapotranspiration (ET_0), a crop coefficient (which is characteristic of the crop height, canopy resistance, and soil evaporation rate), and a water stress coefficient obtained through a daily water balance (as in Tuninetti *et al* (2015) [13]). We assume that crop properties (e.g. planting date, length of the growing period) and soil characteristics (e.g. available soil water content) remain constant along the study period due to lack of more detailed data. Differently, we account for inter-annual fluctuations of potential evapotranspiration and precipitation integrating the annual climatic data provided by the CRU database [43] and the GAEZ database [14]. The CRU database covers the period between 1961 and 2013 providing for each year gridded potential evapotranspiration and precipitation at 30 × 30 arc minute resolution on monthly basis. The values given by the GAEZ database cover the period between 1961 and 2000 with yearly temporal resolution on a $5' \times 5'$ grid. The combination of the two databases allows one to achieve the best spatio-temporal resolution in the estimation of the ET_0 values and precipitation.

For the crop yield, time series of gridded yield data are not available at the spatial resolution required by equation (3) for the period 1961–2013. Therefore, in order to obtain time-variable gridded data, we adjust the values provided by Monfreda *et al* (2008) [44] at $5' \times 5'$ resolution for year $t = 2000$, i.e. $Y^{Mo}_{i,t=2000}$, with two factors, namely

$$Y_{i,t} = \alpha^{cl}_{i,t} \cdot \alpha^{\mathrm{man}}_{c,t} \cdot Y^{M_o}_{i,t=2000}\left[\frac{\mathrm{ton}}{\mathrm{ha}}\right]. \tag{4}$$

The factor $\alpha^{cl}_{i,t}$ accounts for climate-driven yield changes while the factor $\alpha^{\mathrm{man}}_{c,t}$ accounts for the yield changes induced by technological advances and agricultural improvements, ascribable to the anthropic (man) role in agriculture. Depending on data availability, $\alpha^{cl}_{i,t}$ can be defined at the cell level while $\alpha^{\mathrm{man}}_{c,t}$ can only be defined at the country scale.

The factor $\alpha^{cl}_{i,t}$ accounts for yearly fluctuations of crop yield at the cell level, due to year-to-year changes in crop evapotranspiration. Such changes are assumed to impact the yield according to the relation proposed by Doorenbos *et al* (1979) [45],

$$1 - \frac{Y^{cl}_{i,t}}{Y_{i,t=2000}} = k_y \cdot \left(1 - \frac{ET_{i,t}}{ET_{i,t=2000}}\right), \tag{5}$$

where, $Y^{cl}_{i,t}$ is the yield in year t when only variations in crop evapotranspiration are considered. Thus, the subscript cl marks the new yield determined by climatic changes only. Equation (5) relates the relative change in evapotranspiration to the relative change in crop yield through the yield response factor, k_y [45]. We refer the changes to year $t = 2000$ because the yield dataset $Y^{Mo}_{i,t=2000}$ [44], is representative for that year. The value of $\alpha^{cl}_{i,t}$ is determined by equations (4) and (5) assuming $\alpha^{\mathrm{man}}_{c,t} = 1$ and thus $Y_{i,t} = Y^{cl}_{i,t}$, namely

$$\alpha^{cl}_{i,t} = 1 - ky \cdot \left(1 - \frac{ET_{i,t}}{ET_{i,t=2000}}\right). \tag{6}$$

When only climatic variations are taken into account, the yield value reads

$$Y^{cl}_{i,t} = \alpha^{cl}_{i,t} \cdot Y^{M_o}_{i,t=2000}. \tag{7}$$

Gridded yield values obtained with equation (7) are then aggregated at the country scale through a weighted mean, i.e.

$$Y^{cl}_{c,t} = \frac{\sum_{i \in c} Y^{cl}_{i,t} \cdot A_{i,t=2000}}{\sum_{i \in c} A_{i,t=2000}}, \tag{8}$$

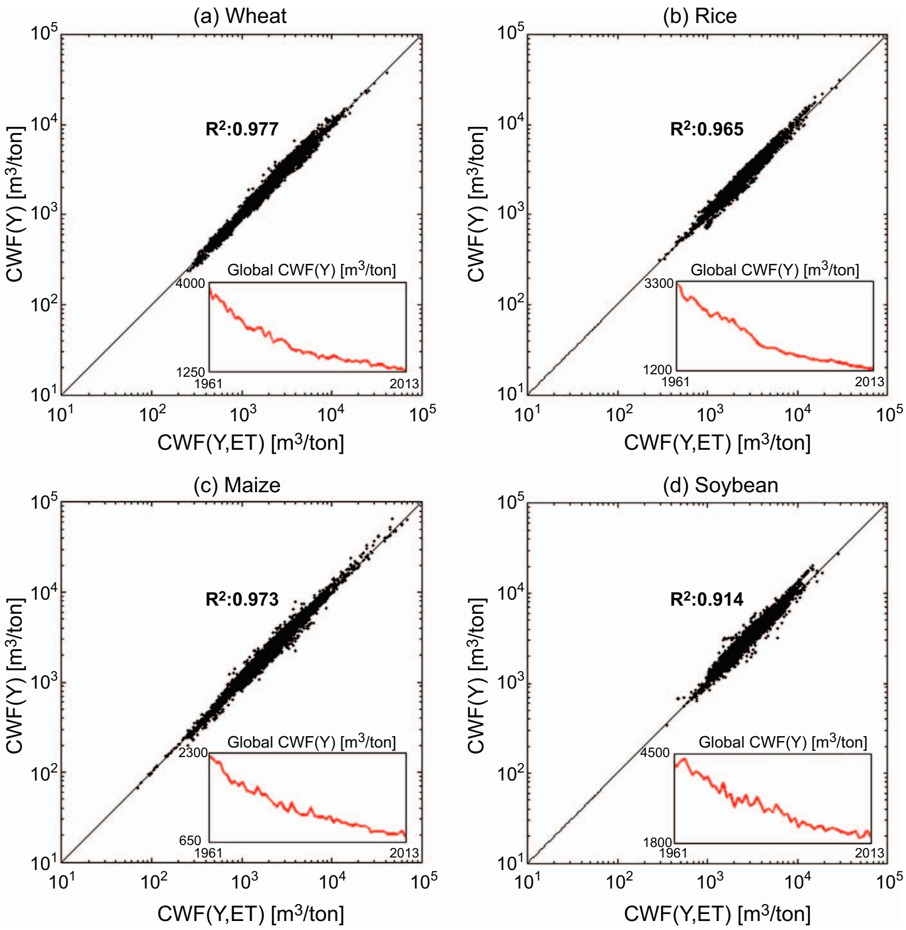

Figure 1. Comparison of the annual *CWF* estimates obtained by the Fast Track approach, *CWF* (*Y*), with the values obtained with the detailed methodology accounting for both yield and evapotranspiration variations, *CWF* (*Y, ET*). The comparison is made at the country scale across the period between 1961 and 2013 for wheat (*a*), rice (*b*), maize (*c*), and soybean (*d*). The R^2 value indicates the coefficient of determination between the two estimates. The inset of each panel reports the global trend of the average crop water footprint evaluated with the FT method. Such annual global value is obtained through a weighted mean of the country estimates, using the annual country production as weight.

using the gridded harvested area of year 2000, $A_{i,t=2000}$, provided by Portmann *et al* (2010) [46] as weight. These country values are used in the following to determine the $\alpha_{c,t}^{\text{man}}$ factor.

The $\alpha_{c,t}^{\text{man}}$ factor expresses the yield variability due technological and mechanical advances in the agricultural management (e.g. use of pesticides, application of fertilizers, extensive irrigation) and it is thought as a correction factor to the $Y_{c,t}^{cl}$ values in order to account for all other aspects beyond climate. It is defined as the ratio between the FAO country scale yield, $Y_{c,t}^{\text{FAO}}$, and the national $Y_{c,t}^{cl}$ values calculated with equation (8)

$$\alpha_{c,t}^{\text{man}} = \frac{Y_{c,t}^{\text{FAO}}}{Y_{c,t}^{cl}}. \tag{9}$$

With the adoption of equations (3, 4) it is now possible to determine the annual crop water footprint in each cell. Country estimates of $CWF_{c,t}(Y, ET)$ are then obtained through a production-weighted mean of the gridded values, where cell production is given by the product between the $Y_{i,t}$ values (expressed in ton·ha^{-1}) and the harvested area $A_{i,t=2000}$ (in ha) provided by Portmann *et al* (2010) [46].

3. Results

3.1. Validation of the FT approach

In figure 1 we compare the annual *CWF* estimates obtained with the Fast Track approach ($CWF_{c,t}$ (*Y*)), only accounting for the yield variability, with those accomplished by the detailed method ($CWF_{c,t}$ (*Y, ET*)) accounting not only for yield but also for the evapotranspiration variability. Each point in the scatter represents the national crop water footprint in year *t* within the period 1961–2013. The estimates obtained with the two approaches compare well for all crops: in fact, all points are mostly aligned along the 1:1 line with limited scatter, as confirmed by the values of the coefficient of determination, R^2 (that read 0.977 for wheat, 0.965 for rice, 0.973 for maize, and 0.914 for soybean). The overall agreement between the two methods confirms that the temporal variability of the crop water footprint is mainly driven by yield variations, while the variability of crop

Table 1. Statistics of the error, ϵ, associated to the methodology described by Tuninetti *et al* (2015) [13] and statistics of the error, ϵ', associated to the FT method assumption of invariable evapotranspiration. The $l\ (\epsilon)$ and $l\ (\epsilon')$ values indicate the length of the error samples available for each crop.

		log (ϵ)			log (ϵ')	
	$l\ (\epsilon)$	μ_ϵ	σ_ϵ	$l\ (\epsilon')$	$\mu_{\epsilon'}$	$\sigma_{\epsilon'}$
Wheat	5689	−0.001	0.296	107	−0.022	0.093
Rice	5405	0.012	0.286	97	−0.016	0.099
Maize	6958	0.036	0.266	126	−0.066	0.104
Soybean	3680	0.041	0.254	73	−0.086	0.135

evapotranspiration, that is kept constant over time in the FT method (and not in the refined method), appears to play a negligible role. We remark that this does not correspond to neglect the relevance of the climatic variations on the *CWF*: as the climatic signature remains in the yield time series. In fact Ray *et al* (2015) [47] have found that around 30% of the wheat, rice, maize and soybean yield variability is explained by climate variability through the inter-annual fluctuations of precipitation and temperature values.

Moreover, the FT method performs well independently of the presence of yield trends. In fact, there are countries in the database where yield has improved over time inducing the decrease in *CWF*; whereas, in other countries, yield has stagnated or decreased, making the *CWF* values remain constant or increase. According to Ray *et al* (2012) [16], wheat, rice, maize, and soybean are experiencing yield increases in around 70% of their harvested areas, stagnation in over 20% of the areas and collapse in the remaining areas. Despite the strong spatial heterogeneity of the *CWF* trends worldwide, the global average water footprint of each crop has sharply decreased from 1961 to 2013, as shown by the red lines in the insets of figure 1 (−68% for wheat, −62% for rice, −66% for maize, and −52% for soybean).

3.2. Uncertainty in the FT approach

The uncertainty of the FT approach is now assessed and decomposed in its main components. Denoting the real (unknown) crop water footprint of country c in year t as $CWF^r_{c,t}$, the error structure is here assumed to be multiplicative to account for the fact that crop water footprint is positive-valued, namely

$$CWF_{c,t}(Y) = CWF^r_{c,t}\cdot\epsilon_{c,T}\cdot\epsilon'_{c,t}. \qquad (10)$$

The $\epsilon_{c,T}$ error is due to the type of model adopted to calculate the crop water footprint; it impacts the $\overline{ET}$ value in equation (1) and the $\overline{CWF}$ value in equation (2). The $\epsilon'_{c,t}$ error arises from the assumption of constant evapotranspiration in the FT approach.

The $\epsilon_{c,T}$ error depends on the model and data used to estimate the crop evapotranspiration (e.g. the data regarding cultivated and irrigated areas, growing periods, crop parameters, soil, climate) and the yield data. In order to quantify such error, we compare the average *CWF* estimates derived from Tuninetti *et al* (2015) [13], and already used in equation (2) at the country scale, with the country estimates given by Mekonnen *et al* (2011) [10] which constitutes the overriding reference study in the literature of water footprint assessment. Both estimations are referred to the period $T = 1996–2005$; we denote as $\overline{CWF}^{Me}_{c,T}$ the estimates by Mekonnen *et al* (2008) and $\overline{CWF}^{Tu}_{c,T}$ the values derived from Tuninetti *et al* (2015).

We calculate, for each country and for each crop, the corresponding $\epsilon_{c,T}$ error, as

$$\epsilon_{c,T} = \frac{\overline{CWF}^{Tu}_{c,T}}{\overline{CWF}^{Me}_{c,T}}. \qquad (11)$$

We thus obtain four samples of $\epsilon_{c,T}$ values, one for each crop (the length of each sample is reported in table 1). We find that each sample is fitted by a two-parameter log-normal distribution, with parameters μ and σ representing the average and standard deviation of the log-transformed data, given in table 1. Overall, μ is around 0 for all crops while σ is between 0.25 and 0.30. These relatively large σ values imply a high sensitivity of the crop water footprint to the model parameters and input data used, as previously shown in other studies [10, 12]. In figure 2 we compare the $\overline{CWF}^{Tu}_{c,T}$ and $\overline{CWF}^{Me}_{c,T}$ estimates; each circle represents a producing-country and the size of the circle indicates the share of the country in the global production. The largest producer of each crop is highlighted by a red circle. Generally, the estimates compare well for all crops with average coefficients of determination, R^2, always higher than 0.7. However, when weighted by country production the R^2_w values suggest better or worse agreement between the estimates provided by Tuninetti *et al* (2015) and Mekonnen *et al* (2011) depending on the crop. For rice and maize (panels (*b*,*c*)), the agreement between the two studies is particularly high, with R^2_w equal to 0.89 and 0.83, respectively. Conversely, for wheat and soybean the R^2_w values are lower, particularly for soybean ($R^2_w = 0.41$).

The proposed assessment of model uncertainty can be extended to other crops and derived crops using the dataset provided by Mekonnen *et al* (2011) [10], which is (to the best of our knowledge) the most complete one.

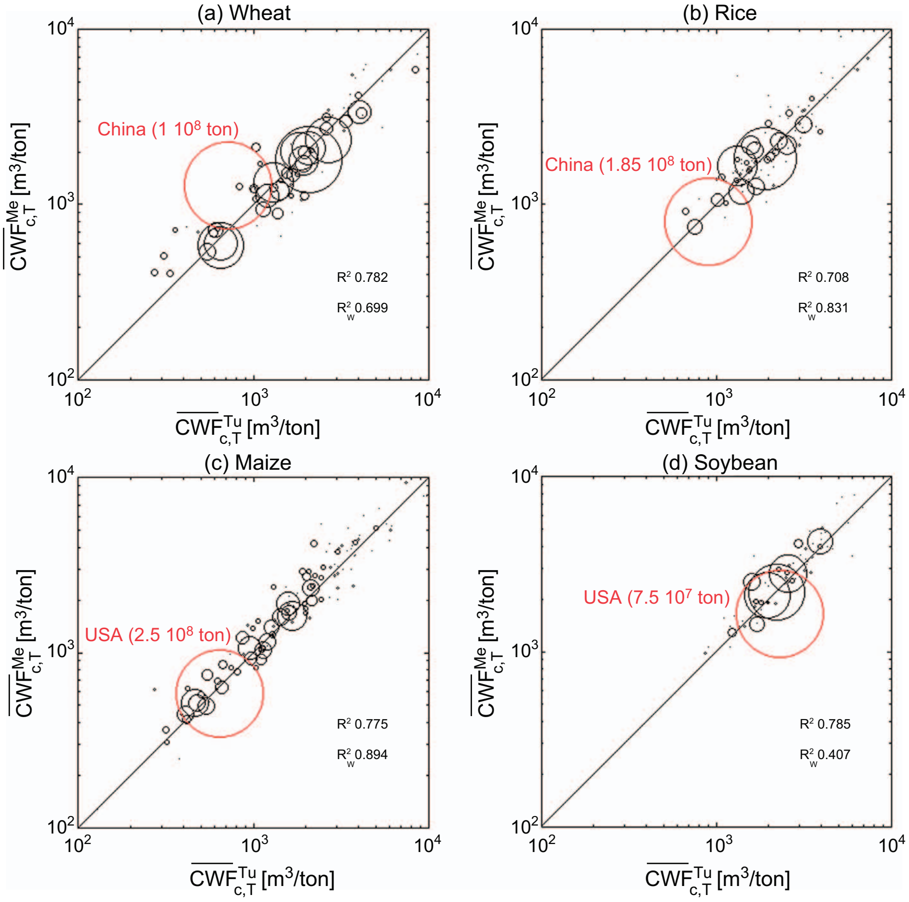

Figure 2. Comparison of the average crop water footprint as estimated with the methodology provided by Tuninetti *et al* (2015) [13], $\overline{CWF}^{Tu}_{c,T}$, with the values taken from Mekonnen *et al* (2011) [10], $\overline{CWF}^{Me}_{c,T}$, for wheat (*a*), rice (*b*), maize (*c*), and soybean (*d*). The area of each circle in the graph is proportional to the share of the country to the global annual production, while the red circles highlight the greatest producing countries. R^2 indicates the overall coefficient of determination and R^2_w stands for the coefficient of determination weighted by countries annual production along the period 1996–2005.

The $\epsilon'_{c,t}$ error is determined as the ratio between the $CWF_{c,t}$ (Y) values, estimated with the Fast Track approach according to equation (2), and the $CWF_{c,t}$ (Y, ET) values achieved with the refined method, i.e.

$$\epsilon'_{c,t} = \frac{CWF_{c,t}(Y)}{CWF_{c,t}(Y, ET)}. \tag{12}$$

As for the $\epsilon_{c,T}$ errors, we find that the $\epsilon'_{c,t}$ values follow a log-normal distribution; the μ and σ values are shown in table 1 together with the length of the $\epsilon'_{c,t}$ samples. For all crops, the precision of the estimates is high, with a standard deviation of the error around 0.1, confirming the good agreement between the two estimators previously shown in figure 1.

The uncertainty in the annual *CWF* estimates ascribable to the assumption of constant evapotranspiration (in the FT approach) results three times lower than the model uncertainty, evaluated as a comparison between the outcomes provided by Mekonnen *et al* (2011) and those derived from Tuninetti *et al* (2015). Therefore, the FT approach is appropriate to deal with the time variability of crop water footprint.

3.3. Example of application: the case of virtual water trade

The time dependent $CWF_{c,t}(Y)$ estimates, obtained for wheat, rice, maize, and soybean with the FT approach, are now used to assess the temporal variations of the virtual water volumes embedded in the international trade. To this aim, we calculate the annual virtual water embedded in each crop exported by country c in year t, $VW_{c,t}$, as the product between the weight of crop, $W_{c,t}$, (in tonnes) exported by country c and the annual water footprint of the crop, $CWF_{c,t}(Y)$, for the period between 1986 and 2011. The $W_{c,t}$ values are available from the FAOSTAT database, whereas the crop water footprint values have been estimated by equation (2). The total virtual water trade, VWT_t, is then built by summing up the $VW_{c,t}$ of all crops and countries, and shown by the solid line in figure 3. During the period 1986–2011 countries have been displacing growing volumes of virtual water, embedded in the four study crops, worldwide: from 300 km^3 in 1986 to 540 km^3 in 2011 (refer to the solid line, figure 3).

In order to provide evidence of the importance of using time dependent *CWF* values, we report in the same graph the annual virtual water trade data

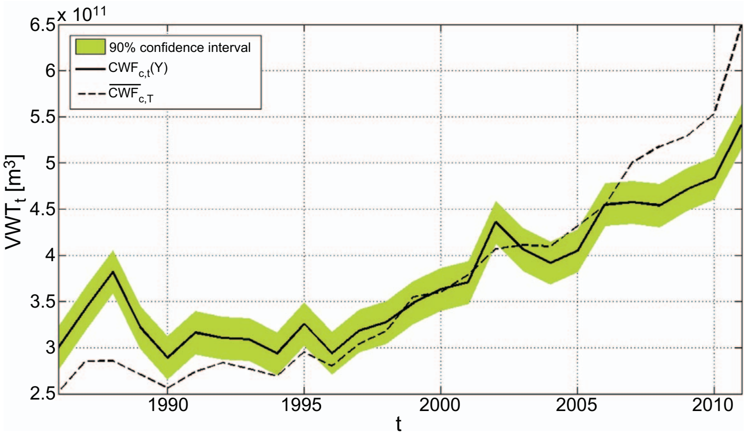

Figure 3. Temporal trend of the virtual water volume associated to the international trade of wheat, rice, maize, and soybean in the period between 1986 and 2011. The black dashed line represents the virtual water trade evaluated with the time-averaged $\overline{CWF}_{c,T}$ values; the black solid line refers to the VWT obtained using the annual $CWF_{c,t}(Y)$ values estimated with the FT method. The green area displays the 90% confidence interval of the FT method error, due to the assumption of constant crop evapotranspiration.

obtained using the annual trade from the FAOSTAT database and the average $\overline{CWF}^{Tu}_{c,T}$ values over the period 1996–2005 taken from Tuninetti *et al* (2015) [13]. In this case, the virtual water content of each crop is kept constant over time and the VWT trend is only driven by the amount of products that are internationally exchanged over time, i.e. $W_{c,t}$. We observe significant differences between the trend obtained with the time variable $CWF_{c,t}(Y)$ and the time-averaged $\overline{CWF}^{Tu}_{c,T}$ virtual water content: e.g. in year 2011 the difference is around 100 km^3. Such comparison exemplifies for the four study crops the gap existing in the VW trade estimations between the two approaches.

Finally, the green area in figure 3 depicts the 90% confidence interval of the VWT estimation. The confidence interval is determined as $\mathrm{VWT}_t \pm z^* \cdot \sigma_{\mathrm{VWT}}$, where z^* is the 95th percentile of a standard normal variate and σ_{VWT} is the standard deviations of the total virtual water flow. The square value σ^2_{VWT} is equal to the sum of the variance associated to the virtual water trade of each crop cr (assuming independence of the four virtual water flows). Such variance is calculated as the product among (i) the variance of the ϵ' errors (see equation (12) and table 1), $\sigma^2_{\epsilon'_{cr}}$, (ii) the square of the total trade of each crop averaged over the period 1986–2011, $\overline{W}^2_{cr}$, and (iii) the square of the global average crop water footprint over the same period, $\overline{CWF}^2_{cr}$, i.e.

$$\begin{aligned}\sigma^2_{\mathrm{VWT}} &= \sum_{cr=1}^{cr=4} \sigma^2_{\epsilon'_{cr}} \cdot \overline{W}^2_{cr} \cdot \overline{CWF}^2_{cr} \\ &= \sum_{cr=1}^{cr=4} \sigma^2_{\epsilon'_{cr}} \cdot \overline{\mathrm{VW}}^2_{cr}. \end{aligned} \tag{13}$$

The product between $\overline{W}_{cr}$ (expressed in ton) and $\overline{CWF}_{cr}$ (expressed in $\mathrm{m}^3 \cdot \mathrm{ton}^{-1}$) gives the average water volume virtually embedded in the traded crops, i.e. $\overline{\mathrm{VW}}_{cr}$.

The width of the 90% confidence interval with respect to the distance between the $CWF_{c,t}(Y)$ line and the $\overline{CWF}_{c,T}$ line suggests that assuming constant evapotranspiration over time has less impact on the VWT estimates than the adoption of a time-constant crop water footprint.

4. Conclusion

In this Letter, we demonstrate the feasibility of the Fast Track approach to provide estimates of the temporal variability of crop water footprint. The method is tested by comparing the annual *CWF* country values of wheat, rice, maize, and soybean obtained through the FT approach with those obtained by a detailed model accounting for the changes of yield and evapotranspiration over time. The two estimates compare well with a coefficient of determination close to 1 for all crops. This suggests that inter-annual variations of crop water footprint is mostly driven by yield variability, while the effects of evapotranspiration not embedded in yield variations [16, 47] seem to be marginal when compared to yield, thus confirming the assumption of the FT approach.

To accomplish the assessment of the FT approach, we have evaluated the associated uncertainty due to considering constant evapotranspiration, finding a general low uncertainty of the *CWF* estimates with a standard deviation of the error around 0.1. Such uncertainty is three times lower than that of the model used to estimate the crop water footprint. Finally, the time dependent crop water footprint estimates have been applied to evaluate the virtual water volume associated to the international trade of wheat, rice, maize, and soybean over the period 1986–2011. Comparing this pattern with the one obtained using constant *CWF* values, as previous studies did [26, 28], confirms the importance of including time dependent crop water footprint in the computation of virtual water trade. Our results prove the suitability of the FT approach, which represents a very useful tool thanks to its low computational cost, and its easy and fast applicability.

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