# Assessment of potential implications of agricultural irrigation policy on surface water scarcity in Brazil

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**Abstract.** Expanding irrigated cropping areas is one of Brazil's strategies to increase agricultural production. This expansion is constrained by water policy goals to restrict water scarcity to acceptable levels. We therefore analysed the trade-off between levels of acceptable water scarcity, and feasible expansion of irrigation. The appropriateness of water use in agricultural production was assessed in categories ranging from acceptable to very critical based on the river flow that is equalled or exceeded for 95% of the time (Q95) as indicator for physical water availability. The crop water balance components were determined for 166,842 sub-catchments covering all of Brazil. The crops considered were cotton, rice, sugarcane, bean, cassava, corn, soybean and wheat, together accounting for 96% of the harvested area of irrigated and rainfed agriculture. On currently irrigated land irrigation must be discontinued on 54% (2.3 Mha) for an acceptable water scarcity level, on 45% (1.9 Mha) for a comfortable water scarcity level and on 35% (1.5 Mha) for a worrying water scarcity level, in order to avoid critical water scarcity. An expansion of irrigated areas by irrigating all 45.6 Mha of rainfed area would strongly impact surface water resources, resulting in 26.0 Mha experiencing critical and very critical water scarcity. The results show in a spatially differentiated manner that potential future decisions regarding expanding irrigated cropping areas in Brazil must, while pursuing to intensify production practices, consider the likely regional effects on water scarcity levels, in order to reach sustainable agricultural production.

## 1 Introduction

In 2013 the Brazilian government took a step towards the consolidation of a national irrigation policy through the enactment of Law 12,787 (www.planalto.gov.br/CCIVIL_03/_Ato2011-2014/2013/Lei/L12787.htm), with two of the objectives being to encourage the expansion of irrigated areas and to increase productivity on an environmentally sustainable basis. According to

Law 12,787, policy implementation would have to be based on regional and national plans estimating expansion potential and indicating suitable areas for prioritisation of public investments. However, to date, a national plan has not yet been developed and the official study available to support the plan is expected to be fully reviewed in 2019 (FEALQ-IICA-MI, 2015). Underlying policy goals include to strive for equitable socio-economic development (VanWey et al., 2016), for a continued large role of biofuels in national energy production and for a strong agricultural sector serving national and international demands of commodities such as soybean (Dalin et al., 2012). One of the governing principles in this policy is the sustainable use and management of land and water resources for irrigation, thereby not negatively affecting communities or sacrificing water resources, unique ecosystems and the services they provide (Alkimim et al., 2015; Castello and Macedo, 2016; Lathuillière et al., 2016).

The extent to which irrigation is a suitable measure to achieve these goals is debated in the literature. Both Fachinelli and Pereira (2015) and Scarpare et al. (2016) find that in the Paranaíba river basin, covering about 25% of the Brazilian Cerrado biome, irrigation increases sugarcane yield, in particular in projected expansion areas, but also in the central region of the basin where sugarcane production is already established. Irrigation shows potential to reduce costs, thereby enhancing the economic viability of sugarcane expansion. Yet both studies caution not to compromise available water resources and hence to restrict irrigation practices to areas where water is sufficiently available, which, according to Scarpare et al. (2016), generally corresponds to most of the central and western portions of that basin. In a study on the Amazon region Lathuillière et al. (2016) identify that the best land-water management would be one that intensifies agricultural production by expanding cropland into pasture and considering irrigation, while avoiding conflicts with downstream users such as electricity production and reducing pressure on aquatic ecosystems in the Amazon Basin. The expansion of rain-fed agriculture in Southern Amazonia is known to reduce water vapour supply to the atmosphere (Lathuillière et al., 2018). Lathuillière et al. (2018) note that this effect could slow down or be reversed by an increase in vapour supply to the atmosphere following widespread irrigation, but not without consequences on surface or groundwater resources.

The Cerrado in central Brazil with a savannah climate is a region with both a strong trend over the last several years of advancing large-scale agribusinesses for agriculture and livestock, and potential for more sustainable land management (Dickie et al., 2016). For example, Alkimim et al. (2015) propose that it is possible to expand sugarcane production in Brazil by converting existing pasturelands into cropland without further environmental losses, whereby they estimate that an area of 50 Mha is moderately or highly suitable for sugarcane production. In another study, Strassburg et al. (2014) assess that current productivity of Brazilian cultivated pasturelands is one third of its potential, and that increasing the productivity to one half of the potential would suffice to meet national demands for meat, crops, wood products and biofuels until at least 2040, thereby avoiding additional conversion of natural ecosystems. Sparovek et al. (2015) analyse comprehensive scenarios with a spatially explicit land-use model for Brazilian agriculture production and nature conservation. They find that a substantial increase in crop production, using an area 1.5-2.7 times the current cropland area, is feasible with much of the new cropland being located on current pastureland.

Land use and land management affect the utilisation of water resources, so every strategy and decision with respect to land is also a strategy and decision with respect to water. This holds for both the precipitation-supplied water stored in the soil matrix (termed green water) and the water in streams, lakes, wetlands and aquifers (termed blue water) (Falkenmark, 1995). While Brazil may be considered well-endowed with water resources, these resources are unevenly distributed across the country. Hence, efficient, sustainable and equitable strategies must be developed, thereby considering the spatially and temporally varying water availability. To that end, Getirana (2016) points out that ineffective energy development and water management policies in Brazil have magnified the impacts of recent severe droughts, which include massive agricultural losses, water supply restrictions, and energy rationing.

Metrics of water scarcity and stress have evolved from simple threshold indicators to holistic measures characterising human environments and freshwater sustainability (Damkjaer and Taylor, 2017). The Brazilian national water agency ANA (Agência Nacional de Águas) uses blue surface water availability in operational management, whereby the river discharge, partly delivered by regulated reservoir flows, is compared to water withdrawals. ANA distinguishes water scarcity classes based on the risk of river flow to fail to support environmental services (ANA, 2015).

In studying possible expansion of irrigated areas, as encouraged by the Brazilian Government under Law 12,787, this paper addresses the trade-off between the choice of the level of blue water scarcity that is deemed acceptable, and the feasible expansion of the irrigated area complying with that limitation. In addressing this issue, we restrict the analysis to irrigation expansion on cropping areas in the production year 2012, representing the situation just before law 12,787 came into effect in 2013.

Our assessment entails the following steps:

i. the spatially explicit calculation of green and blue water consumption for the main crops cultivated in Brazil for both rainfed and irrigated production systems,

ii. the estimation of blue water scarcity due to the blue water consumption of a reference scenario (irrigated areas in 2012) and an expansion scenario, i.e. under the assumption that all rainfed areas are irrigated, thereby considering surface water availability, and

iii. the spatially explicit analysis to what extent expansion of irrigation areas is sustainable.

Our overall objective is to evaluate the feasibility of irrigation expansions in Brazil. We thereby investigate the following research question: Is expansion of irrigated areas, as encouraged by the Brazilian government, environmentally sustainable from a surface water resources point of view? The Cerrado biome, a region of significant agricultural expansion and a biodiversity hotspot (Mittermeier et al., 2005; Strassburg et al., 2017), is considered in particular detail.

## 2 Data

Precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed data for the production year 2012 were obtained from Xavier et al. (2016), who developed a daily gridded dataset for Brazil with a 0.25°×0.25°

resolution of these meteorological variables based on 3,625 rain gauges and 735 weather stations. In order to determine the required soil properties, data on bulk density, organic carbon content, and fractions of sand, silt, clay have been extracted from the ISRIC SoilGrids1km database (Hengl et al., 2014).

Saturation and residual water content $\theta_s$ and $\theta_r$ [m$^3$ m$^{-3}$] and the parameters $\alpha$ and $n$ of the van Genuchten function (van Genuchten, 1980) were estimated using the level 3 pedotransfer function of Tomasella et al. (2000) for Brazilian soils, under the assumption that coarse and fine sand fraction have an equal share of the total sand content. Field capacity and wilting point were determined as soil water content at -33 kPa and -1,500 kPa, respectively, following van Genuchten (1980). Soil types were determined using the nomenclature of the United States Department of Agriculture (USDA). Data on harvested area and yield of nine main crops for the production year 2012 as provided by IBGE were utilised in this study. The crops considered are cotton, rice, sugarcane, *Vigna* spp. and *Phaseolus* spp. bean, cassava, corn, soybean and wheat. Combined those nine crops account for 96% of harvested area [ha], 98% of production mass [ton] and 90% of production value [Brazilian Real] in Brazil in the year 2012 (IBGE, 2012). Planting and harvesting dates for the sub-regions considered were taken from Conab (2015). For some crops, multiple harvests per year are considered, following information provided by IBGE. Catchment-scale data on surface water supply were obtained from the ANA Geonetwork (http://metadados.ana.gov.br/geonetwork/srv/pt/main.home). An overview of the underlying data is given in Table 1.

**Table 1 here**

## 3 Methods

In order to assess water consumption of potential expansion of irrigation, impacts on water scarcity, and limits to irrigation expansion under scarcity thresholds, we applied a site-specific crop water balance model at the catchment scale. To this end, high-resolution gridded data on climate and soil were combined with statistical information on irrigation management to run a countrywide daily crop water balance model for 166,842 sub-catchments in Brazil to determine rainfed and irrigated water requirements. The crops considered were cotton, rice, sugarcane, Vigna spp. and Phaseolus spp. bean, cassava, corn, soybean and wheat.

### 3.1 SPARE:WATER

#### 3.1.1 Calculation of green and blue water consumption

The open source crop water balance and footprint model SPARE:WATER (Multsch et al., 2013) was used to determine green and blue water consumption in crop production. The tool was applied to investigate several topics related to water resources management in recent years, e.g. the predicted future irrigation demands and impact of technology in the Nile river basin

(Multsch et al., 2017a), managing desalinated seawater use in agriculture in Saudi Arabia (Multsch et al., 2017b), and characterising groundwater scarcity caused by large scale irrigation in the USA (Multsch et al., 2016).

First, the daily crop water balance was calculated at 0.25°x0.25° grid-level for each crop per growing season, utilising the gridded climate and soils data (see Table 1). Second, the contribution of crop production to the regional water balance at the level of municipalities was derived by multiplying crop water consumption per growing season, averaged over the grids in the municipality, with the respective municipal cropping area [ha $a^{-1}$]. Note that the information regarding irrigated areas and the fraction of irrigated area per crop was also available at municipality level (Table 1). Thirdly, the total water consumption was determined per sub-catchment, which was then contrasted with water supply in each one of the 166,842 sub-catchments and aggregated to municipality level. These steps are shown in Figure A1.

Consumptive water use was separated into green ($CW_g$) and blue ($CW_b$) crop water consumption in [$m^3$ $ha^{-1}$] at grid level. To achieve this simulations were carried out twice for the entire country, once for purely rainfed conditions (fraction irrigated $f$=0), to determine green water consumption $CW_g$, and once for purely irrigated conditions (fraction irrigated $f$=1) $CW_b$, in order to determine additional blue water consumption, following earlier work by Mekonnen and Hoekstra (2010) and Siebert and Döll (2010). The blue water consumption was estimated as the difference between the two simulations:

$$CW_g = ET_{f=0} \tag{1}$$

$$CW_b = ET_{f=1} - ET_{f=0} \tag{2}$$

### 3.1.2 Calculation of crop water balance

In SPARE:WATER, the crop water balance is calculated based on the crop water balance model proposed by Allen et al. (1998). Reference evapotranspiration ($ET_o$) [mm $d^{-1}$] was derived as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad , \tag{3}$$

with net radiation $R_n$ [MJ $m^{-2}$ $d^{-1}$], soil heat flux density $G$ [MJ $m^{-2}$ $d^{-1}$], air temperature $T$ at 2 m height [°C], wind speed at 2 m height $u_2$ [m $s^{-1}$], saturated vapour pressure $e_s$ [kPa], actual vapour pressure $e_a$ [kPa], slope of the vapour pressure curve Δ [kPa °$C^{-1}$] and the psychrometric constant $\gamma$ [kPa °$C^{-1}$]. $ET_o$ is adapted to specific field crops by a crop coefficient ($K_c$), which varies over time and is adjusted to field conditions by a water stress coefficient ($K_s$) resulting in $ET_{act}$ [mm $d^{-1}$] according to:

$$ET_{act} = ET_o \times K_c \times K_s \tag{4}$$

whereby $K_c$ and $K_s$ are dimensionless values. $K_c$ reflects canopy development and changes over the course of the growing period, as measured by the number of days after sowing ($DAS$). The growing period was divided into the four periods initial period ($L_{ini}$), growth period ($L_{dev}$), mid period ($L_{mid}$) and late period ($L_{end}$). A crop coefficient is related to three of the periods: $K_{c,ini}$, $K_{c,mid}$ and $K_{c,end}$. The crop coefficient of $L_{dev}$ was interpolated in relation to the respective $DAS$ and the values of $L_{ini}$ and $L_{mid}$.

The water stress coefficient $K_s$ was derived on the basis of a simple water balance approach from the total available soil water ($TAW$), the actual root zone depletion ($D_r$) and a crop specific water extraction coefficient ($p$) [-] following Allen et al. (1998):

$$K_s = \frac{TAW - D_r}{(1-p)TAW} \quad (5)$$

with the $TAW$ and $D_r$ in [mm]. $TAW$ was derived from the wilting point, field capacity and the actual rooting depth ($Z_r$) according to Allen et al. (1998):

$$TAW = 1000(\theta_{FC} - \theta_{WP})z_r \quad (6)$$

with the water content at field capacity ($\theta_{FC}$) and wilting point ($\theta_{WP}$) in [m³ m$^{-3}$] and the rooting depth $z_r$ in [m]. The daily soil water depletion $D_r$ [mm] at day $i$ was derived for soil layer $r$ from the water balance components:

$$D_{r,i} = D_{r,i-1} - P_{eff,i} - Irr_i - CR_i + ET_{act,i} + DP_i \quad (7)$$

with daily effective precipitation ($P_{eff}$), irrigation ($Irr$), capillary rise ($CR$) and deep percolation $DP$ in [mm]. In order to account for the case $f$=1 (full irrigation) the daily irrigation depth $Irr$ was calculated to fill up the soil water compartment to field capacity when the critical depletion was reached, i.e. any water stress is avoided. This approach reflects full irrigation practices. $P_{eff}$ was computed as $P$–$RO$, where precipitation $P$ is taken from the meteorological input data and surface runoff $RO$ was estimated on the basis of the curve number method according to Bosznay (1989), while $CR$ was neglected.

### 3.2 Blue water scarcity

#### 3.2.1 Calculation of current and potential blue water consumption

The expansion area, i.e. the rainfed areas to be converted to irrigated land, was assessed considering and contrasting water consumption and water availability. The potential blue water consumption for full expansion of irrigation was calculated based on the irrigation required of all rainfed areas. Blue water consumption was derived for two scenarios. First, for the irrigated areas in 2012, which is subsequently denoted as reference scenario. Second, for an expansion scenario under the assumption that all rainfed areas are irrigated.

Knowing the potential consumption, the expansion of irrigated areas was then assessed with respect to the available blue water resources. Water available for expansion was determined by subtracting the available blue water from the water consumption under the reference scenario (actually irrigated areas). The remainder is available to expand irrigation to rainfed areas.

For each municipality the allocation of expansion of irrigated area for the crops was assumed proportional to the ratio of the crops grown in the reference case. If the volume of available blue water is insufficient to meet the reference blue water consumption of formerly rainfed areas, the expansion areas for each crop are reduced proportionally to the cropping fractions in the municipality.

### 3.2.2 Blue water availability

Following Flach et al. (2016), availability of blue water was taken from the national Brazilian water resources inventory (ANA, 2016). There, Q95, i.e. the river flow that is equalled or exceeded 95% of the time, and increased by regulated flow from reservoirs, is taken as an indicator of physical availability of water. In essence, Q95 is a measure for discharge in the low-flow season, thereby including regulated flows. Note that ANA provides the Q95 values as averages over the time period 2008 to 2016. The production year 2012 studied here is at the centre of this average.

### 3.2.3 Scarcity levels

The ratio of gross water withdrawal to physical water availability is often called withdrawal-to-availability ratio (Vanham et al., 2018), and is used as an indicator of water scarcity. Using the Q95 indicator for water availability, Brazilian water authorities consider the appropriateness of the water withdrawal, as a fraction of water availability (i.e. scarcity levels), to be acceptable when it remains below 5%, comfortable between 5 and 10%, worrying between 10 and 20%, critical between 20 and 40% and very critical above 40% (ANA, 2015). This classification is inspired by threshold values for water exploitation suggested by Raskin et al. (1997), and also used by the United Nations (UN, 1997).

In this paper, net water withdrawal (or blue water consumption) rather than gross water withdrawal is compared to water availability, often termed consumption-to-availability ratio (Vanham et al., 2018). Therefore, the scarcity levels described above were adjusted to reflect that withdrawals also include non-consumptive losses at field scale and losses during transport of water to the field, which are not considered when calculating blue water consumption. To account for this a factor of 2 was applied, which is a central estimate of the ratio between withdrawal and consumptive blue water use reported in Wriedt et al. (2008). The resulting scarcity levels represent the same classes of water scarcity from acceptable to very critical, but are adapted to the threshold values of 2.5, 5, 10 and 20%.

Using these thresholds for consumptive blue water use, blue water scarcity was analysed both for the reference situation and for a complete expansion of irrigation on the rainfed cropping area. Note that in the case of expansion of irrigation on the rainfed cropping areas the approach applied here does not account for dynamic changes in regional water availability due to increased upstream water consumption and hence an altered water availability downstream. The results provided here summarise the scarcity assessment with respect to the pre-defined scarcity levels.

## 3.3 Calculation of the extent of sustainable irrigation areas

The sustainable expansion of irrigated areas on rainfed cropping areas was assessed through the water consumption-to-availability ratio. Three management strategies are presented by limiting the available water under the assumption of scarcity levels acceptable, moderate and worrying. Each management strategy has been mapped spatially for reference and expansion scenarios. The volume of water available for consumptive blue water use in irrigation was calculated at the level of municipalities for the different threshold levels of water scarcity. If this volume of blue water exceeds the consumptive blue water requirement in the reference situation, the excess volume was allocated to irrigation expansion. For the irrigation expansion scenario the growing areas of the crops considered have been upscaled using the proportion of crops grown in the reference scenario. The overall extent of the expansion is chosen to either use all of the excess volume of blue water assumed to be available, or to use all of the rainfed cropping area. If the volume of available blue water (depending on the threshold for scarcity chosen) is insufficient to meet the reference blue water requirement, the irrigated areas for each crop were reduced proportionally to achieve the chosen level of scarcity. Viable expansions at municipal level were aggregated to regions for each of the threshold levels of water scarcity.

# 4 Results

## 4.1 Spatial explicit modelling using SPARE:WATER

### 4.1.1 Crop water balance modelling

The crop water balance components show significant differences between crops, partly due to differences in cropping locations within Brazil, different growing seasons, and between rainfed and irrigated production systems (see Table 2). Average $ET_{act}$ values vary between 154 mm (3rd *Vigna* spp. and *Phaseolus* spp.) and 925 mm (sugarcane) on rainfed areas. $ET_{act}$ is consistently higher on irrigated areas with average values between 260 mm (3rd *Vigna* spp. and *Phaseolus* spp.), i.e. 69% higher than rainfed, and 1,508 mm (sugarcane), i.e. 63% higher than rainfed. Effective precipitation $P_{eff}$ varies between 229 mm (3rd *Vigna* and *Phaseolus* spp.) and 1,574 mm (sugarcane), with high values relating to crops with comparably long growing periods. Crops with a high Irrigation *IRR* are wheat (291 mm) and particularly sugarcane (644 mm), mainly due to the growing periods extending into the dry seasons. Another important fact is that even if effective rainfall could often cover potential *ET* in total, the rainfall was not available at the time of high crop water demands and could not be stored by the soil in sufficient quantity, making it unavailable to the crop. Thus, irrigation is often required even if total rainfall is enough.

**Table 2 here**

In Table 3 the results for $ET_{act}$, $P_{eff}$, *IRR*, cropping area, green and blue water consumption are summarized for the Cerrado region, one of the main areas of agricultural development and a biodiversity hotspot. $ET_{act}$ is below the Brazilian average values in the cases of cotton (6%), wheat (47%) and sugarcane (14%), as well as for bean for the first sowing date (51%). Other crops show an $ET_{act}$ that is higher by 4% to 14%. $P_{eff}$ is lower in the Cerrado for all crops by 7% to 65%. A slightly higher $ET_{act}$ (by 1 to 6%) is estimated for irrigated production in the Cerrado region for all crops when compared to the average of Brazil. The irrigation depths in the Cerrado are found to exceed the Brazilian averages, e.g. +17% for cotton, +20% for sugarcane, +23% for the 2nd sowing date for corn, +30% for wheat as well as +7% and +26% for the 2nd and 3rd sowing date of bean.

**Table 3 here**

#### 4.1.2 Green and blue water consumption

The total water consumption of the nine crops considered in this study is 285.5 km³ in the production year 2012 (Table 2). Green water is dominating with 95% of the total consumption. The majority (91%) of the green water consumption was consumed on rainfed areas (53.8 Mha, including double/triple cropping) and only a minor fraction on irrigated areas (4.9 Mha). The spatial distribution of the total, green and blue water consumption in crop production is shown in Figure 1. The North of Brazil (States: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins) consumes only a minor fraction (3%) of the national total volume. Agriculture is not intensive in this area and many regions are not cultivated because of climate conditions, non-suitability of soils and nature protection in the Amazonas region. The highest percentage of green water consumption is found in the Centre-West (34%) (States: Goiás, Mato Grosso, Mato Grosso do Sul, Distrito Federal) and the highest percentage of blue water consumption occurs the North-East (States: Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, Sergipe) and the South-East (States: Espírito Santo, Minas Gerais, Rio de Janeiro, São Paulo) with 31% and 39%, respectively. Water consumption displays a distinct change in pattern from West to East (western areas: rainfed; eastern areas: irrigated). The majority of green water is consumed by soybean, sugarcane and corn with 37.8%, 28.6% and 21.5%, respectively. Regarding blue water, sugarcane (10.0 km³ $a^{-1}$), rice (2.3 km³ $a^{-1}$), corn (1.1 km³ $a^{-1}$) and soybean (0.9 km³ $a^{-1}$) consume with 92.9% the highest fraction.

The Cerrado (Figure 1, delimited by black line) is one of the most sensitive landscapes and is comprised of about half of both irrigated and rainfed areas in Brazil with 46% and 47%. The large extent of agricultural areas comes with a high green and blue water consumption of 132 $km^3$ $a^{-1}$ and 5.7 $km^3$ $a^{-1}$ (together 48% of the total across Brazil). The average field scale water consumption [mm $a^{-1}$] shows a higher green (~5%) and lower blue (~19%) water consumption when compared to Brazil's average.

**Figure 1 here**

### 4.2 Blue water scarcity

Blue water availability and scarcity are shown in Figure 2. The available water flows have been classified according to seven groups between 80 mm $a^{-1}$ and greater than 2,560 mm $a^{-1}$ related to water scarcity levels of 2.5, 5, 10 and 20%. The highest values are located in the North near the Amazonas River with a median Q95 of 765 mm $a^{-1}$. Q95 decreases in particular in the eastern areas with 26 mm $a^{-1}$ and 197 mm $a^{-1}$ in the North East and South East. The Cerrado area has also comparable low values with a median of 177 mm $a^{-1}$.

The blue water scarcity for current irrigated areas (Figure 2b) shows a specific regional pattern. Most of the agricultural areas are classified as to either meet acceptable (35%) or very critical (38%) water scarcity. In the Cerrado region 44% of the area are in the category acceptable and 23% of the area are in the category very critical. The highest quantity of very critical catchments is located in the North East and South with 64% and 49%, respectively. The largest percentages of areas in the category acceptable lie in the North (94%) and Center-West (65%).

The situation would change significantly when also rainfed areas are irrigated as shown in Figure 2c, with an increase of the category very critical with 48% and a lower fraction in the class acceptable with 24%. A similar change can be observed for the Cerrado region with 38% of very critical catchments. The catchments with a higher scarcity are located in the southern and eastern area of Brazil, as well as in the eastern part of the Cerrado itself.

**Figure 2 here**

The higher scarcity for the potentially irrigated area can be caused by two additive impacts, i.e. a low Q95 and a high additional water demand. Two regions stand out regarding water availability: the northern and north-eastern parts with comparably high availability, and the eastern regions with low availability. The other parts of the country show mixed water availability, with regions of higher and lower values (Figure 2a). The maximum and minimum quantities of water availability and consumption are heavily skewed to the blue water scarcity classes acceptable and very critical. For example, water scarcity in most catchments is classified as acceptable or very critical for current irrigated areas (Fig 3a). In this case, the class acceptable is dominated by agriculture fields with an average blue water consumption below 80 mm $a^{-1}$. The catchments classified as very critical are dominated by agriculture fields consuming more than 640 mm $a^{-1}$. The highest water availability (often larger than 1,280 mm $a^{-1}$) is attributed to catchments classified as acceptable (Figure 3b). Catchments with a lower water availability (<160 mm $a^{-1}$) are mostly characterized as very critical. This distribution is similar for current (Figure 3a,b) and rainfed (Figure 3c,d), i.e. potentially irrigated, areas.

**Figure 3 here**

### 4.3 Extent of sustainable irrigation areas

Three scarcity levels were analysed in detail, namely acceptable, comfortable and worrying (Table 4). Current irrigated areas add up to 4.29 Mha without accounting for multiple cropping. Only 1.99 Mha of this area, i.e. 46.4%, should be irrigated when an acceptable blue water scarcity level is to be realised. The areas that do not meet the threshold of acceptable water scarcity (1.57 Mha) lie in catchments that are currently classified as very critical. Allowing higher scarcity levels (comfortable, worrying) would allow 2.38 Mha and 2.78 Mha of the current irrigation areas to remain irrigated. Note that worrying water scarcity is the highest level of scarcity that avoids critical conditions. Expanding irrigation in order to irrigate all rainfed fields would result in an additional irrigated area of 45.56 Mha (i.e. the rainfed area without the multiple cropping areas listed in Table 1), with 22.00 Mha of the additional area in catchments with very critical and 4.02 Mha with critical water scarcity. Expansion of irrigation area by 16.68 Mha (36.6%), 20.68 Mha (45.4%) or 24.89 Mha (54.6%) would be achievable for the blue water scarcity levels acceptable, comfortable and worrying.

**Table 4 here**

The extent of sustainable irrigation areas is shown in Figure 4 in classes ranging from 20% to 100% for each catchment. The classes represent the percentage change needed to reach a certain level of water scarcity. For example, a countrywide acceptable scarcity level for the reference scenario (Figure 4a) is only achievable if the currently irrigated areas in large parts of eastern Brazil as well as in the south and west are reduced to 20% of the actual extent. The sustainable irrigation area for scarcity levels comfortable and worrying are shown in Figure 4b and 4c, respectively. The highest reductions are required in the North-East, the eastern part of the Cerrado, and in southern regions of Brazil. A similar calculation has been conducted for potentially irrigated areas (Figure 4d-f). Only a modest fraction of the currently rainfed areas should be irrigated, while keeping blue water scarcity at acceptable, comfortable or worrying levels, as shown in Figure 4d, 4e and 4f, with expansions mainly feasible in the South-East, the western part of the Cerrado and in the Amazon basin.

**Figure 4 here**

## 5 Discussion

In the present study the biophysical boundaries of said strategy have been specified in a quantitative manner by comparing the potential water demand to fully cover the water demand of rainfed areas by irrigation with the available river flows. The underlying environmental and agronomic data were carefully selected to account for the high spatial variation of hydrological conditions across Brazil. A few choices and the resulting implications require further attention.
With respect to the choice of a water availability indicator, Q95 as has been selected in order to provide a conservative water availability scenario. This is important due to the high variability of hydrological conditions in Brazil and to account for dry periods over time. Moreover, choosing Q95 complies with the indices utilised by the Brazilian Water Agency and decision makers.

The selection of crop-specific parameter sets was an important aspect in the design of such a study. Crop coefficients and length of growing seasons of the individual crops studied here have been assembled from a well-recognised source (Allen et al., 1998, i.e. parameters implemented in the FAO CROPWAT model), a Brazilian study (Hernandes et al., 2014) and regional information for Brazil, as provided by Companhia National de Abastecimento (Conab) (https://www.conab.gov.br/). We acknowledge that further spatial differentiation is desirable, should reliable data be available. We have chosen the procedures put forth by Allen et al. (1998), as their high level of robustness, transferability and repeatability have been shown (Pereira et al., 2015). Moreover, in a large-scale irrigation requirement study for the Murray-Darling basin, Multsch et al. (2013) report that the choice of the potential evapotranspiration calculation method outweighs the role of the local refinement of crop coefficients. Lastly, planting dates are known to change based on the onset of the rainy season (Arvor et al., 2014), which is strong evidence for the use of a window of planting dates based on precipitation regimes different regions. To address this, the actual and region-specific crop calendars (Conab, 2015) were utilised for the determination of crop water requirements to account for varying conditions in different parts of Brazil.

The blue soil water content and the blue water fluxes could be further separated into blue water originating from irrigation water and blue water originating from capillary rise, as for example in Chukalla et al. (2015), to track which fractions of ET originate from rainwater, irrigation water and capillary rise, respectively.

An important aspect when assessing water scarcity caused by agricultural water consumption are return flows, e.g. due to evapotranspiration recycling (Berger et al., 2014) or water losses in irrigation systems (Pereira et al., 2002; Jägermeyr et al., 2015). We neglect evapotranspiration recycling effects in the present study, since great care has been taken to subdivide the study area into sub-catchments with sizes where this effect does not play a significant role. The calculated blue water consumption represents net water requirements, which only includes evapotranspiration by crops and from soils.

Determination of water scarcity was carried out here using the consumption-to-availability ratio. Two aspects require further discussion: the effect of environmental flow requirements and of non-consumptive losses. Environmental flow requirements (EFR) were not included here. Considering EFR results in a reduction of blue water availability (Boulay et al., 2018; Hoekstra et al., 2011) and hence the water scarcity levels determined here would increase. It is challenging to determine the level of environmental flow requirements for a given region (Hoekstra et al., 2011). Such an analysis is beyond the scope of the current study. A broad range of methods is available in the literature (e.g. Abdi and Yasi, 2015; Hoekstra et al., 2012; Książek et al., 2019; Richter et al., 2012; Smakhtin et al., 2004; Tennant, 1976). In future work it is recommended to select an adequate method to determine EFR and to include such EFRs to carry out a detailed assessment of the impacts of different potential cropping systems on the water cycle, thereby including a quantification of land and water resources trade-offs in the context of agricultural intensification, as suggested by Lathuillière et al. (2018). Losses, e.g. at field scale and during transport, were considered by adjusting the scarcity levels. The adjustment was based on the work by Wriedt et al. (2008), who estimated gross irrigation demands in the European Union and Switzerland to be 1.3-2.5 times higher than field requirements, depending on the efficiency of transport and irrigation management. To consider these non-consumptive losses, the scarcity levels in the current study were adjusted from those originally used by ANA (2015) (acceptable below 5%, comfortable between 5 and 10%, worrying between 10 and 20%, critical between 20 and 40% and very critical above 40%) using a central factor of 2. Applying the lower (1.3) or higher (2.5) bound found by Wriedt et al (2008) would result in higher (3.8, 7.7, 15.4 and 30.1%)

and lower (2, 4, 8 and 16%) scarcity thresholds, respectively, than those employed here using the factor of 2 (2.5, 5, 10 and 20%).

It is critical to note that pumping river water for irrigation, as investigated here, has likely impacts on natural systems and should be carefully evaluated, thereby considering water management measures. In addition, the effect of land conversion requires attention. Recent studies show the potential effects of future land use and land cover change scenarios in the Amazonian region of Brazil on the hydrological regime in the region (Abe et al., 2018; Dos Santos et al., 2018). The results of the spatially explicit quantification regarding water resources of this study add information on several aspects as explained below.

## 5.1 Expansion and intensification of irrigation areas

The agricultural policy of Brazil has been investigated with a focus on water resources. By using a spatially explicit and process-oriented modelling approach the extent of sustainable irrigation areas was quantified. Future policy will need to decide on the level of the expansion and intensification of agricultural areas. Others (Alkimim et al., 2015; Sparovek et al., 2015; Spera, 2017; Strassburg et al., 2014) made a strong case that agricultural expansion into currently uncultivated areas can be avoided through efficient utilisation of currently cultivated areas, mainly those allocated to extensive grazing. The quantification of sustainable irrigation areas has shown that the use of irrigation as a large scale intensification strategy is limited. On the one hand, even actual irrigated areas (reference scenario) must be reduced in order to achieve an acceptable scarcity level. Thus, intensification would be in some areas highly unfavourable and current mechanisms of water use monitoring and control need to be improved. On the other hand, some rainfed areas (expansion scenario) maybe irrigated in the future without resulting in higher scarcity due to adequate blue water availability. Thus, this spatial explicit analysis can inform agricultural policy making with regard to water resources management in order to implement likely agricultural expansion in the future in a sustainable manner. This in turn can be linked to trade of agricultural commodities. For example, da Silva et al. (2016) determined that the northeast region of Brazil, with low water availability (see Figure 2), shows substantial import of agricultural commodities.

Regarding intensification, employing state of the art irrigation technology and further development of such technology would be in line with an objective of Brazil's irrigation policy through Law No. 12,787, i.e. to train human resources and foster the creation and transfer of technologies related to irrigation. Fachinelli and Pereira (2015) point out the potential yield increase through irrigation, and hence an opportunity to reduce related land requirements for sugarcane expansion. Future work should assess the potential of efficient use of water resources regarding irrigation technology to further refine the quantification of sustainable irrigation areas, including not only biophysical variables but also infrastructure availability (ANA, 2019) and socioeconomic conditions. Needless to say that in future work groundwater availability and water available in small dams previously used for cattle drinking water (Rodrigues et al., 2012) should be considered in addition to surface water availability, as was done in the current work.

### 5.2 Protecting the Cerrado

The Brazilian government has identified new areas for agricultural development in the northeastern part of the Cerrado, which became an agricultural frontier since the early 2000s. How would such a policy impact water resources? To answer this question, some knowledge regarding the landscape level development must be provided. On May 6, 2015, Brazilian Decree no. 8447 officially committed government support for the agriculture and livestock development plan PDA MATOPIBA for the 'MATOPIBA' region, i.e. 337 municipalities that span the states of Maranhão (MA), Tocantins (TO), southern Piauí (PI), and western Bahia (BA) (Spera et al., 2016). It must be noted that around 90% of MATOPIBA lies within the Cerrado biome. Spera et al. (2016) point out that unlike most of the Cerrado, MATOPIBA does not have a history of large-scale cattle ranching. As a result, cropland expansion in MATOPIBA is advancing primarily through clearing native vegetation rather than by using previously cleared pasturelands. It has been pointed by others that careful planning for the region should allow for large-scale agriculture to grow and contribute to rural economic development in a way that harmonises with other uses of the landscape and other economic development pathways (Dickie et al., 2016).

A further policy evaluation is feasible now that the blue water scarcity levels as presented in the current study are available. Nearly the half of Brazil's irrigated and rainfed area is located in the Cerrado area and requires a similar fraction for water consumption. Thus, policy strategies for Brazil regarding agricultural expansion will have a significant impact on that region, in particular on water resources. Currently, the scarcity levels of the area are mostly acceptable and comfortable and most areas under worrying and critical scarcity lie outside of the Cerrado area. Irrigation of rainfed areas would tremendously change this situation and increase blue water scarcity to a worst-case situation. In order to maintain sustainability with respect to surface water resources, less than 20% of rainfed areas should be irrigated.

### 5.3 Green water management

In addition to the spatial aspects regarding expansion, the temporal variability of water availability and consumption is crucial to support policymaking. The high evaporative deficit on rainfed areas as shown by the crop water balance model deserves special attention. Although rainfall rates can potentially cover the crop ET in many regions, the plant available soil moisture is not sufficient to store and provide enough water, especially in lighter-textured (sandy or sandy loam) soils. Additionally, a low infiltration capacity makes soils classified as clay or clay loam soils unable to store high-intensity rainfall.

Measures focusing on managing green water resources as proposed elsewhere (e.g. Multsch et al., 2016; Rockström et al., 2010; Rost et al., 2009) for agriculture systems worldwide can potentially improve the water holding capacity. While restricting water use of irrigated crops to green water may lead to substantial production losses (Siebert and Döll, 2010), improved irrigation practices can support reduction of non-beneficial water consumption, without compromising yield levels (Jägermeyr et al., 2015). Different measures to improve green water management have been evaluated by Jägermeyr et al. (2016) on the global scale showing that the kilocalories derived from agricultural production could be enhanced by 3-14% by soil moisture conservation and by 7-24% by water harvesting. In order to store the high surface run-off which occurs in Brazil's agricultural systems, in-situ rainfall harvesting by conservation tillage and mulching may be helpful measures in order to improve agricultural productivity in a sustainable manner.

Based on the work shown here specific scenarios can be evaluated, such as cultivation of a 2nd and/or 3rd cropping cycle for selected crops, using water resources for bridging dry spells during the growing season only (supplemental irrigation), or utilisation of water resources to avoid late planting due to unfavourable climatic conditions. Thus, this study provides a basis to further investigate specific measures, thereby considering various agriculture management strategies in space and time.

### 5.4 Water recycling

Another important aspect of sustainable irrigation is the effect on the amount of water recycled to the atmosphere via evapotranspiration. Spera et al. (2016) find by analysis of remote sensing data that the conversion of Cerrado vegetation into cropland resulted in changes in water recycling that show dependency on the cropping frequency, with double cropping behaving more akin to the natural system. Future investigations of this kind should include the additional effect of various irrigation strategies, combined with the effect of cropping frequency and area response to climate variability, whereby the importance of the latter has been highlighted by Cohn et al. (2016).

## 6 Conclusions

Based on the assessment of crop water consumption as fraction of water availability (in terms of Q95) and classifying the results regarding water scarcity for Brazil the following can be concluded:

- *Avoiding critical water scarcity on currently irrigated land:* In order to avoid critical water scarcity, irrigation must be discontinued on 54% of the area (2.3 Mha) for an acceptable water scarcity level, on 45% (1.9 Mha) for a comfortable water scarcity level and on 35% (1.5 Mha) for a worrying water scarcity level of 4.3 Mha currently irrigated land (not considering multiple cropping).
- *Avoiding critical water scarcity on currently rainfed land*: For 37% (16.7 Mha) of the currently 45.6 Mha rainfed land the blue water scarcity level would remain acceptable, for 45% (20.7 Mha) comfortable and 55% (24.9 Mha) worrying under irrigation (not considering multiple cropping).
- *Expansion of agriculture into currently uncultivated areas*: Given that there is potential for additional irrigation areas and taking into account estimates by FAO, which estimates that a cropping intensity of 120% can be achieved on irrigated land (www.fao.org/nr/water/aquastat/countries_regions/BRA/), production on currently cultivated land can overall be made more efficient through investment in irrigation infrastructure. This lends support to the statement made in other work that an expansion into currently uncultivated land is not required in order to increase agricultural productivity.

- *Decision support for stakeholders and decision-makers*: The results cover different water scarcity categories, which allows for a trade-off analysis among stakeholders and decision makers as to which level of water scarcity and the related consequences are acceptable to reach a given goal.
- *Global virtual water flows*: The agricultural policy will affect local farmers, but also global markets, given the global dimension of Brazil's agriculture. Brazil is a country, which imports blue water resources and exports its green water resources (Fader et al., 2011). The vast green water exports have been attributed to soybean, which are strongly requested on the world market, in particular by China (Dalin et al., 2012), to sustain human diet and livestock nutrition. A similar picture applies to sugarcane, since Brazil has a share of 30% of global production (Gerbens-Leenes and Hoekstra, 2012). An expansion of irrigated areas would therefore significantly alter global virtual water flows.

In studying possible expansion of irrigated areas, as encouraged by the Brazilian Government under Law 12,787, this paper addresses the trade-off between the choice of the level of blue water scarcity that is deemed acceptable, and the feasible expansion of the irrigated area complying with that limitation. In addressing this issue, we restrict the analysis to irrigation expansion on cropping areas in 2012, representing the situation just before law 12,787 came into effect in 2013.

Expanding irrigation can be an effective measure to increase agricultural production. Using a spatial explicit modelling tool sensible, forward-looking and sustainable planning of expansion areas can be achieved by avoiding an expansion in areas where high water scarcity would be the consequence. This applies in particular to the Cerrado biome. Moreover, the temporal variations regarding crop water requirements have been addressed by process-oriented modelling with respect to the local cropping calendar. This work provides a sound basis for further assessment of water management strategies in order to achieve nation-wide development and implementation of sustainable agricultural policies.

*Code availability*. The code written for this analysis can be made available by the first author upon request.

*Data availability*. Data used in this study are available from the following sources: Climate data (Xavier et al., 2016) from http://careyking.com/data-downloads/, soils data (Hengl et al., 2014) from https://www.isric.org/explore/soilgrids, crop data (IBGE, 2012) from http://www.sidra.ibge.gov.br/, extent of irrigted areas (IBGE, 2012) from http://www.sidra.ibge.gov.br/, fraction of irrigated area per crop (IBGE, 2006) from http://www.sidra.ibge.gov.br/ and surface water supply (ANA, 2016) from http://metadados.ana.gov.br/geonetwork/srv/pt/metadata.show?id=307. Other data used here, but not accessible online, can be accessed via the references listed in the references section.

*Appendices*.

Table A1. Crop coefficients $K_c$ [-] and lengths L [days] of crop development stages of the crops considered in this study.

| **Crop** | $\mathbf{K_{c,ini}}$ | $\mathbf{K_{c,mid}}$ | $\mathbf{K_{c,end}}$ | $\mathbf{L_{ini}}$ | $\mathbf{L_{dev}}$ | $\mathbf{L_{mid}}$ | $\mathbf{L_{late}}$ |
|---|---|---|---|---|---|---|---|
| Corn[1] | 0.65 | 1.1 | 0.6 | 30 | 40 | 50 | 30 |
| Soybean[1] | 0.6 | 1.05 | 0.6 | 10 | 40 | 50 | 20 |
| Sugarcane[1] | 0.5 | 1.25 | 0.8 | 30 | 60 | 180 | 95 |
| Cassava[2] | 0.3 | 0.8 | 0.3 | 20 | 40 | 90 | 60 |
| Rice[2] | 1.05 | 1.2 | 0.75 | 30 | 30 | 60 | 30 |
| Cotton[2] | 0.35 | 1.2 | 0.6 | 30 | 50 | 55 | 45 |
| Wheat[2] | 0.7 | 1.15 | 0.25 | 15 | 30 | 65 | 40 |
| Phaseolus[2] | 0.5 | 1.05 | 0.9 | 20 | 30 | 30 | 10 |
| Vigna[2] | 0.5 | 1.05 | 0.9 | 20 | 30 | 30 | 10 |

[1] Source: Hernandes et al. (2013), [2] Source: Allen et al. (1998)

Table A2. Planting and harvesting dates of the different crops and the five sub-regions considered in this study (Source: Conab, 2015). Note that "2nd" and "3rd" are the second and third planting dates for double- and triple-cropping within one growing season, i.e. a successive multiple cropping practice.

| | **North** | | **North-East** | | **Center-West** | | **South-East** | | **South** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Crop | Sowing | Harvest | Sowing | Harvest | Sowing | Harvest | Sowing | Harvest | Sowing | Harvest |
| Cassava | 01.09. | 29.03. | 01.09. | 29.03. | 01.09. | 29.03. | 01.09. | 29.03. | 01.09. | 29.03. |
| Corn | 01.12. | 29.04. | 15.01. | 13.06. | 15.11. | 13.04. | 15.11. | 13.04. | 15.10. | 13.03. |
| 2nd Corn | 10.04. | 06.09. | 01.05. | 27.09. | 15.02. | 14.07. | 15.03. | 11.08. | 15.02. | 14.07. |
| Cotton | 15.01. | 13.07. | 15.02. | 13.08. | 15.12. | 12.06. | 01.12. | 29.05. | 15.11. | 13.05. |
| Phaseolus | 15.12. | 14.03. | 15.11. | 12.02. | 15.11. | 12.02. | 01.11. | 29.01. | 01.10. | 29.12. |
| 2nd Phaseolus | 01.04. | 29.06. | 01.03. | 29.05. | 15.02. | 15.05. | 01.03. | 29.05. | 01.02. | 01.05. |
| 3rd Phaseolus | 15.05. | 12.08. | 15.05. | 12.08. | 15.05. | 12.08. | 01.05. | 29.07. | 01.05. | 29.07. |
| Rice | 15.11. | 13.04. | 01.01. | 30.05. | 15.11. | 13.04. | 15.11. | 13.04. | 01.11. | 30.03. |
| Soybean | 01.12. | 30.03. | 01.12. | 30.03. | 15.11. | 14.03. | 15.11. | 14.03. | 15.11. | 14.03. |
| Sugarcane | 01.10. | 30.09. | 01.10. | 30.09. | 01.07. | 30.06. | 01.07. | 30.06. | 01.07. | 30.06. |
| Vigna | 15.12. | 14.03. | 15.11. | 12.02. | 15.11. | 12.02. | 01.11. | 29.01. | 01.10. | 29.12. |
| 2nd Vigna | 01.04. | 29.06. | 01.03. | 29.05. | 15.02. | 15.05. | 01.03. | 29.05. | 01.02. | 01.05. |
| 3rd Vigna | 15.05. | 12.08. | 15.05. | 12.08. | 15.05. | 12.08. | 01.05. | 29.07. | 01.05. | 29.07. |
| Wheat | 15.04. | 11.09. | 15.04. | 11.09. | 15.04. | 11.09. | 01.05. | 27.09. | 15.06. | 11.11. |

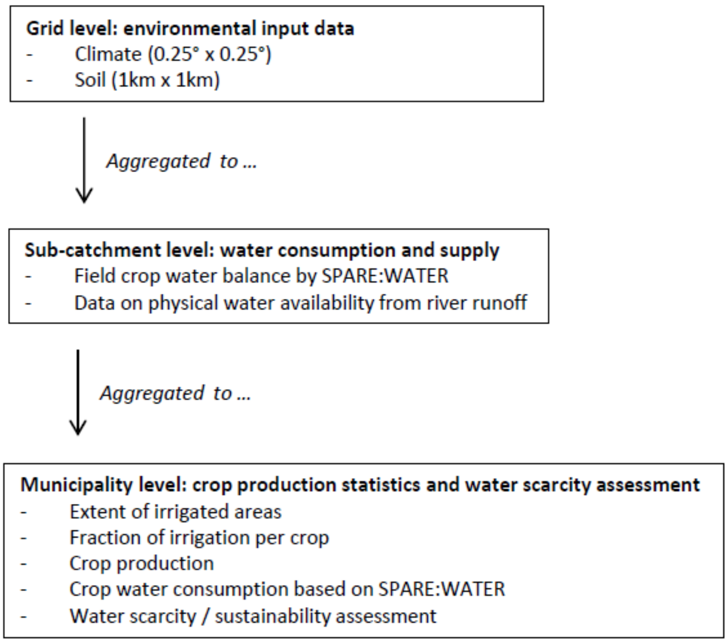


Figure A1. Spatial aggregation steps in the analysis.

*Author contribution*. MP, QL and MK initiated the study. SM and MP jointly developed the concept and methodology, with contributions by MK and LB. SM, MP, AA and AB pre-processed the input data for the analysis. SM carried out the calculations and prepared the figures. SM, MP, MK and LB analysed the results. SM, MP and MK wrote the first draft of the manuscript. The final version of the manuscript has been prepared based on revisions that have been contributed by all authors.

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## TABLES

**Table 1. Data used in this study and respective sources (Note: *Brazil is administratively divided into 5,565 municipalities; **For hydrological analyses, Brazil is subdivided into 166,842 catchments).**

| Data type | Source | Spatial scale |
|---|---|---|
| Climate data | Xavier et al. (2016) | 0.25°x0.25° |
| Soil data | Hengl et al. (2014) | 1 km |
| Crop production | IBGE (2012) Produção Agrícola Municipal (PAM) | Municipality* |
| Crop coefficients (see Table A1) | Allen et al. (1998); Hernandes et al. (2014) | - |
| Planting and harvesting date (see Table A2) | Conab (2015) | - |
| Surface water supply | ANA (2016) | Catchment** |
| Extent of irrigated areas | IBGE (2012) Produção Agrícola Municipal (PAM) | Municipality* |
| Fraction of irrigated area per crop | IBGE (2006) Censo Agropecuário | Municipality* |

**Table 2. Crop water balance and water consumption of rainfed and irrigated crops in Brazil for the production year 2012. "1st", 2nd" and "3rd" are the first, second and third planting dates for successive multiple cropping practice within one growing season. Crop development stages are provided in Table A1 and planting/harvesting dates are provided in Table A2.**

| | Crop | $ET_{act}$ [mm] | $P_{eff}$ [mm] | IRR [mm] | Cropping area [ha] | Green water [$km^3 a^{-1}$] | Blue water [$km^3 a^{-1}$] |
|---|---|---|---|---|---|---|---|
| rainfed | *Vigna* spp. 1st | 244 | 648 | | 6,097 | 0.010 | |
| | *Phaseolus* spp. 1st | 244 | 648 | | 799,232 | 1.824 | |
| | Cotton | 447 | 954 | | 1,315,585 | 5.643 | |
| | Cassava | 443 | 1,114 | | 1,491,520 | 5.864 | |
| | Corn 1st | 438 | 975 | | 6,613,805 | 31.076 | |
| | Soybean | 355 | 823 | | 23,692,402 | 92.524 | |
| | *Vigna* spp. 2nd | 214 | 389 | | 6,097 | 0.009 | |
| | *Phaseolus* spp. 2nd | 214 | 389 | | 799,232 | 1.593 | |
| | Corn 2nd | 328 | 477 | | 6,613,805 | 21.534 | |
| | Wheat | 310 | 406 | | 1,827,587 | 6.066 | |
| | *Vigna* spp. 3rd | 154 | 229 | | 6,097 | 0.008 | |
| | *Phaseolus* spp. 3rd | 154 | 229 | | 799,232 | 0.913 | |
| | Rice | 462 | 956 | | 1,652,877 | 7.754 | |
| | Sugarcane | 925 | 1,574 | | 8,143,700 | 70.145 | |
| | **Subtotal** | | | | **53,767,270** | **244.963** | |
| irrigated | *Vigna* spp. 1st | 299 | 648 | 138 | 770 | 0.001 | 0.002 |
| | *Phaseolus* spp. 1st | 299 | 648 | 138 | 99,053 | 0.218 | 0.124 |
| | Cotton | 592 | 954 | 216 | 66,322 | 0.248 | 0.175 |
| | Cassava | 565 | 1,114 | 183 | 189,305 | 0.684 | 0.489 |
| | Corn 1st | 532 | 975 | 206 | 438,283 | 2.041 | 0.459 |
| | Soybean | 432 | 823 | 180 | 1,176,186 | 4.630 | 0.875 |
| | *Vigna* spp. 2nd | 276 | 389 | 106 | 770 | 0.001 | 0.001 |
| | *Phaseolus* spp. 2nd | 276 | 389 | 106 | 99,053 | 0.174 | 0.115 |
| | Corn 2nd | 494 | 477 | 245 | 438,283 | 1.272 | 0.619 |
| | Wheat | 514 | 406 | 291 | 58,916 | 0.193 | 0.036 |
| | *Vigna* spp. 3rd | 260 | 229 | 159 | 770 | 0.001 | 0.001 |
| | *Phaseolus* spp. 3rd | 260 | 229 | 159 | 99,053 | 0.111 | 0.143 |
| | Rice | 623 | 956 | 236 | 753,691 | 3.220 | 2.342 |
| | Sugarcane | 1,508 | 1,574 | 644 | 1,507,080 | 12.386 | 9.979 |
| | **Subtotal** | | | | **4,927,531** | **25.181** | **15.360** |
| | **Total** | | | | **58,694,801** | **270.145** | **15.360** |

**Table 3. Crop water balance and water consumption of rainfed and irrigated crops in the Cerrado region of Brazil for the production year 2012. "1st", 2nd" and "3rd" are the first, second and third planting dates for successive multiple cropping practice within one growing season. Crop development stages are provided in Table A1 and planting/harvesting dates are provided in Table A2.**

| | Crop | $ET_{act}$ [mm] | $P_{eff}$ [mm] | IRR [mm] | Cropping area [ha] | Green water [$km^3$ $a^{-1}$] | Blue water [$km^3$ $a^{-1}$] |
|---|---|---|---|---|---|---|---|
| rainfed | *Vigna* spp. 1st | 285 | 607 | | 534 | 0.001 | |
| | *Phaseolus* spp. 1st | 285 | 607 | | 240,816 | 0.681 | |
| | Cotton | 419 | 700 | | 1,232,061 | 5.226 | |
| | Cassava | 498 | 997 | | 228,505 | 0.980 | |
| | Corn 1st | 477 | 793 | | 2,854,404 | 14.000 | |
| | Soybean | 402 | 724 | | 12,081,675 | 49.685 | |
| | *Vigna* spp. 2nd | 204 | 265 | | 534 | 0.001 | |
| | *Phaseolus* spp. 2nd | 204 | 265 | | 240,816 | 0.493 | |
| | Corn 2nd | 274 | 273 | | 2,854,404 | 9.456 | |
| | Wheat | 211 | 144 | | 95,376 | 0.270 | |
| | *Vigna* spp. 3rd | 102 | 82 | | 534 | 0.000 | |
| | *Phaseolus* spp. 3rd | 102 | 82 | | 240,816 | 0.249 | |
| | Rice | 483 | 816 | | 533,050 | 2.560 | |
| | Sugarcane | 813 | 1,179 | | 4,136,773 | 35.580 | |
| | | | | | **24,740,298** | **119.182** | |
| | | | | | | | |
| irrigated | *Vigna* spp. 1st | 312 | 607 | 553 | 95 | 0.000 | 0.000 |
| | *Phaseolus* spp. 1st | 312 | 607 | 553 | 39,378 | 0.110 | 0.016 |
| | Cotton | 624 | 700 | 2,606 | 60,942 | 0.231 | 0.156 |
| | Cassava | 591 | 997 | 1,175 | 29,508 | 0.135 | 0.047 |
| | Corn 1st | 565 | 793 | 1,349 | 237,558 | 1.164 | 0.167 |
| | Soybean | 454 | 724 | 892 | 759,294 | 3.145 | 0.216 |
| | Vigna 2nd | 285 | 265 | 1,149 | 95 | 0.000 | 0.000 |
| | *Phaseolus* spp. 2nd | 285 | 265 | 1,149 | 39,378 | 0.074 | 0.035 |
| | Corn 2nd | 507 | 273 | 3,170 | 237,558 | 0.703 | 0.359 |
| | Wheat | 530 | 144 | 4,165 | 13,109 | 0.033 | 0.020 |
| | *Vigna* spp. 3rd | 268 | 82 | 2,149 | 95 | 0.000 | 0.000 |
| | *Phaseolus* spp. 3rd | 268 | 82 | 2,149 | 39,378 | 0.041 | 0.056 |
| | Rice | 627 | 816 | 1,703 | 72,836 | 0.389 | 0.050 |
| | Sugarcane | 1,577 | 1,179 | 8,040 | 783,690 | 6.575 | 4.530 |
| | | | | | **2,312,915** | **12.60** | **5.65** |
| | | | | **Total** | **27,053,214** | **131.78** | **5.65** |

**Table 4. Extent of current and potential irrigated areas under various scarcity levels for the reference and expansion scenario.**

| | ***Reference scenario* Irrigated areas - target blue water scarcity** | | | | ***Expansion scenario* Potentially irrigated areas - target blue water scarcity** | | | |
|---|---|---|---|---|---|---|---|---|
| | Without | Acceptable | Comfortable | Worrying | Without | Acceptable | Comfortable | Worrying |
| | Mha | | | | | | | |
| Acceptable | 1.49 | 1.49 | 1.49 | 1.49 | 11.69 | 11.69 | 11.69 | 11.69 |
| Comfortable | 0.32 | 0.23 | 0.32 | 0.32 | 3.71 | 2.62 | 3.71 | 3.71 |
| Worrying | 0.38 | 0.13 | 0.27 | 0.38 | 4.14 | 1.35 | 2.89 | 4.14 |
| Critical | 0.47 | 0.08 | 0.17 | 0.34 | 4.02 | 0.58 | 1.32 | 2.87 |
| Very critical | 1.63 | 0.06 | 0.13 | 0.25 | 22.00 | 0.44 | 1.07 | 2.5 |
| Total | 4.29 | 1.99 | 2.38 | 2.78 | 45.56 | 16.68 | 20.68 | 24.89 |

## FIGURES

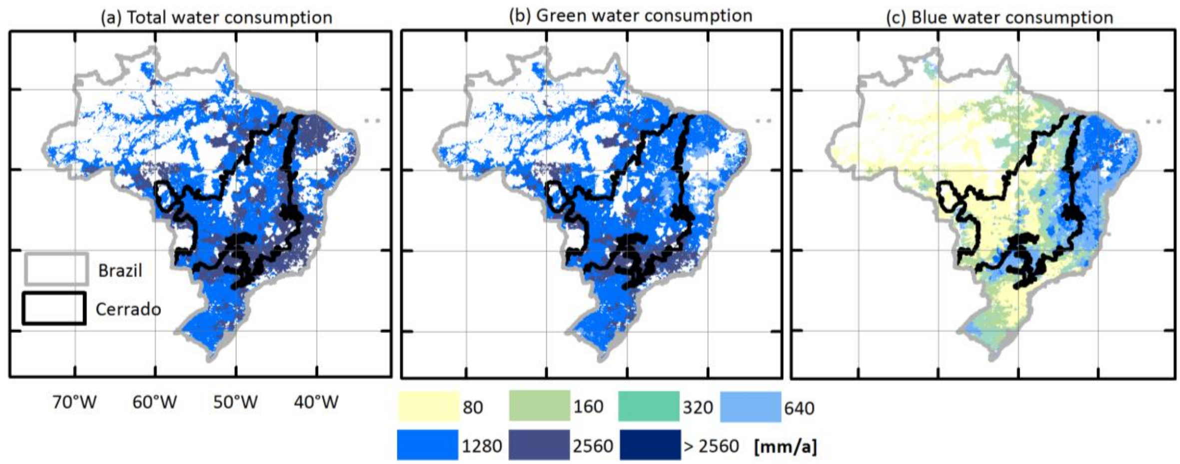



**Figure 1. Spatial distribution of the water consumption in crop production in Brazil for the crops considered in this study: (a) total, (b) green and (c) blue water consumption. The black line delimits the Cerrado region.**

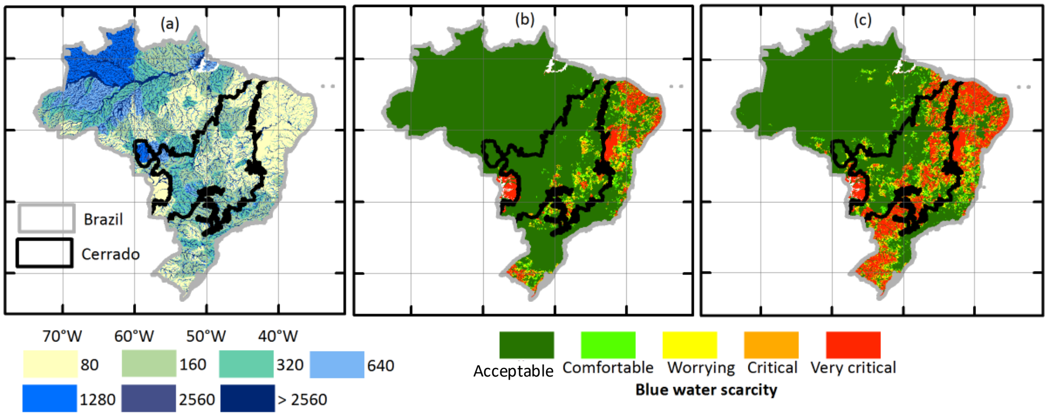



**Figure 2. Water scarcity of 166,844 catchments across Brazil. (a) Annual average water availability Q95. (b) Blue water scarcity classification of irrigated areas. (c) Blue water scarcity classification of rainfed areas when irrigated. The black line delimits the Cerrado region.**

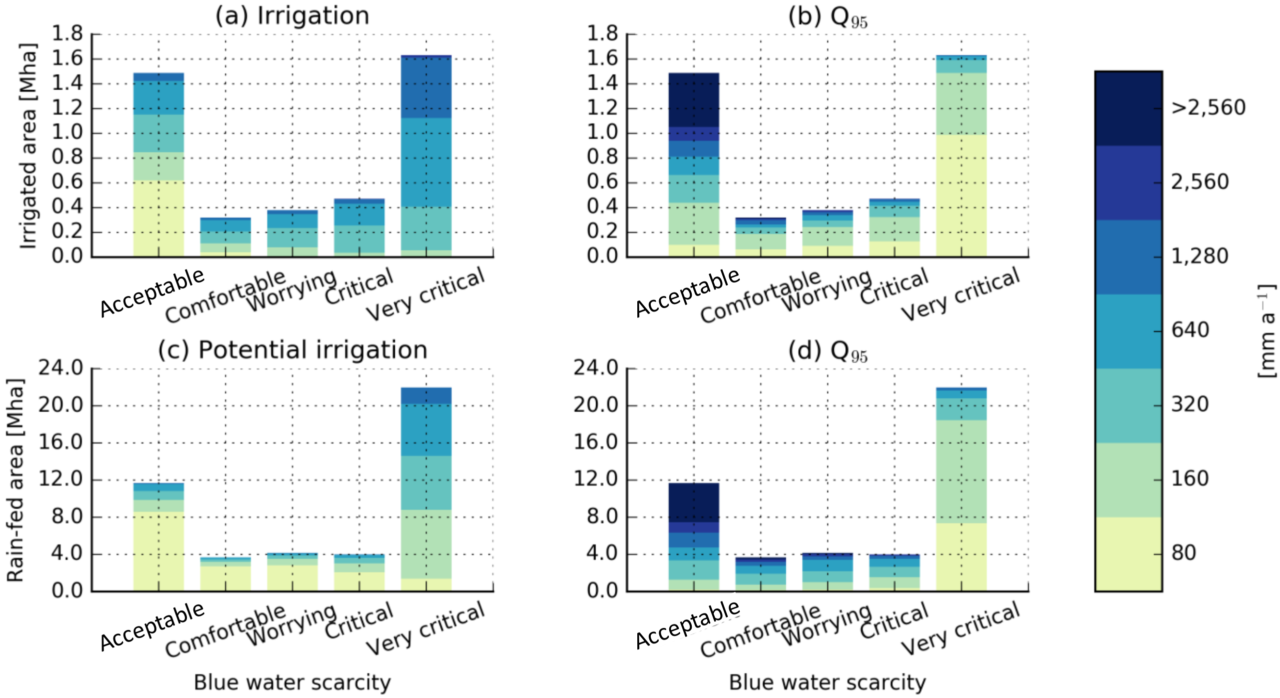
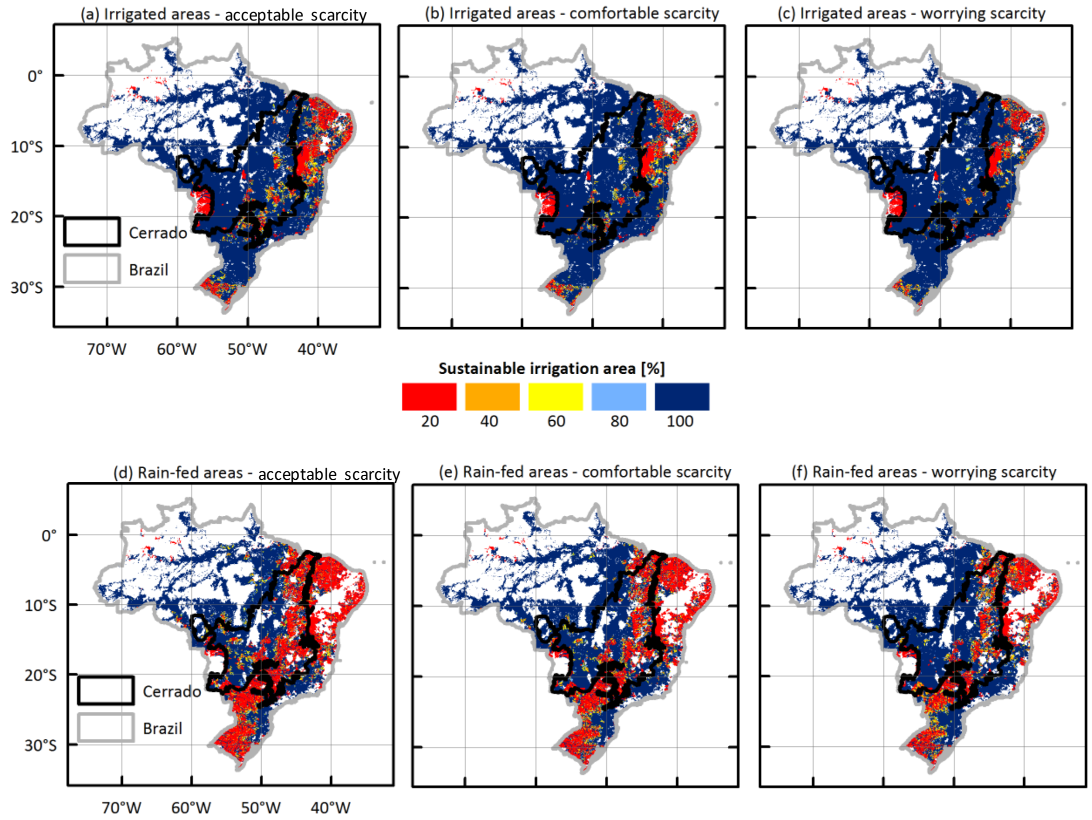



**Figure 3. Classification of blue water consumption (a, c) and blue water availability (b,d) for irrigated areas (a,b; 4.29 Mha) and potential irrigated areas (c,d; 45.56 Mha) according to blue water scarcity levels.**




720 **Figure 4. Fraction of current irrigated areas (a,b,c) and potentially irrigated areas (d,e,f) which can be sustainably irrigated according to a target blue water scarcity level of acceptable (a,d), comfortable (b,e) and worrying (c,f).**