Supporting information for the manuscript

Towards more spatially explicit assessment of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities

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1. METHODOLOGICAL APPROACH

The analysis described in this paper includes a nation-wide assessment of water embedded in the trade of soy and sugar cane at a national and municipal resolution. A tiered approach is used, in which the role of international demand for water resources is analysed at a municipal scale and critical regions are identified (Table 1).

A global water footprint accounting model from Mekonnen & Hoekstra (2011) was adapted from the period 1996-2005 to the period 2001-2011 to reflect changes in production and harvested area at the municipal scale SI. Thereafter, the SEI-PCS model was used to link global consumption with production at the municipal scale. Finally, the virtual water trade of soy and sugar cane were estimated by multiplying the estimated water footprint with the amount of soy and sugar respectively, in each municipality.

In order to estimate the impact of virtual water trade at the local scale, we use a set of high resolution data on water stress and scarcity (ANA 2013). This data is thus used in the analysis to assess potential environmental impacts related to water of the sub-national water footprints.

Table 1 Summary of the three steps combined for the Water Footprint Assessment carried out in this study.

	Water Footprint Accounting	**Material Flow Estimation**	**Water Stress Assessment**
Traditional analysis	Water footprint accounting for the period 1996-2005 [1]	Country-to-country flows [2]	--
This paper´s approach	Water footprint accounting adapted for the period 2001-2011	Spatially-explicit flows [3]	Brazilian Water Agency data for estimating water stress

2. WATER FOOTPRINT ACCOUNTING

This study did not attempt to run one model applying climate, soil and crop data in Brazil for estimating water footprints, but instead it adapted global water footprint results from Mekonnen and Hoekstra (2011) to Brazilian crop footprints beyond the spatial and temporal resolutions of their study. Mekonnen and Hoekstra (2011) quantified the green, blue and grey water footprint of global crop production for the period 1996–2005, estimating the water footprint of 126 crops at a 5 by 5 arc minute grid; this model takes into account the daily soil water balance and climatic conditions for each grid cell. The results from this study are freely available and are widely used by researchers and practitioners worldwide; for example they have been previously applied for estimating Brazilian crop water footprints (Rocha & Studart 2013).

Water footprint flow accounting is sensitive to uncertainties related to precipitation, potential evapotranspiration, temperature, and crop calendar (Zhuo et al. 2014). As the footprints in Mekonnen and Hoekstra (2011) were estimated for the period between 1996 and 2005, not coinciding with the period of analysis chosen for this study, an analysis of the climatic changes between these periods was performed to establish if the climate differences between the two periods are significant, and where these changes are more

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[1] (Mekonnen and Hoekstra 2011)

[2] (Kastner, 2011)

[3] (Godar et al., 2015)

pronounced. Reanalysis gridded climate data were obtained from CRU TS3.21 - Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (University of East Anglia Climatic Research Unit et al., 2013) – and analysed for the periods between 1995-2006 and 2001-2011.

The first step in adapting the water footprint accounting was to aggregate the model results from Mekonnen and Hoekstra (2011) in raster format in the unit of mm/year, to values of water footprint in m^3/year per municipality. This regionalization can be carried out first by multiplying the water footprints in each pixel by the pixel area and then aggregating these values per municipality, as described by Equation 1.

$$\mathrm{WF}[\mathrm{m}^3/\mathrm{yr}] = 0.1 * \sum \mathrm{wf}\left[\frac{\mathrm{mm}}{\mathrm{yr}}\right] * \text{pixel area [ha]} \tag{1}$$

If, however, the pixel sizes are considered reasonably homogeneous within the same municipality, the following equivalence shown in Equation 2 can be considered valid.

$$\sum wf * pixel\ area \cong \sum wf * \sum pixel\ area \cong Total\ area * \sum wf \tag{2}$$

That can be considered the case in Brazilian municipalities, and the equivalence described below was shown to be satisfactory. Thus, In this study we aggregated the values in mm/year by municipality through a zonal statistic function in QGIS and then multiplied by the municipality area available in IBGE (2015), as shown in Equation 3.

$$\mathrm{WF}[\mathrm{m}^3/\mathrm{yr}] = 0.1 * \text{ Mun. Area [ha] } * \sum \mathrm{wf}\,[\mathrm{mm/yr}] \tag{3}$$

Besides the changes in climate, changes in the distribution of crop production in Brazil, the harvested area and consequently the yield were corrected. Equations 4 to 6 demonstrate how the water footprint of a certain municipality in 2011 can be corrected for changes in yield for soy production.

$$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = WF_{1996-2005}^{Soy}\left[\frac{m^3}{yr}\right] * \frac{Yield_{1996-2005}^{Soy}}{Yield_{2011}^{Soy}} \tag{4}$$

$$Yield = \frac{Production}{Harvested\ Area}\left[\frac{ton}{ha}\right] \tag{5}$$

$$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = WF_{1996-2005}^{Soy} * \frac{HA_{2011}}{HA_{1996-2005}} * \frac{Production_{1996-2005}^{Soy}}{Production_{2011}^{Soy}} \tag{6}$$

Where WF is the water footprint in a municipality for a certain period, and HA is total municipal harvested area

In this study, both changes in yield and harvested area were corrected from the period of the model simulation (1996-2005) to the study period (2001-2011). Equation 7 demonstrates the general methodology for correcting for changes in yield and harvested area.

$$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = WF_{1996-2005}^{Soy} * c * \left(1 + \frac{\Delta HA}{HA_{1996-2005}}\right)$$

$$c = \frac{HA_{2011}}{HA_{1996-2005}} * \frac{Production_{1996-2005}^{Soy}}{Production_{2011}^{Soy}} \tag{7}$$

In terms of area, fives typologies of change in harvested area between the two periods can be distinguished (Table 2). While most of the producing municipalities either increased or decreased the harvested area, some municipalities' production for a certain crop dropped to zero, and in a few municipalities where there was no harvested area for a certain crop between 1996 and 2005.

Table 2 Calculation method for updating the water footprints, for each type of change in production between 1996-2005 and 2001-2011.

	Equation
Never Produced and Stopped Production	$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = 0$
Reduced Area and Increased Area	$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = WF_{1996-2005}^{Soy} * c * \left(1 + \frac{\Delta HA}{HA_{1996-2005}}\right)\ c = \frac{Yield_{1996-2005}^{Soy}}{Yield_{2011}^{Soy}}$
Started Production	$WF_{2011}^{Soy}\left[\frac{m^3}{yr}\right] = \left[WF_{1996-2005}^{Soy}\left[\frac{m^3}{yr}\right] * Yield_{1996-2005}^{Soy}\right]_{Average} * \frac{1}{Yield_{2011}^{Soy}}$

For the municipalities for which no footprint was calculated in the 1996-2005 period, and fall in the category of the municipalities that started to produce the commodity between the two periods, the footprint was calculated based on an average of water footprints per ton, and corrected for the yield in that municipality in the year of interest.

Uncertainties Due to Climate Variability

As previously mentioned, water footprint accounting is sensitive to uncertainties related to precipitation, potential evapotranspiration, and temperature (Zhuo et al. 2014). Adapting the results from (Mekonnen & Hoekstra 2010) required first the analysis of climatic changes between the two periods. Reanalysis gridded climate data for temperature and precipitation were obtained from University of East Anglia Climatic Research Unit, (2013) and analysed for the periods between 1995-2006 and 2001-2011.

Changes in the average precipitation and temperature for the two periods were calculated, and a t-student test with 95% of significance level was applied to verify the significance of these changes. Figure 1 shows the average temperature for the two periods (maps on the right) and the difference between the two averages (map on the left); the area with significant changes is highlighted with a dashed line. Figure 2 shows the average precipitation for the two periods (maps on the right) and the difference between the two averages (map on the left); the area with significant changes is highlighted with a dashed line.

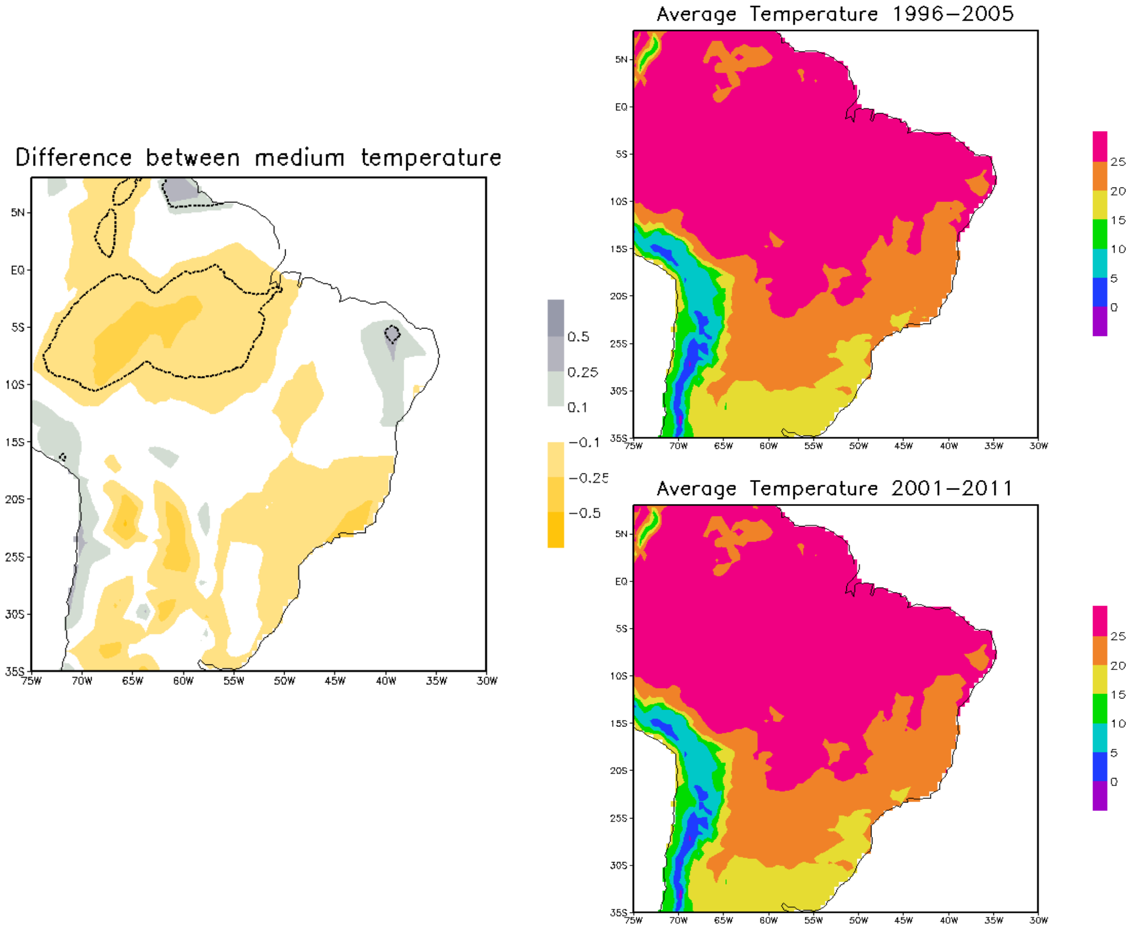

Figure 1 Difference between the medium temperatures in the two periods (left, %) with significance level of 95% in t-student test (dashed line). Average temperature in the 1996--2005 period (above) and in the 2001-2011 period (below) (mm).

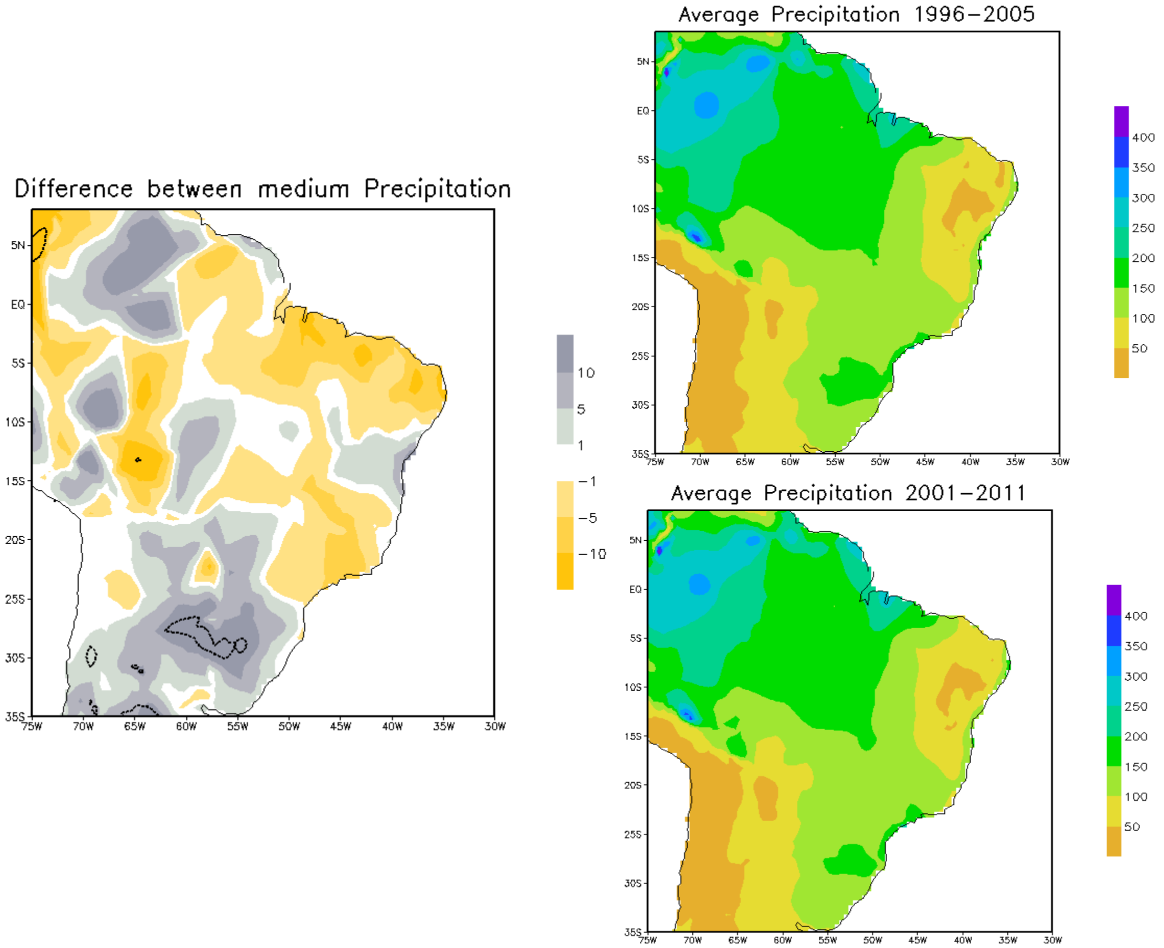

Figure 2 Difference between the medium precipitations in the two periods (left, %) with significance level of 95% in t-student test (dashed line). Average temperature in the 1996-2005 period (above) and in the 2001-2011 period (below) (mm).

Even though by looking to the maps with the average temperature and precipitation for the two periods it is difficult to visualize the differences between the two periods, the maps with the difference between the averages demonstrate the regions with positive and negative changes throughout the country. In terms of temperature, the area with significant positive changes is located in the Amazon basin; this area is likely to have the footprints slightly underestimated for the period of 2001-2011. The changes in precipitation, on the other side, were not significant in most of the country apart from a small region in the south of the country.

3. MATERIAL TRADE FLOWS

The methodology for modelling spatially-explicit trade flows is described at length in Godar et al. (2015). Throughout this paper, soy and sugarcane equivalent are used, and include soybeans, soy cake, soy oil and soy sauce for the soybean crop, and sugar from sugarcane and ethanol for the sugarcane. The traded products defined by the Harmonized Commodity Description and Coding System from the World Customs Organization. Table 3 and Table 4 show the aggregated commodities, their FAO and NCM codes, and their respective conversion factors.

Table 3 Soy NCM trade codes, corresponding FAO codes for traded commodities, calorific content and conversion factor applied to processed soy products to estimate the equivalent tons of soybeans. Obtained from FAO (2001) and FAO (2003).

NCM CODE	FAO CODE	FAO CLASSIFICATION	CONVERSION FACTOR[a]
12010010,12010090, 12011000,12019000	236	Soybean	1
15071000,15079011, 15079019,15121911,15079090	237	Soybean oil	2.639
12081000,23040010,23040090	238	Soybean cake	0.779
21031010,21031090	239	Soy sauce	0.167

[a] Calorific content vs. calorific content of soybean

Table 4 Sugarcane NCM trade codes, corresponding FAO codes for traded commodities, calorific content and conversion factor applied to processed soy products to estimate the equivalent tons of soybeans. Obtained from FAO (2001) and FAO (2003).

NCM CODE	FAO CODE	FAO CLASSIFICATION	CONVERSION FACTOR[a]
17011100|17011400|17019100	156	Sugar Cane	1
17011400|17011100	162	Sugar Raw Centrifugal	7.6077
17019900	164	Sugar refined	7.6077
17011300	167	Sugar nes	7.6077
22071000|22071010|22071090|22072010|22072011|22071019	2207	Ethanol	15.95291

4. WATER STRESS ASSESSMENT

A typology of water criticality was projected based on an indicator of water stress, which made it possible to differentiate water footprints from regions with different degrees of water stress, and identify critical regions. First, the data used to produce these indicators are described, as well as its source and estimation method. Then, the methodology to calculate the three indicators will be described, and the matrix of typologies is demonstrated.

Available Data

The water availability and water demand data were obtained from the Brazilian Water Agency, and the population data was obtained from the National Institute of Geography and Statistics (ANA 2013; IBGE 2011). In 2013 the Brazilian Water Agency (ANA) published the Situation Analysis of Water Resources report, which evaluates the country's water resources in terms of availability, quality, multiple user demand, water conflict resolution and governance (ANA 2013). After the publication of this report, this extensive database of water availability and demand estimated on the micro-basin scale for the entire country was made available. The finer scale data has the spatial resolution of level 12 in the Otto Pfapfstetter catchment coding system (Furnans & Olivera 2001), which results in 168843 polygons with average and maximum area of 5071 and 371245 hectares, respectively.

The Brazilian Water Agency conceptualizes water demand as:

> *"Corresponds to the withdrawal flow, i.e., the water destined to meet diverse consumptive uses. Part of this claimed water is given back to the environment after use, which is denominated as return flow. (...) The non-return water, the consumptive flow, is calculated as the difference between the water withdraw and the return flow".* (ANA 2013)

The water availability, on the other hand, is defined as the $Q_{95\%}$, i.e. the flow in cubic metres per second which was equalled or exceeded for 95% of the flow record, summed to the regularized flow, in case of existence of upstream dams. The water stress indicator estimated by the Brazilian Water Agency is estimated with the same method described by Smakhtin et al. (2004) for estimation of the Water Stress Index (WSI) without consideration of Environmental Water Requirements (EWR).

The indicators of water availability and water demand were obtained in the micro basin level, and were then regionalized to the municipality scale with the use of Geographical Information System analysis. The water stress indicator was calculated both for the municipal and micro basin scale.

For estimation of water stress, a use-to-availability indicator was calculated, by dividing the total water demand by the available water flow in the same area (ANA 2013).

Table 5 shows the thresholds for each class of water stress, based on Raskin et al. (1996).

Table 5 Characterization of water stress use-to-availability ratio (Raskin et al. 1996; adapted from Perveen & James 2011)

Percent withdrawal	Technical water stress
<10	Low water stress
10–40	Medium water stress
>40	High water stress

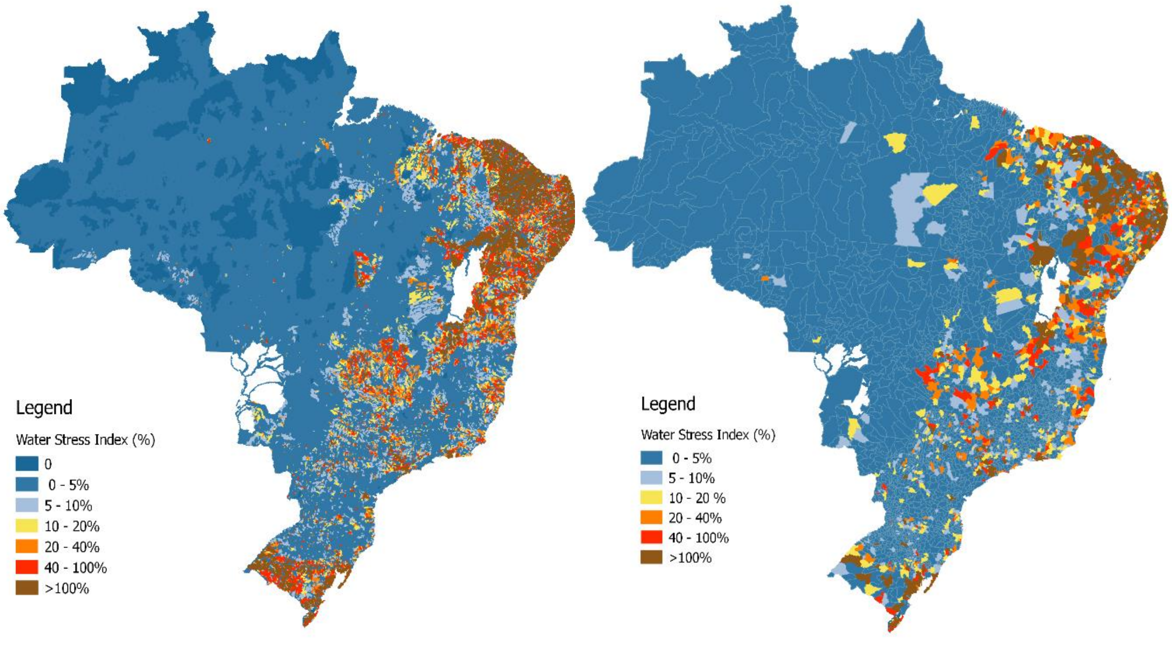

Figure 3 Map of water stress (%) per micro basin (left) and per municipality (right)

Water stress was calculated throughout the country, at the micro-basin and municipality levels (Figure 3). It can be seen that, although low levels of water stress are observed throughout most of the country, there is great variability. Although the water stress indicator outlines the relationship between demand and availability, it does not identify the causes of stress, which might be due to low availability, high demand, or both; it also does not identify which is the main use that determines high demand – industrial, urban, agricultural, etc. The Brazilian Water Agency differentiates, however, between three different main causes of stress, that can be identified in this map: low water availability in the north-eastern semi-arid, high irrigation demand for rice fields in the extreme south, and high urban demand in the main metropolitan regions, mainly in the southeast (ANA 2013).

It can be observed that finer scales provide significantly more relevant information in terms of assessment of water stress, and the use of aggregate national and regional averages can mask local scarcity found in some cities and metropolitan areas. It can also be observed, when comparing basin-level and municipal indicators, that some regions with high water stress when analysed in basin scale are perceived to have less stress on the municipal scale; this happens as a result of the fact that, when regionalizing water availability throughout the municipality area, the flows from one or more water-abundant areas within the municipality are summed to the general municipal water availability. This implies that water can be transported from more abundant to scarce basins within the municipality to other more scarce areas, which might not be the reality.

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