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The effects of cropping intensity and cropland expansion of Brazilian soybean production on green water flows

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Abstract

As land use change alters how green water is appropriated, cropland expansion is instrumental in re-allocating green water towards agriculture. Alongside cropland expansion, agricultural intensification practices modify crop water use and land and water productivity. Particularly, one form of agricultural intensification known as multi-cropping (the cultivation of a piece of land sequentially more than once a year) can result in greater agricultural output per unit of land, as well as more productive use of the available water throughout the annual rainfall cycle. We assess the influence of these two processes, cropland expansion and agricultural intensification, in agricultural green water use in Brazilian agriculture. We applied the biophysical crop model Environmental Policy Integrated Climate (EPIC) to estimate green water use for single and double cropping of soybean (*Glycine max*) and maize (*Zea mays*) in Brazil. The first part of our study analyses changes in soybean green water use and virtual water content nationwide between 1990 and 2013, and in a second part we look into the effect of double-cropping on water use for soybean and maize in the Brazilian states of Paraná and Mato Grosso between 2003 and 2013. The results show that cropland expansion plays a more prominent effect in green water use for production of soybean than intensification, and harvested area increase was responsible for the appropriation of an additional 95 km^3 of green water in 2013 when compared to 1990, an increase of 155%. We estimate that an additional green water use of around 26 km^3 related to second season maize was appropriated through increase of cropping frequency, and without expansion of cropland, in 2013 in the selected states. We discuss the importance of considering multi cropping practices when assessing green water sustainability, and the importance of differentiating green water appropriation through expansion and through cropping frequency changes.

1. Introduction

One of the main limitations for the increase in agricultural production in the future, to meet increasing demands for food, feed and biomass, is the availability of water and land resources. Agriculture is already by far the largest consumer of water and land resources worldwide (Ellis and Ramankutty 2008, Rost, Gerten and Heyder 2008). Furthermore, agricultural production and related cropland expansion has been one of the main drivers of habitat and biodiversity loss worldwide (Gibbs *et al* 2010, IPBES 2019).

Availability of blue and green water, here defined respectively as surface or groundwater available for irrigation, and precipitation water available in the soil (Hoff *et al* 2010), is highly controlled by location. Global crop production depends mostly on green water, and it is estimated that food production consumes about

4–5 times more green than blue water (Hoff *et al* 2010). Still, agriculture accounts globally for around 70% of total anthropogenic blue water consumption (Wisser *et al* 2008). Increasing limitations to expansion of irrigation, i.e. appropriation of blue water, is evidenced worldwide both by a growing number of river basin 'closures' (Falkenmark and Molden 2008) and overuse of non-renewable groundwater resources (Wada and Bierkens 2014). As any expansion of agricultural land also increases the appropriation of green water, cropland expansion is instrumental in re-allocating green water towards agriculture, or towards one certain type of agricultural production (Ridoutt and Pfister 2010, Quinteiro *et al* 2015, Schyns *et al* 2019). The availability of green water is limited, however, in absolute terms by precipitation regimes, and in relative terms by limits to cropland expansion for protection of ecosystems and their services (Schyns *et al* 2015, 2019).

The way green water is consumed in agricultural land is not only influenced by cropland expansion, but also by agricultural management. Agricultural intensification that results in yield increases changes the water productivity (here defined as amount of crop obtained per drop of green water used, in units of crop weight by volume of water) of agricultural regions (Rockström and Barron 2007). One of the forms of agricultural intensification is multi-cropping. Even though the multi-cropping concept can refer to a range of agricultural practices, in this manuscript we will focus on double-cropping, where two crops are harvested sequentially in a calendar year (Borchers *et al* 2014). Even though the same crop can be harvested twice sequentially, in some cases this practice can be considered a phytosanitary risk (Garcia *et al* 2015). The average number of crops harvested sequentially per year is defined as cropping intensity (Siebert *et al* 2010).

Globally, the regions where crops are usually harvested two or more times per year are situated in highly populated, often irrigated tropical or subtropical lowlands (Siebert *et al* 2010). The proportion of cropland with double-cropping was 2% in the United States between 1999 and 2012 (Borchers *et al* 2014), around 35% in 2005 in India (Biradar and Xiao 2011), and 34% in 2002 in China (Yan *et al* 2014). Even though each crop grown in a multi-cropping system might have equal or even lower yields than in single-cropping systems, the overall annual productivity of the land, measured in kg ha^{-1} yr^{-1}, increases as a result of an increase in cropping frequency (Guilpart *et al* 2017).

Between 2000 and 2010, harvested area grew roughly four times faster than cropland area globally (Ray and Foley 2013), and global harvest areas could be further expanded by up to 37.5% of current global cropland by closing cropping frequency gaps (Wu *et al* 2018). Beyond the effects on agricultural production, multiple cropping practices have different effects on the Earth system: satellite data has shown that multiple cropping practices were responsible for a large observed increase in leaf area, mainly in India and China (Chen *et al* 2019). Nevertheless, cropping frequency and multiple-cropping practices are commonly not explicitly taken into account in global water footprint assessments (Hanasaki *et al* 2010, Liu and Yang 2010, Mekonnen and Hoekstra 2011), and when assessing limits to appropriation of green water (Schyns *et al* 2015, 2019). Data sources like the FAO database (FAO 2019) contain annual production and annual harvested data, allowing for cropping frequency to be implicitly taken into consideration in some of the studies mentioned above.

In Brazil, the development of soybean varieties with more flexible planting dates and cycle length options allowed farmers to plant a second crop after soybean in the same field (Pires *et al* 2016). Double-cropping is the most common type of multi-cropping practice in Brazil, usually in soybean-maize or soybean-cotton forms of production (Abrahão and Costa 2018). Although the soybean-cotton and soybean-soybean combinations are also used, the soybean-maize double-cropping mode is by far the most common form of double-cropping in Brazil (Abrahão and Costa 2018), and the focus of this manuscript. The harvested area with second season maize reached around 8 million hectares (IBGE 2017), and around 58% of Brazilian maize was planted as a second crop in 2015 (Pires *et al* 2016). In the state of Mato Grosso, the proportion of the cultivated area harvesting two successive crops increased from 6% to 30% in only six years (Arvor *et al* 2014).

The objective of our study is to estimate and evaluate the influence of expansion and intensification in water use associated to soybean production in Brazil, and to analyse the particular influence of double-cropping in conjunction with maize on water use. The first part of the analysis is focused on the effect of expansion and intensification on soybean production in Brazil from 1990 to 2013. In the second part of this article, we present a case study of water use of soybean and maize in single and double-cropping soybean-maize systems in the states of Paraná and Mato Grosso. We selected these states for detailed analyses because they have the highest soybean production and rates of double cropping. Around 48% of the country's soybean were produced in these two states, and 65% of their maize production occurred as a second crop in 2013 (IBGE 2017).

Here we assumed all single and double-cropping production to be rainfed, and therefore we focused only on green water use. Although there are areas in Brazil where irrigated production occurs, this is not the case for most of the country's soybean production; only 3.7% of the harvested area is irrigated (ANA 2017, FAO 2017). Furthermore, by modelling rainfed conditions we could also investigate the relationship between production, water use, and precipitation variability in these agricultural production systems.

Finally, we discuss the importance of cropping frequency in the estimation of green water use, and identify the ways in which not considering these management practices biases the accounting of water use and footprints,

Table 1. Summary of all the data sources used to produce the results presented in this article, and in which phase of the analysis each dataset was used.

Type	Source	Application
Weather	Daily gridded meteorological variables in Brazil (1980–2013) (Xavier *et al* 2016).	Model input
Soil	SoilGrids250: Global gridded soil information based on machine learning (Hengl *et al* 2014).	Model input, simulation unit delimitation
Terrain	SRTM 90 m Digital Elevation Database v4.1 (Jarvis *et al* 2008).	Model input, simulation unit delimitation
Land Use	Patterns of land use, extensification, and intensification of Brazilian agriculture (Dias *et al* 2016).	Simulation unit delimitation
Agricultural Production	SIDRA Database—Brazilian Institute for Geography and Statistics (IBGE 2017).	Simulation unit delimitation, result Analysis
Crop Calendars	Planting windows for single- and double-crop soy in Brazil (Abrahão and Costa 2018)	Model Input
	Data set of global crop planting and harvesting dates (Sacks *et al* 2010).	

and the implications these biases could have in the assessment of the sustainability of green water use. The results presented here provide insights to the importance of cropland expansion to appropriation of green water resources, as well as the importance of management for the better use of these resources.

2. Methods

2.1. Data sources

Table 1 describes the data sources used in this study, and the part of the methodology in which they are used.

2.2. Water use indicators

Water use indicators were calculated based on statistics for harvested area and crop production, combined with crop water use estimated with the Environmental Policy Integrated Climate (EPIC) crop model (see section 2.3). The model provides the actual growing season evapotranspiration (GSET) for each simulation unit, crop, and cropping cycle. The GSET per municipality was calculated as the area-weighted average of the GSET values in the simulation units within the municipality. In each municipality, the total green water use per year (GWU) is calculated as:

$$GWU = 10^{-8} * GSET * Harvested\ Area \tag{1}$$

Where GWU is the annual green water use in each municipality in km^3, GSET is given in millimeters, and the harvested area in that municipality in hectares. To aggregate the water use to the state, regional and national levels, we sum up the crop specific water use in km^3 for each municipality within these spatial units. Figure S1 is available online at stacks.iop.org/ERC/2/071001/mmedia shows the division of the country in states and regions.

The terms 'water use' and 'water footprints' have been used in the scientific literature to refer to various indicators of water embedded in crop production, whether it is embedded per unit of product, per area, or same as herein as an indicator of total volumetric water use (Mekonnen and Hoekstra 2011). Here we refer to green water use as an indicator of volumetric water use by crops, as this is most suitable to analyse contrasting impacts of land expansion and cropping intensity.

To calculate the virtual water content (VWC, $m^3\ ton^{-1}$) on different spatial units, we divided the GWU in that spatial unit by the total amount of crop produced in that area in that year. Here we use the definition virtual water content as the inverse of water productivity, as it was applied previously by, among others, Fader *et al* (2010), Hanasaki *et al* (2010) and Liu (2009). Consequently, a reduction in virtual water content means that there is an increase in water productivity. We chose to display our results with this particular indicator to facilitate comparison with previous work, namely Lathuillière (2011) and Tuninetti *et al* (2017).

$$VWC = 10^{9} * GWU/Production \tag{2}$$

Where VWC is given in $m^3\ ton^{-1}$, GWU in km^3, and 'production' refers to the municipal production of that crop in that year, in tonnes. The average annual crop evapotranspiration in a spatial unit corresponds to:

$$ACET = 10^{-8} * GWU/Harvested\ Area \tag{3}$$

Where ACET is given in millimetres, GWU in km^3, and harvested area in hectares. This indicator represents the area-weighted evapotranspiration cycle of the two crops (alone or in combination) during their cropping season, and excludes soil evaporation outside of the cropping season, or cover crops.

The data on harvested area and production for each crop and municipality was obtained from the SIDRA Database of the Brazilian Institute for Geography and Statistics (IBGE 2017). Crop models have limitations in reproducing reported yields, especially over time, due to lack of spatially and temporally explicit use of agronomic inputs such as fertilizer and exogenous stresses such as pests (see section 2.3). To estimate resource use intensity we used instead statistical data, which also reflect changes in nutrient inputs and pest management. The use of a process-based crop model is still important, as it considers the complete soil hydrology including runoff, percolation, and water storage capacity as opposed to simpler water balance models typically used in remote-sensing or inventory data-based assessments.

The data on harvested area and production of second season maize is only available after 2003. We assumed here that all harvested area overlap between soybean and second season maize corresponds to harvested area of double-cropping soybean, and the remaining is considered single-cropping soybean harvested area. Even though there are no national data on systems with specific multi-crop combinations, we assumed this based on the fact that the soybean-maize crop pair is the most common kind of double-cropping in Brazil (Abrahão and Costa 2018).

2.3. Estimation of crop water use

We use the crop model Environmental Policy Integrated Climate (EPIC) (Williams *et al* 2015) to simulate evapotranspiration in soybean and maize production in Brazil for single and double cropping systems. Albeit the estimation of crop yields is a main purpose of crop models, the accuracy at large scales is often highly limited due to lack of suitable data for calibration, lack of spatially explicit management data, and exogenous factors affecting yields such as pests and diseases, which are typically not represented in crop models. Hence, we opted to use the crop model for estimating crop water requirements while relying on reported production statistics.

We classified the Brazilian territory in more than 80 thousand simulation units, and set up the model input based on the assumption that these units are homogeneous in terms of elevation, slope, soil hydro and physical properties, as well as agricultural management (Skalský *et al* 2008).

We designed three different model simulation setups, for (i) single-cropping system soybean, (ii) single-cropping system maize, and (iii) soybean and maize grown in a double-cropping system. When we refer to single-cropping soybean and maize, we refer to these crops when they are harvested independently, as single crops. When we refer to 'double-cropping soybean' and 'double-cropping maize', we refer to soybean as grown as a first crop, and maize as a second crop in a double-cropping succession. The maize harvested after soybean is also called second season maize. Finally, when we refer to the 'double-cropping system', we are referring to the overall biophysical properties of the two consecutive crops together.

The water use was calculated with the use of the estimated growing season evapotranspiration (GSET) of the selected crops. As these results are highly dependent on the start and duration of the cropping season, we analysed the sensitivity of the model results to these two factors. Within the EPIC model it is possible to choose from five different methods for calculating potential evapotranspiration; here we used the Hargreaves method (Hargreaves and Samani 1985). We also tested the sensitivity of the model results to the chosen evapotranspiration estimation method (see figures S6 to S9).

The crop calendars for soybean and soybean-maize production were obtained from the dataset of planting windows for single- and double-cropping system soybean in Brazil (Abrahão and Costa 2018), while the calendars for maize production was obtained from the dataset of global crop planting and harvesting dates (Sacks *et al* 2010). We set up scenarios of planting and harvesting dates based on these calendars, performed a sensitivity analysis of these calendar scenarios, and selected the calendar options that yielded the highest overall productivity. EPIC uses daily accumulated heat units to regulate crop growth, and requires an estimation of potential heat units (PHUs, °C) accumulated by a crop from sowing to maturity. We calculated the PHUs based on the planting and harvesting dates, and the available climate data.

Due to the complexity of Brazilian agriculture and Brazil's geographical heterogeneity, simplifications were necessary in our EPIC modelling approach. We did not consider the effect of tillage and pest control, and the cultivar parameters were considered homogeneous for the entire territory. In order to isolate the effect of rainy season length and evapotranspiration on the crops, we assumed minimal levels of nutrient stress in our modelling approach, and allowed the model to implement automatic fertilization with a trigger of 20% of nutrient stress. This methodology was designed to better account for geographical variability by identifying the most appropriate range of planting and harvesting dates within the pre-defined planting windows from the input datasets. It is also important to highlight that we only considered here water quantities, and did not take into consideration changes in water quality that could result from agricultural management and intensification.

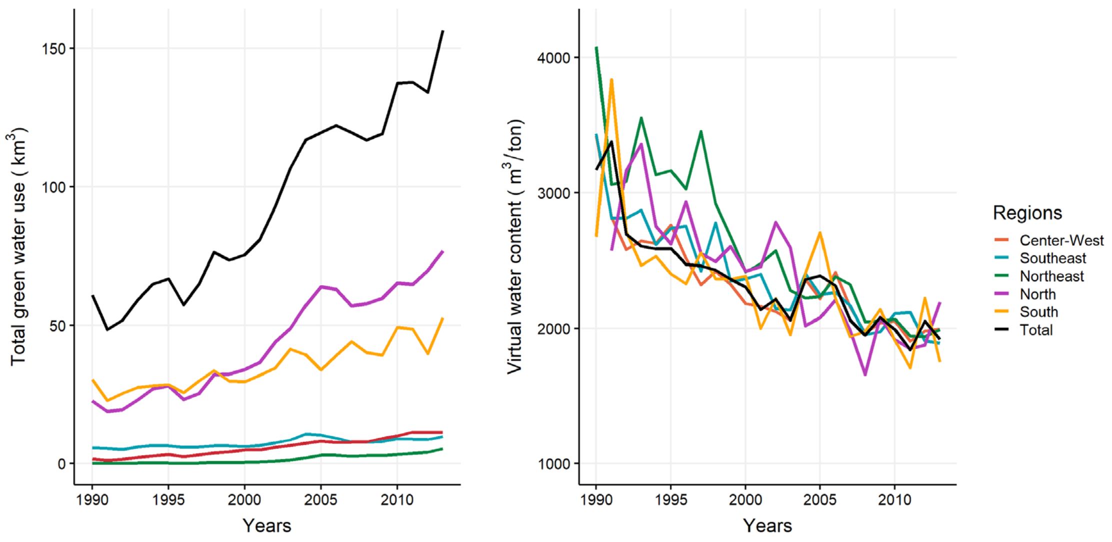

Figure 1. Time series of total green water use for production of soybean (left, km^3) and of virtual water content (right, m^3 ton^{-1}) for Brazil, between 1990 and 2013.

Section 2 of the supplementary material presents more detailed information on the EPIC model, the data sources used in this study, the methods used to delimitate the simulation units, the crop calendars, the calculation of the potential heat units, and a flowchart explaining all components of the model simulation (figure S5). Section 3 of the supplementary material provides greater insight on EPIC's methodology for estimation of evapotranspiration, and sensitivity of our model setup to different calendar options and potential evapotranspiration methods.

3. Results

3.1. Effects of expansion and intensification on soybean green water use across Brazil

With the use of the annual GSET estimations, we evaluated the evolution of the total green water use and virtual water content for production of soybean between 1990 and 2013. In order to analyze solely the effect of expansion and productivity improvements, we assumed all soybean were grown in single-cropping systems, and analyzed intensification only through the changes in yields. Figure 1 shows the changes in green water use in km^3 for all Brazilian macro-regions, as well as the virtual water content of soybean in m^3 ton^{-1}, between 1990 and 2013.

The overall growth in green water use for soybean production happened mostly as a consequence of cropland expansion, accompanied with a steady increase in water productivity. The most dramatic changes happened in the center-west and south regions of the country, where most of the cropland expansion occurred in the period of analysis. The reduction in virtual water content—and therefore increase in water productivity - was observed consistently across all regions, reaching an average value around 2000 m^3 ton^{-1}, similar to values previously reported for Brazilian soybean (Hanasaki *et al* 2010, Tuninetti *et al* 2017).

In order to further illustrate the differentiated influence of expansion and intensification on water use and productivity, figure 2 shows the relative changes in use and use intensity of land during this period. The increase in land and water productivity results in a de-coupling between the increases in harvested area and water use, and the increase in production. While the output of soybean grew 308% during this period, the harvested area and water use increased 143 and 156%, respectively. The virtual water content was reduced by 37%. It is possible to see in the graph as well that harvested areas are increasing much faster than yields, especially after 2003. This further highlights the role of cropland expansion in increasing green water appropriation for the production of this crop.

3.2. Water use under single and double cropping systems in selected states

In this section we assess the accounting of green water use considering the increase of double-cropping systems in the states of Paraná and Mato Grosso between 2003 and 2013. The results for the entire country can be found in section 3 of the Supplementary Material.

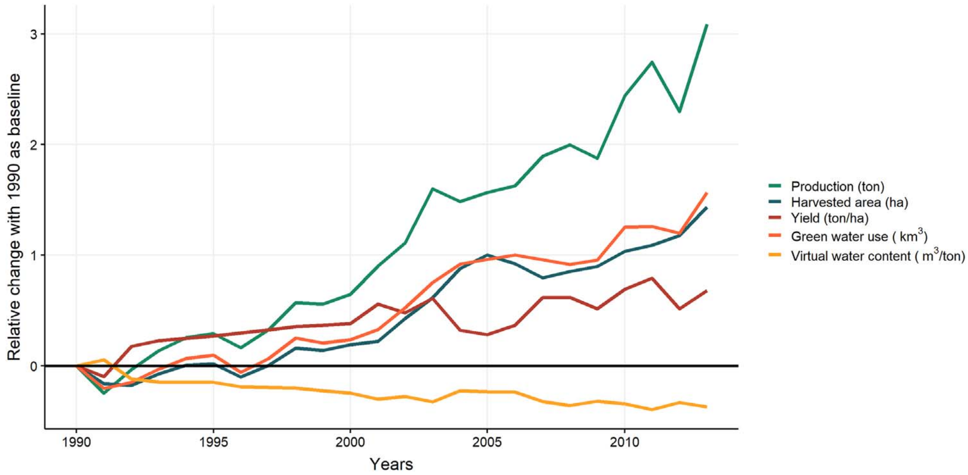

Figure 2. Relative change for production, harvested area, green water use and virtual water content for soybean production in Brazil, between 1990 and 2013 using 1990 as the baseline.

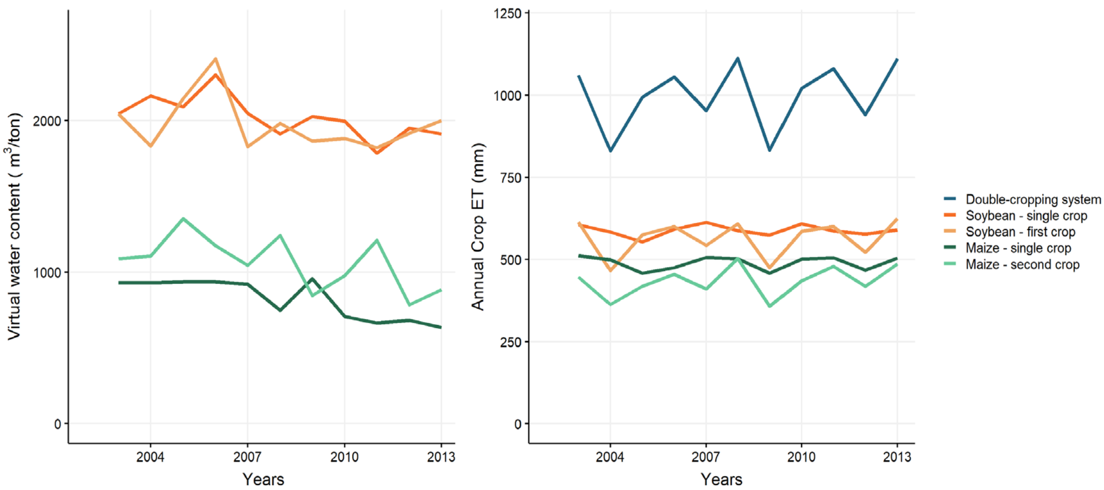

Figure 3. Virtual water content (m^3 ton^{-1}, left) and annual crop evapotranspiration (mm, right) for single and double-cropping soybean and maize in Paraná and Mato Grosso. Here, 'single-cropping' maize and soybean refer to simulations in which these crops were grown in single-cropping systems. 'Double-cropping' maize and soybean refers the simulations in which these crops were grown in double-cropping systems, where maize is planted after soybean. 'Double-cropping system' refers to the total ACET of the two crops harvested sequentially in a double-cropping system.

3.2.1. Water productivity

The growing season evapotranspiration for double-cropping crops are in general lower due to a shorter cropping season, and presents higher interannual variability (figure 3, figure S12). The virtual water content, on the other hand, is influenced both by the crop evapotranspiration and land productivity. In the states of Mato Grosso and Paraná, the water productivity of soybean is rather similar for the two cropping practices, as a result of both similar yields and similar water use. That is not the case at the national scale, as yields in areas with high rates of double-cropping tend to be higher than the national average (figure S13). In the case of maize, the VWC of single-cropping maize is lower due to the fact that single-cropping maize yields in these states are outstandingly high when compared to the yields for second season maize, as well as with the national average (figure S2).

By taking better advantage of the length of the rainy season, double-cropping systems increase the crop evapotranspiration across the annual cycle (see figure S15). We found that the average ratio between the growing season evapotranspiration and the total crop annual evapotranspiration for single-cropping soybean and maize are similar, and around 0.6, while the ratio for double-cropping systems is in average around 0.9 (figure S16).

3.2.2. Evolution of resource use

The total green water use for soybean and maize is the sum of the water use of both crops cultivated sequentially in the two cropping seasons (figure 4). The total water use of soybean and maize increased by 40 (from 70 to 110) km^3

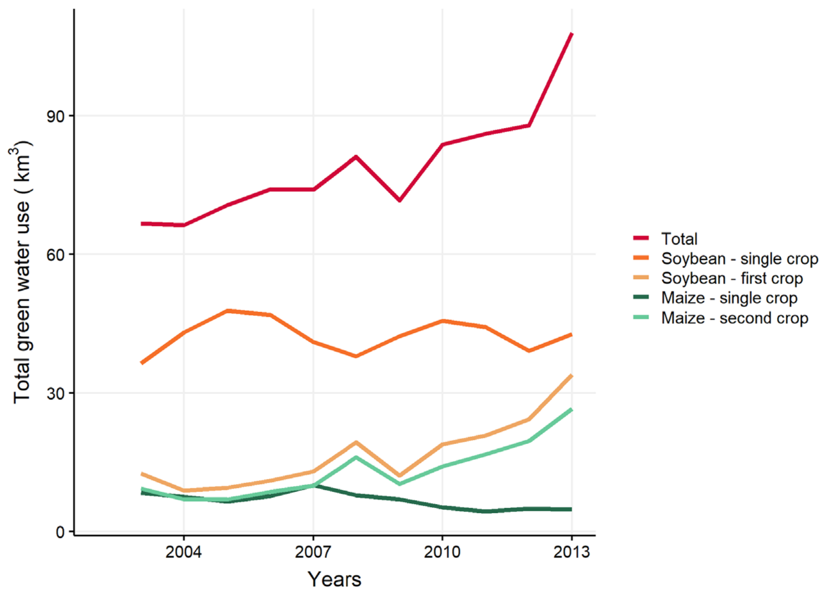

Figure 4. Total green water use (km^3) estimates in Mato Grosso and Paraná for soybean and maize as single crops or combined for double-cropping conditions.

between 2003 and 2013 in the two states. Out of this increase, 13 km^3 (32%) happened in areas with double-cropping systems. In 2013, second season maize was responsible for 26 km^3 of the green water use. As a consequence, a large share of the additional green water resources appropriated in the two states during this period was a result of changes in cropping intensity, and not a result of cropland area expansion.

The consideration of cropping intensity did not only influence the relationship between water and land resources, but also influenced the estimation of water use for each of these crops. This is a result of the fact that the growing season evapotranspiration for crops in multiple-cropping systems tends to be shorter, in order to fit the rainy season (see figures 3 and S12). The final effect in the water use accounting in this case is a smaller overall use when considering double-cropping. In the context of this study, considering double-cropping systems resulted in values of annual total water use 0.5%–20% lower than under assumed single-cropping calendars.

4. Discussion

4.1. Soybean production: larger green water use, higher water productivity

Brazil is a world leader in production and export of agricultural products, and one of the world's main virtual water exporters (Dalin *et al* 2012, da Silva *et al* 2016). The country's agricultural sector has undergone substantial changes in the last decades, at the same time modernizing and expanding its cropland area (Dias *et al* 2016, Zalles *et al* 2019). That is particularly the case for soybean and maize, the country´s two most prominent rainfed crops. Soybean production has been at the forefront of these changes, being responsible not only for a large share of the cropland expansion, but also of the expansion-related deforestation (Gibbs *et al* 2010, 2015) and impacts on the water resources (Hunke *et al* 2015, Spera *et al* 2016).

The results presented here demonstrate that the expansion of soybean production is connected to an increase from 61 to 156 km^3 in green water use during the same period. The additional appropriation of around 95 km^3 of green water was enabled by the increases in harvested area observed in this period (figure 1). Most of this additional resource constitutes green water that became available to the international market, as a large share of this production is intended for the external markets in the European Union and China (Godar *et al* 2015, Flach *et al* 2016).

Our results demonstrate a decrease in the virtual water content from 3045 to 1913 m^3 ton^{-1} between 1990 and 2013. This result resembles closely the decrease in virtual water content estimated by Tuninetti *et al* (2017) for global soybean production, and by (Lathuillière 2011) for soybean production in Mato Grosso, Brazil.

4.2. Cropping frequency and improving agricultural water use assessments

Explicitly accounting for double-cropping practices results in more realistic assessments of water use, the relationship between water and land use, as well as the limits to availability of water for agriculture. Given the high levels of multi-cropping practices in the tropics (Biradar and Xiao 2011, Yan *et al* 2014, Zhao *et al* 2016) and the growth of these practices in other regions of the world (Borchers *et al* 2014, Estel *et al* 2016), it is important to consider the biases implied in not considering these practices. Here we identified some of the ways in which overlooking multi-cropping practices can generate uncertainty, or reduce the relevance of water use assessments.

One source of uncertainty is derived from the diversity of planting and harvesting calendars. As demonstrated in our study, evapotranspiration values are very sensitive to the start and length of the cropping season (section 3.a in Supplementary Material), which was also identified by Tuninetti *et al* (2015). We found that growing season ET values vary both due to differences in the length or the start of the cropping season, but also due to inter-annual variability (figure 3). The overall error in estimating the total green water appropriation for the states of Mato Grosso and Paraná ranged between 0.5 and 20%, depending on the year.

The annual crop evapotranspiration in a double-cropping system in a given area is the sum of the growing season evapotranspiration for the two crops, and consequently the water use per unit of area is significantly higher than for any of the other single crops on their own (figure 3). Calculating the annual crop evapotranspiration of these two crops as single-crops, the average annual evapotranspiration of the soybean and maize production across the territory of the two states would be around 560 mm/year. However, by considering the mixture between single- and double-cropping systems, the average annual crop evapotranspiration corresponds to around 685 mm/year.

Another source of bias is related to how the relationship between crop evapotranspiration to total evapotranspiration is accounted. Values previously reported in the literature range from 0.6 (Hanasaki *et al* 2010) and 0.8 (Liu and Yang 2010). We found the values for the single crops to be very similar, of 0.6 for the single crops, but that in the Brazilian double-cropping soy-maize system this value can reach much higher values, approaching an average of 0.9.

4.3. Implications for green water sustainability

The results we discussed in the previous sections have implications also for the analysis of green water scarcity, and how we understand the limits to green water availability. As green water is accessed through land use change, additional cropland area can be seen as expansion of green water appropriation for a certain activity, either by conversion of natural ecosystems or by conversion of other land use purposes. Expansion of agriculture into areas with 'unused green water flows', and closing the cropping frequency gap, are two of the main ways of tapping into unused green water sources (Wu *et al* 2018, Schyns *et al* 2019).

The main contribution of the water use assessment presented in this manuscript is to demonstrate the importance of differentiating the green water appropriation that happens through cropland expansion, and through changes in cropping frequency. Our results show that in 2013, 24% of the total use for that year (26 km^3) was dedicated to second season maize in the two selected states. This means that around a quarter of the additional green water resources appropriated in this period in the two states required no expansion in cropland area.

Green water is of particular importance when analysing the relationship between cropping intensity and the use of water resources due to its connection with land use, as shown in this study. However, cropping intensity can affect the use of blue water resources in several ways as well. The improvement of green water management and productivity has been identified as one possible avenue to increase global food production while alleviating the intensity of the use of blue water resources (Rockström *et al* 2009, Rost *et al* 2009). On the other hand, precipitation is often a major limitation for tropical multi-cropping systems, and the increase in blue water use and infrastructure is touted as one of the requisites to increase the resilience of these multi-cropping systems (Abrahão and Costa 2018, Wu *et al* 2018). Accordingly, one important future avenue of investigation is to understand the quantitative balance between the potential increase in blue water demand under multi-cropping, and the resulting changes in overall water productivity.

While our study provided an assessment of the volumetric water use changes in single and double-cropping systems, it did not further investigate the potential environmental impacts of the green water use (Lathuillière *et al* 2018). Land use change affects the partitioning of blue and green water and the local moisture recycling capacity, its impacts depend on what type of potential natural vegetation or previous land use was replaced (Quinteiro *et al* 2015).

5. Conclusions

In this paper we presented an assessment of water use for Brazilian soybean and maize taking into account the role of expansion and intensification processes, with special attention to the effects of double-cropping practices. We verified the influence of area expansion in green water use, observing an increase of 143% and 156% in soybean harvested area and water use, respectively. During the same period, the virtual water content was reduced by 37%, demonstrating the role of yield improvements on a more productive use of water resources throughout the country.

We demonstrate the application of a study case considering the effects of double-cropping practices on water use. Our results show that several biases can be found when not considering multiple-cropping practices when assessing crop water use, especially regarding the relationship between land and water use. We find that a sizeable share of the additional green water use appropriated in the study period was a result of changes in cropping frequency, rather than cropland expansion. We make a case for further investigation of the importance of cropping frequency on the sustainability and on the limits to green water use. However, we highlight that further investigation is necessary to investigate the locally-specific environmental impacts of these practices on water flows.

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