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Research article

Hydrological impacts of ethanol-driven sugarcane expansion in Brazil

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ABSTRACT

Ethanol production in Brazil is projected to double between 2012 and 2030 in order to meet increased global demand, resulting in the expansion of sugarcane cultivation. Sugarcane expansion drives both direct and indirect land-use changes, and subsequent changes in hydrology may exacerbate problems of (local) water scarcity. This study assesses the impacts of projected ethanol-driven sugarcane expansion on agricultural and hydrological drought in Brazil. Drought due to sugarcane expansion is modelled using a spatial terrestrial hydrological model (PCR-GLOBWB) with spatiotemporally variable land-use change and climate change scenarios as input. We compare an ethanol scenario with increased ethanol demand to a reference situation in which ethanol demand does not increase.

The results show that, on average, 29% of the Centre West Cerrado region is projected to experience agricultural drought between 2012 and 2030, and the drought deficit in this region is projected to be 7% higher in the ethanol scenario compared to the reference. The differences between the ethanol and the reference scenario are small when averaged over macro-regions, but can be considerable at a local scale. Differences in agricultural and hydrological drought between the ethanol and reference scenario are most notable in the Centre West Cerrado and Southeast regions. Locally, considerable changes may also occur in other regions, including the Northeast Coast and Northern Amazon region.

Because the South East and Centre West Cerrado regions are responsible for a large proportion of agricultural production, increased agricultural drought may result in significant economic losses, while increased hydrological drought could exacerbate existing problems of water supply to large metropolitan areas in these regions. The identification of areas at risk of increased droughts can be important information for policy makers to take precautionary measures to avoid negative hydrological impacts of increased ethanol demand.

1. Introduction

Agriculture is responsible for over 70% of global water withdrawals (Molden 2007). Growing demand for food, feed, and fibre is expected to increase the existing stress on freshwater resources (Gerbens-Leenes et al., 2009), exacerbated by a rapid increase in the production of biofuels (Watkins et al., 2015). One of the key sustainability concerns related to biofuel production is its potential impact on water resources (Guarenghi and Walter 2016; Berndes 2002). Brazil has strongly increased its biofuel production over the last decade (IEA 2018), consisting largely of sugarcane-based ethanol (IEA 2018). Brazilian sugarcane production has increased from 4 Mha in 1990 to 10 Mha in 2015 in order to satisfy both domestic and international ethanol demand, making Brazil the largest sugarcane producer in the world (FAO 2020). Sugarcane expansion has taken place mainly at the expense of pasture and cropland (Pereira et al., 2013; Adami et al., 2012; Guarenghi and Walter 2016). Sugarcane production is currently concentrated in south-eastern Brazil, which has sufficient rainfall for rainfed sugarcane production (Scarpare et al., 2016a). However, future expansion of sugarcane into dryer areas may result in hydrological impacts.

Global demand for bioethanol is expected to grow from $95.6 \cdot 10^9$ L in 2012 up to $168 \cdot 10^9$ L in 2030, of which $53 \cdot 10^9$ L is expected to be produced in Brazil (van der Hilst et al., 2018). As a consequence, Brazilian sugarcane area is projected to increase from 10.1 Mha in 2012 to 13.6 Mha in 2030 (which corresponds to a 35% increase in area) (Verstegen et al., 2016; van der Hilst et al., 2018). Sugarcane expansion is

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projected to occur predominantly in the Centre West Cerrado (CWC) and Southeast (SE) regions of Brazil (Scarpare et al 2016a, 2016b; van der Hilst et al., 2018; Verstegen et al., 2016). Besides direct land-use change (sugarcane expansion over other land uses), indirect land-use change (ILUC) is also expected to occur (Verstegen et al., 2016; van der Hilst et al., 2018; Adami et al., 2012; Lapola et al., 2010). Although the precise location is highly uncertain, ILUC is projected to occur mainly in the sugarcane growing regions of the Center West Cerrado and the Southeast, but some indirect land-use change is also projected in regions outside of sugarcane growing areas, including the Northern Amazon (Verstegen et al., 2016; van der Hilst et al., 2018).

Land-use change can have a strong influence on hydrological processes (Bosmans et al., 2017), e.g. by contributing to flooding and drought. Drought has been defined as 'a deficit of water relative to normal conditions' (Sheffield and Wood 2012). Brazil has abundant freshwater resources (Martinelli and Filoso 2008) and overall water resources volume should be sufficient to accommodate current and future biofuel demand (Berndes 2002). However, water availability is unevenly distributed (Flach et al., 2016; Hernandes et al., 2013; Moreira 2007), and several sub-basins in Brazil's south-eastern and central regions are facing water scarcity problems (Scarpare et al., 2016a). The Cerrado biome, into which sugarcane is expected to expand, has a longer dry spells and soils with a lower water storing capacity than the current sugarcane cultivation areas (Scarpare et al 2016a, 2016b; Cabral et al., 2012; Marin et al., 2011). Therefore, concerns have been raised about the potential impacts of sugarcane expansion in Brazil on droughts (de Cerqueira Leite et al., 2009).

Drought can be categorized into meteorological, agricultural and hydrological drought (Pedro-Monzonís et al., 2015). *Meteorological drought* is defined as a continuous shortage of rainfall (Pedro-Monzonís et al., 2015). Meteorological drought can cause *agricultural drought* when soil moisture deficits lead to hydric stress in plants (Pedro-Monzonís et al., 2015). Land-use change affects soil moisture, e.g. through changes in evapotranspiration and the interception of precipitation. Agricultural drought can cause water stress for natural systems and may reduce agricultural yield significantly (Hisdal et al., 2004). The 2014 drought resulted in economic losses of about US$ 5.25 billion in the Brazilian agricultural sector (Nobre et al., 2016). *Hydrological drought* occurs when soil moisture deficit and/or increased evapotranspiration results in reduced river discharge (Hisdal et al., 2004; Pedro-Monzonís et al., 2015), which may severely impact downstream communities and natural areas (Hisdal et al., 2004). For example, the 2014 drought jeopardized the water supply of 28 million people in the south-east region of Brazil (Melo et al., 2016).

Because the hydrological impacts of sugarcane expansion are expected to vary over space and time, it is important to assess hydrological impacts of sugarcane expansion in a spatiotemporally explicit manner. A number of spatially explicit studies have assessed the hydrological impacts of sugarcane expansion, and other land-use changes in Brazil. The majority of these studies focus on hydrological impacts within a single river basin (Pereira et al., 2013; Scarpare et al., 2016b; Costa et al., 2003) or a particular region in Brazil (Oliveira et al., 2014; Georgescu et al., 2013; Loarie et al., 2011; Hernandes et al., 2013). For example, an increase in agricultural area at the expense of natural vegetation resulted in an increased discharge of the Tocantíns river basin (Costa et al., 2003). On the other hand, expansion of sugarcane, predominantly over pasture, resulted in a decrease runoff in the Rio Grande basin (Pereira et al., 2013). These findings indicate that land-use change due to sugarcane expansion may have different impacts on droughts in different areas. Furthermore, ethanol-driven land-use change is projected to extend beyond boundaries of regions or river basins (van der Hilst et al., 2018), and impacts on hydrological processes thus transcend the catchment level. This emphasizes the importance of studying hydrological impacts of increased ethanol demand on a geographical scale that surpasses the river basin or regional level.

The aim of this study is to assess the impacts of increased ethanol demand in Brazil on agricultural and hydrological drought in a spatiotemporally explicit manner. We include all watersheds in Brazil to assess the hydrological effects of both direct and indirect land-use change due to sugarcane expansion. Hydrological impacts are assessed based on spatiotemporal land-use projections and climate change scenarios using an adapted version of the terrestrial hydrological model PCR-GLOBWB (Wada et al 2011a, 2011b, 2014; van Beek et al., 2011). By simulating all effects – sugarcane expansion, indirect land-use change due to sugarcane expansion, land-use change due to other drivers, and climate change, we can put the hydrological effects of increased ethanol demand into perspective.

2. Methods

2.1. General approach

We assessed the impact of increased demand for Brazilian ethanol on agricultural and hydrological drought using the spatial terrestrial hydrological PCR-GLOBWB model (van Beek et al., 2011; Wada et al, 2011b, 2014). The study area constitutes the hydrological catchment areas situated entirely or partly in Brazil (Annex 1). The model calculates water flows and storage, including soil moisture and discharge, based on input of meteorological and land-use data (Fig. 1). Land-use types included in the model are defined by a set of land-use specific hydrological parameters. Soil moisture and discharge modelled in PCR-GLOBWB are used to identify occurrence of droughts. We compared indicators of agricultural and hydrological drought for an *ethanol scenario*, which assumes increasing ethanol demand, to a hypothetical *reference scenario*, in which ethanol demand remains static. Both meteorological and land-use projections are based on the Shared Socio-economic Pathway 2 (van Vuuren et al., 2014), a middle-of-the-road pathway assuming no strong shifts from historical patterns (Fricko et al., 2017).

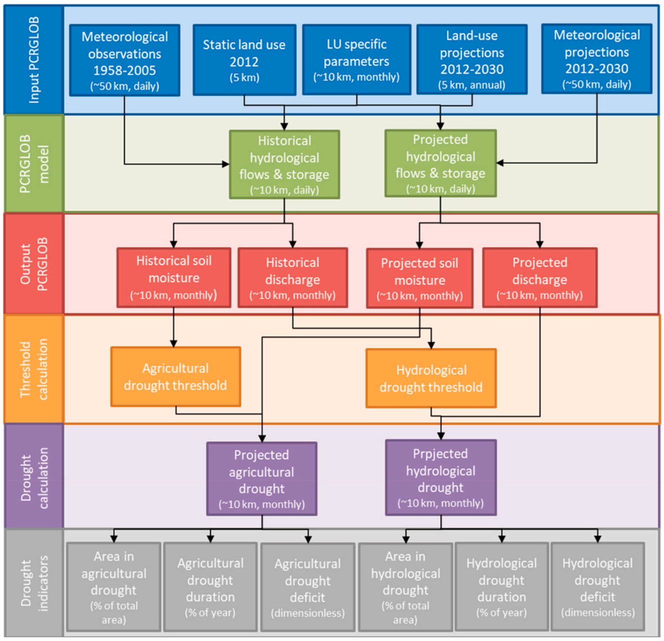

Fig. 1. Overview of the PCR-GLOBWB modelling process, with input (blue), modelling (green), output (red), threshold calculation (orange) and drought calculations based on output and threshold values (purple). For spatial data, spatial and temporal resolution is provided between brackets. A spatial resolution of 5 arcmin, which equals about 10 km, is given as ~10 km. For drought indicators, the unit is provided between brackets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Soil moisture and discharge output maps were used to calculate indicators of agricultural and hydrological drought respectively using the *threshold method* (Wanders and Van Lanen 2015; Yevjevich 1967). Droughts between 2012 and 2030 were defined in terms of relative values of soil moisture or discharge; those values below a spatially variable threshold derived from a historical reference were defined as drought. Drought events were quantified by calculating:

- Area in drought
- Drought duration
- Drought deficit

These indicators provide information on different aspects of drought: spatial prevalence (area in drought), temporal prevalence (drought duration) and an integrated measure of intensity and duration of drought (drought deficit). Agricultural drought can affect hydrological drought in a number of ways by reducing lateral flow of soil moisture and groundwater, and by increasing water demand for irrigation (Annex 9).

2.2. PCR-GLOBWB model

PCR-GLOBWB is a spatial terrestrial hydrology model which calculates water storage in the soil and groundwater, lateral flows as well as vertical water flows between soil, groundwater and atmosphere at 5' resolution and daily timesteps, based on input data including land-use and meteorological data. The model includes both natural water flows and anthropogenic water consumption. We included the following land-use types in PCR-GLOBWB: urban, forest, grass- and shrubland, pasture, rice paddy, irrigated crops, rainfed crops, irrigated sugarcane and rainfed sugarcane. The PCR-GLOBWB model was adapted to include irrigated and rainfed sugarcane as separate land-use types, which required adaptation of the land-use parameterization (see below). The model was used to simulate water flows for a historical period (1958–2005) to establish a historical baseline of soil moisture and discharge. We used historical meteorological data from the WATCH (WATer and global CHange) project (Weedon et al., 2011) as climate input for the historical period. The model was then run for land-use projections and climate change scenarios between 2012 and 2030, resulting in spatiotemporally explicit PCR-GLOBWB output for soil moisture and discharge. Although PCR-GLOBWB calculates water flows and storage (including soil moisture and discharge) with daily timesteps, output was reported as monthly averages due to data storage and processing limitations. The performance of PCR-GLOBWB in modelling river discharge was validated by e.g. (van Beek et al., 2011; Sutanudjaja et al., 2018). Because of adapted land-use parameterization used in this study, we repeated the validation for discharge by comparing simulated and measured river discharge in the study area (Annex 2). We calculated the Kling-Gupta Efficiency (KGE) coefficient (Gupta et al., 2009), which provides a measure of bias and differences in amplitude and timing between the measured and simulated datasets. Our results show that 92% of stations have KGE values between 1 and -1, where a KGE value of 1 means a perfect agreement of observed GRDC data and simulated data. These results are in line with previous studies that validated the PCR-GLOBWB model, and show that PCR-GLOBWB is able to model discharge accurately in most areas.

2.3. Land-use change scenarios

Land-use projections for the period 2012 and 2030 were taken from previous studies (van der Hilst et al., 2018; Verstegen et al., 2016). We used an *ethanol scenario*, which assumes Brazilian ethanol production to increase by $26 \cdot 10^9$ L to $53 \cdot 10^9$ L (96% increase) to meet current and planned ethanol mandates worldwide. Global increase in demand for ethanol is expected to result in an expansion of sugarcane area of $3.5 \cdot 10^6$ ha (35% increase) between 2012 and 2030. The ethanol scenario was compared to a hypothetical *reference scenario,* in which demand for ethanol was kept static up to 2030 at the 2013 level of $27 \cdot 10^9$ L. Both scenarios assume a small increase in demand for sugar derived from sugarcane. In the reference scenario, this leads to a slight increase in demand for sugarcane, despite the static demand for ethanol (Verstegen et al., 2016). Sugarcane yields are assumed to increase according to extrapolation of historical trends (van der Hilst et al., 2018; Jonker et al., 2015). The scenarios also assumed increasing production of crops (82%), livestock (24%), and wood products (20%) (van der Hilst et al., 2018). Land-use projections included the land-use types urban, crops, sugarcane, planted pasture, grass- & shrubland, rangeland, natural forest, planted forest, bare soil, water and abandoned land, and consist of annual land-use maps at a 5 km resolution. Land use outside Brazil was kept static throughout the modelling period, because no land-use projections were available for this area. The allocation method used to create the initial land-use map for Brazil (Verstegen et al., 2016) (Annex 3) was applied to classify land use for the study area outside of Brazil, based on the Globcover v2.2 land-use map (Bicheron et al., 2008). Over 90% of projected sugarcane expansion occurs in the CWC and SE regions, which are currently the main sugarcane producing regions. About 70% of indirect land-use change driven by sugarcane expansion is also projected to occur there, while 30% (about 18.000 km^2) is projected to occur in other regions (Annex 4). This highlights the importance of including areas outside the main sugarcane growing areas in impact assessments in order to capture the full impact of both direct and indirect land-use change.

2.4. Land-use parameterization

Projection land-use types (5 km resolution) were reclassified into PCR-GLOBWB land-use types (Annex 5) and resampled to 5' resolution (~10 km). Since PCR-GLOBWB includes sub-grid variability of land use, the resulting PCR-GLOBWB cells can contain fractions of multiple land-use types. This resulted in PCR-GLOBWB grid-cells containing fractions of multiple land-use types. PCR-GLOBWB requires hydrological parameters related to root and vegetation structure for each land-use type (Van Beek and Bierkens 2009) (Annex 6). These land-use specific parameters vary both spatially and temporally, and consist of interception capacity, groundcover, root depth and root fraction. These parameters were assigned to each land-use fraction in each cell. For all non-agricultural land-use types, we applied PCR-GLOBWB default parameter values (van Beek et al., 2011) (Annex 6). Additionally, we derived parameters for the land-use types irrigated sugarcane, rainfed sugarcane, irrigated crops and rainfed crops using the method applied to calculate PCR-GLOBWB default values (van Beek et al., 2011) (see Annex 6). Parameters for rainfed and irrigated sugarcane are shown in Table 1. We assumed the following growing seasons; from September to April in the Northeast and from May to November in the Center-South. Sugarcane LAI increases during the growing season until sugarcane is harvested at the end of the growing season, resulting in a drop in LAI and a subsequent reduction in evapotranspiration and interception of rainfall. Root depth and root fraction differ between irrigated and rainfed sugarcane but do not vary spatially or temporally.

PCR-GLOBWB determined for each sugarcane cell whether or not it was irrigated. This was done based on 1) relative suitability for rainfed versus irrigated sugarcane from the Global Agro-Ecological Zones (GAEZ) (Fischer et al., 2012), and 2) a function of proximity (based on the MIRCA2000 dataset (Portmann et al., 2010)) and slope gradient. This means that a cell is considered to contain irrigated sugarcane if the location is considered more suitable for cultivation of irrigated than for rainfed sugarcane, if the area is relatively flat and if irrigated sugarcane is already present in close proximity to the newly established cell.

2.5. Climate scenarios

Future incidents of drought are expected to be affected by climate

Table 1
Parameters used to define hydrological properties of irrigated and rainfed sugarcane in PCR-GLOBWB modelling.

Parameter	Source	Spatial resolution	Temporal resolution	Unit	Value	
					Rainfed	Irrigated
Crop coefficient	GWCM[a]	5 arc min	Bimonthly	dimensionless	Ranges from 0.7 to 0.9	
Ground cover	GWCM[a]	5 arc min	Bimonthly	m^{2}/m[b]	Ranges from 0.8 to 1	
Interception capacity	GWCM[a]	5 arc min	Bimonthly	m/m^{2}	Ranges from 1.2 × 10^{-3} to 1.8 × 10^{-3}	
Leaf area index	Pereira et al.[b]	2 regions: north-east, centre-south	Monthly	m^{2}/m[b]	Ranges from 3 to 9	
Vegetation fraction	Land-use projections[c]	5 arc min	Yearly	fraction	Ranges from 0 to 1	
Crop calendar	USDA[d]	2 regions: north-east, center-south	Monthly	Start month, end month	Northeast = sep-apr Center-south = may–nov	
Max root depth fraction	GWCM[a]	5 arc min	Yearly	fraction	1.01	
Min root depth fraction	GWCM[a]	5 arc min	Yearly	fraction	0.99	
Root fraction layer 1	GWCM[a]	5 arc min	Yearly	fraction	0.8	0.9
Root fraction layer 2	GWCM[a]	5 arc min	Yearly	fraction	0.2	0.1
Total root depth	GWCM[a]	5 arc min	Yearly	m	1.8	1.2
Location of rainfed and irrigated sugarcane	MIRCA[e]	5 arc min	One map for the year 2000	occurrence	1 or 0	

[a] (Siebert and Döll 2008).
[b] (Pereira et al., 2013).
[c] (van der Hilst et al., 2018; Verstegen et al., 2016).
[d] (Board 1994).
[e] (Portmann et al., 2010).

change (Marx et al., 2018; Wanders and Van Lanen 2015; Wanders and Wada 2015). We used climate projections from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014) to define future climatic conditions, applying projections from five General Circulation Models (GCMs) (Taylor et al., 2012) (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M) for the underlying Representative Concentration Pathway RCP6.0 for atmospheric CO$_2$-equivalent concentrations (Moss et al., 2010; van Vuuren et al., 2011) and Shared Socioeconomic Pathway 2 (O'Neill et al., 2017) for future political, demographic, technological and economic development. The five climate models provide different projections for changes in precipitation between 2012 and 2030 (Annex 7). The soil moisture and discharge values per grid cell were averaged over the 5 GCMs to control for variation in climate change projections. The degree of agreement amongst output of runs using different GCMs, and thereby a measure of robustness of results, is provided in Annex 7.

2.6. Calculation of drought indicators

We applied a threshold method (Yevjevich 1967) to PCR-GLOBWB output of soil moisture (m^3/m^3) and discharge (m^3/s) to define agricultural and hydrological drought. This threshold method defines drought according to a threshold based on a historical reference. The 10th percentile of the historical (1958–2005) monthly average model output for soil moisture and discharge was chosen as the threshold level, in line with earlier drought studies (Tallaksen and Hisdal 1997; Prudhomme et al., 2014; Demuth and Heinrich 1997). The threshold was determined for each month of the year and for each cell. Thus, a location- and time-specific relative measure of drought was derived.

Location specific historical and projected soil moisture and discharge timeseries were standardized using equation (1), drought events were defined using equation (2). Drought indicators area in drought, drought duration and drought deficit were calculated using equations (3)–(6) according to (Wanders and Van Lanen 2015; Wanders et al., 2015).

$$stZ(t,n) = \frac{Z(t,n) - \overline{Z}(n)}{\sigma Z(t,n)} \tag{1}$$

$$D(t,n) = \begin{cases} 1\, for\ stZ(t,n) & < stZ10(t,n) \\ 0\, for\ stZ(t,n) & \geq stZ10(t,n) \end{cases} \tag{2}$$

$$AID(t) = \frac{\sum_{n=1}^{N} D(t,n)}{N} * 100 \tag{3}$$

$$Ddur_{i,n} = \frac{\sum_{t=Si}^{Li} D(t,n)}{12} * 100 \tag{4}$$

$$Ddef(t,n) = \begin{cases} Z10(t,n) - Z(t,n) & for\ D(t,n) = 1 \\ 0 \quad for\ D(t,n) = 0 \end{cases} \tag{5}$$

$$Ddef_i(n) = \sum_{t=Si}^{Li} Ddef(t,n) \tag{6}$$

where *Z(t,n)* is hydrological parameter soil moisture (m^3/m^3) or discharge (m^3/s) at time *t* (in months) for cell *n*, $\overline{Z}(n)$ is the average value over the timeseries for hydrological parameter *Z* for cell *n*, *σZ(t,n)* is the standard deviation of parameter *Z*, *stZ(t,n)* is the standardised hydrological parameter Z parameter and $Z10_{(t,n)}$ is the 10th percentile threshold. *D(t,n)* a Boolean variable indicating whether a grid cell (*n*) is experiencing a drought event (1) or not (0) at time *t*, which is a particular month in a particular year. AID is Area In Drought (% of the total region), N is the total number of cells in the region. $Ddur_{i,n}$ is the drought duration (% of the year) of event *i* at cell *n*, *Si* the first time step (specific month of a specific year) of a drought event *i* and *Li* the last time step of the event. *Ddef(t,n)* is the standardised drought deficit of at time *t* of cell *n*, expressed as the distance (in standard deviations) from the average discharge or soil moisture at time *t* for cell *n*. *Ddef$_i$(n)* is the sum of monthly drought deficits at cell *n* during the drought event.

We mapped the PCR-GLOBWB output for historical soil moisture and discharge at 5′ resolution and averaged the monthly values for the period 1958–2005. Monthly values of drought area, duration and deficit for the ethanol scenario and the reference were averaged for the period 2012–2030 and per region to provide a measure of regional agricultural and hydrological drought. Regions were defined as clusters of states, as in earlier research (Verstegen et al., 2016). We also calculate the difference in drought indicators between the scenarios by subtracting values of the reference scenario from those of the ethanol scenario, we provided maps of the difference in drought deficit between the scenarios at 5’ resolution.

3. Results

3.1. Historical hydrological properties

The assessment of historical hydrological conditions in the study area for the reference period from 1958 to 2005 shows that annual average soil moisture is relatively low in the Northeast Cerrado (NER) and Northeast Coast (NEC) regions (Fig. 2), consistent with areas of relatively low rainfall. Average annual soil moisture is also relatively low Outside of Brazil (OB region), west of the Centre West Cerrado (CWC) region in Bolivia and Paraguay. The dryer patches in the CWC, Southeast (SE) and South (S) overlap with the presence of irrigated crops (including sugarcane). The SE, CWC and OB regions show a strong seasonality in soil moisture, with a dry spell from September to November and a wet season from February to May (Annex 8). Seasonality is less pronounced in the Northern Amazon (NA) and almost absent in the S region. Of the main sugarcane growing areas, the CWC shows a stronger seasonality in soil moisture than the SE region. Discharge is highest for the Amazon river, particularly in the downstream areas in the NA region (Fig. 2).

3.2. Impact of increasing ethanol demand on droughts

Agricultural drought in terms of area, duration and deficit was projected to be highest in the CWC region in both the ethanol scenario and the reference situation (Fig. 3). In both scenarios, on average, 28% of the region experience agricultural drought (averaged over the years 2012–2030 and over the grid cells in the region), which lasts for about 3 months (25% of the year, Annex 10). Hydrological drought is most widespread in the NA region in both scenarios, where on average, 26% of the region experiences drought, while hydrological droughts last longest and are most intense in the NEC region. The NEC, which is a relatively dry area to begin with (Fig. 2), has on average the smallest relative increases in agricultural drought area and duration.

When comparing the ethanol and the reference scenario, the difference in area in agricultural and hydrological drought between the scenarios increases over time, and becomes more seasonal, particularly in the CWC and the SE regions (Annex 8). The CWC region experiences the largest impact of sugarcane expansion on agricultural drought, the regional average of drought deficit was almost 7% higher in this region in the ethanol scenario (Annex 9). The ethanol scenario results in lower regional average drought deficits compared to the reference in the NEC region (Annex 8). Sugarcane expansion had a relatively small impact on regional averages of hydrological drought; differences between the ethanol and reference scenario were less than 1% (Annex 9). Locally, however, larger impacts of increased ethanol demand can be seen. Throughout the study area, there is substantial variation in the difference in agricultural and hydrological drought deficit between the ethanol and reference situation (Figs. 4 and 5). Higher agricultural and hydrological drought deficits (more negative Δ drought deficit in Figs. 4 and 5) in the ethanol scenario occur in the SE and part of the CWC region that borders the SE region, and the western and central area of the CWC. In the SE region and the part of the CWC region that borders the SE region, higher drought deficits in the ethanol scenario are mainly due to the projected expansion of rainfed and irrigated sugarcane at the expense of rainfed and irrigated cropland and grass and shrubland. In the western and central area of the CWC, increased drought deficit in the ethanol scenario is mainly due to projected indirect land-use change where irrigated cropland replaces grass and shrubland. The different climate models (GCMs) generated slightly different output, but showed general agreement in projected trends between most models (Annex 7). In the ethanol scenario, the area of irrigated sugarcane in the CWC increased from 3400 km^2 in 2012 to over 11,000 km^2 in 2030, compared to 6700 km^2 in the reference scenario in 2030 (Annex 9). Lower drought deficits in the ethanol scenario compared to the reference occur in parts of the NEC region (Fig. 5). This is mainly due to indirect land-use change projected for the ethanol scenario in this region, consisting of the expansion of planted forest. Sugarcane is irrigated more, both in terms of irrigated area and volume of water used, in the areas in which sugarcane expands. Water use for sugarcane irrigation projected for 2030 is almost 50% higher in the ethanol scenario than in the reference situation.

4. Discussion

We assessed the impact of ethanol-driven sugarcane expansion in Brazil on agricultural and hydrological drought, for all watersheds in Brazil. Our results show that increased demand for ethanol resulted in small changes in the area and length of agricultural and hydrological drought events throughout the study area. However, the intensity (measured as drought deficit) of agricultural droughts changed more noticeably, particularly in the North East Coast and Centre West Cerrado regions. Even though the area and duration of drought events did not change much due to ethanol-driven sugarcane expansion, an increased intensity in agricultural drought in the CWC region could have adverse effects on crop yields in that region. Differences between the ethanol and reference scenario were mainly localised, within the Centre West Cerrado and Southeast regions showing the highest risk of increased agricultural and hydrological drought when ethanol demand increases. Locally, considerable changes also occurred in other regions, including the Northeast Coast and Northern Amazon region. Sugarcane was

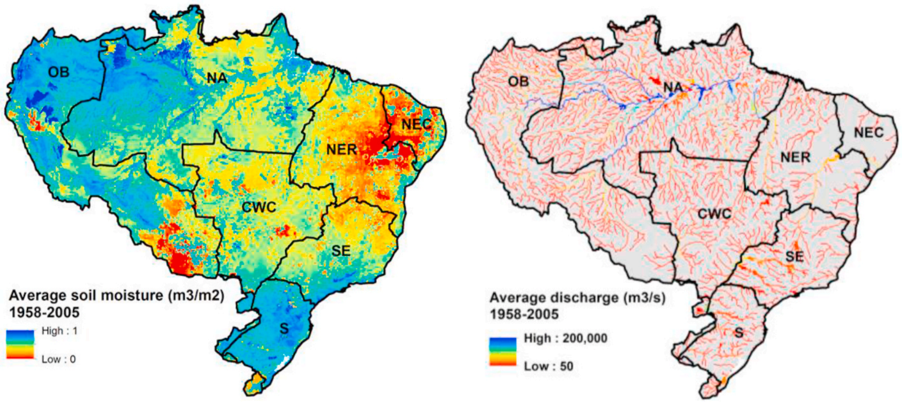

Fig. 2. Annual soil moisture in m^3/m^3 (left) and discharge in m^3/s (right), averaged over the historical period (1958–2005). Abbreviations show region names; OB = outside of Brazil, NA = Northern Amazon, CWC = Centre West Cerrado, NER = North East Cerrado, NEC = North East Coast, SE = South East, S = South.

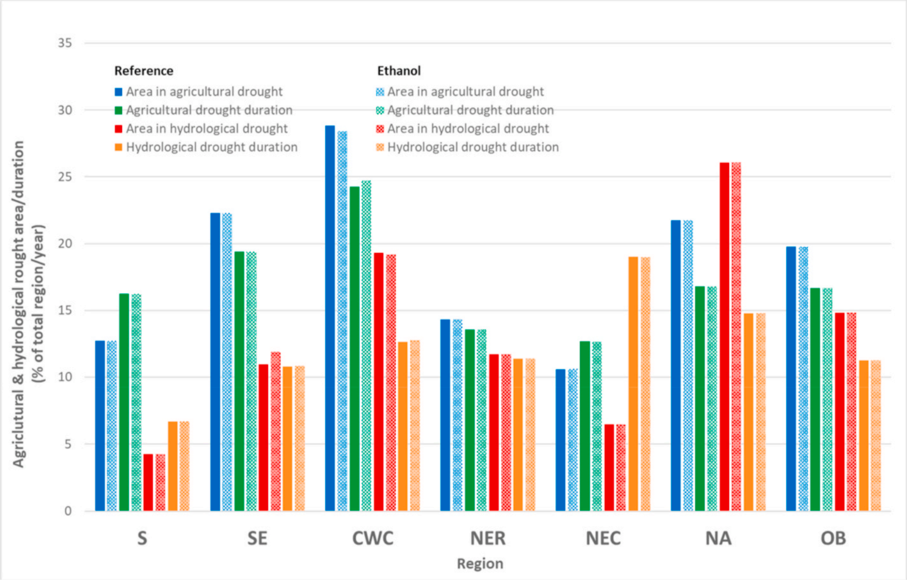

Fig. 3. Average area (in blue) and duration (in green) of drought for the reference situation (solid fill) and the ethanol scenario (shaded bars) per region in percentage of total region area and percentage of the year respectively. Monthly values of area and duration of drought were averaged for the period 2012–2030 and per region. Abbreviations represent region names; S = South, SE = South East, CWC = Centre West Cerrado, NER = North East Cerrado, NEC = North East Coast, NA = Northern Amazon, OB = outside of Brazil. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

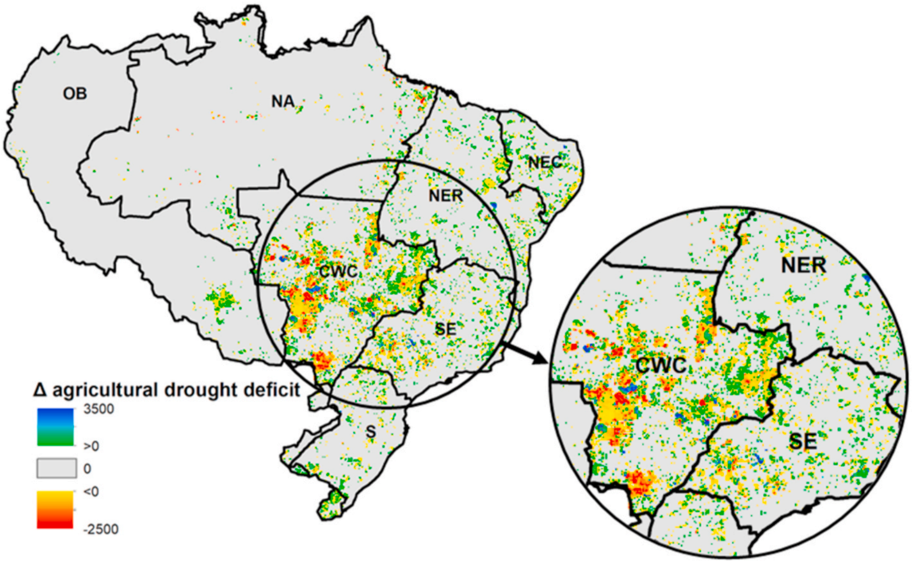

Fig. 4. The difference in standardized agricultural drought deficit (dimensionless) averaged for the period 2012–2030 at 5′ resolution. A negative value means that there was a higher drought deficit in the ethanol scenario, while a positive value means there was a lower drought deficit in the ethanol scenario compared to the reference situation. Abbreviations represent region names; OB = outside of Brazil, NA = Northern Amazon, CWC = Centre West Cerrado, NER = North East Cerrado, NEC = North East Coast, SE = South East, S = South.

irrigated more, both in terms of irrigated area and volume of water used, in the areas in which sugarcane expands. This is in line with (Scarpare et al., 2016b; Dallemand et al., 2015). Our results contradict earlier studies that project that sugarcane expansion will not affect soil moisture content (Georgescu et al., 2013) nor have severe impacts on water stress (Hernandes et al., 2013), which may be due to the spatially aggregated level of these studies. This highlights the importance of a spatial assessment at high resolution, as performed in this study.

The performance of the PCR-GLOBWB model has been validated in previous studies by comparing modelling results to observational data (Sutanudjaja et al., 2018; Van Beek and Bierkens 2009). Validation showed that the PCR-GLOBWB model was able to accurately reproduce discharge patterns including seasonal changes and inter-annual variation (Sutanudjaja, 2018), and PCR-GLOBWB successfully captures trends and seasonality for water storage in most large river basins (Tangdamrongsub et al., 2016). A validation exercise was also carried out in this study for the study area, and found similar results (see Annex 2). However, PCR-GLOBWB does not perform optimally in modelling total water storage of the Amazon basin due to uncertainties in meteorological data and modelled groundwater response time (Sutanudjaja et al., 2018). Validation for soil moisture at the scale of the study area is complicated due to the limitations of available high quality observational data for comparison to our model results. Furthermore, like most hydrological models, PCR-GLOBWB does not include a two-way feedback mechanism between the atmosphere and land, and does not include the marginal impact of lateral groundwater flows. It also does not include effects of albedo.

A number of assumptions and data limitations may have influenced the results. We assumed static land use outside of Brazil, for which projections were not available. Furthermore, we assumed a static demand for water for domestic and industrial use for both historical and projected model runs. However, domestic and industrial water use is expected to increase during the modelling period, since water withdrawal for domestic use increased by 9% between 2006 and 2010, and water withdrawal for industrial purposes increased by 26% in this period (Agencia Nacional de Agua 2013). This could further exacerbate hydrological drought. Climate change will have a significant influence on the occurrence and intensity of droughts change (Marx et al., 2018;

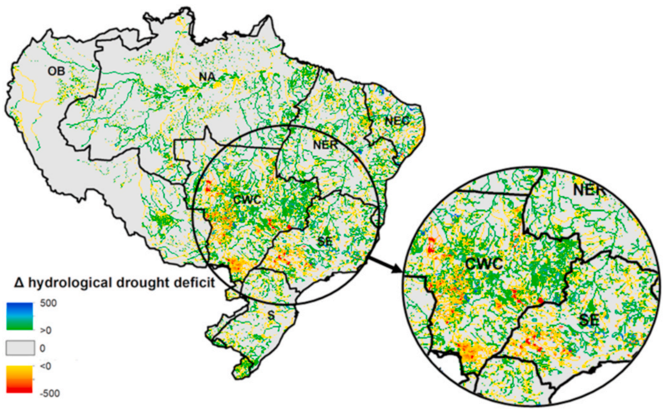

Fig. 5. The difference in standardized hydrological drought deficit (dimensionless) averaged for the period 2012–2030 at 5′ resolution. A negative value means that there was a higher drought deficit in the ethanol scenario, while a positive value means there was a lower drought deficit in the ethanol scenario compared to the reference situation. Abbreviations represent region names; OB = outside of Brazil, NA = Northern Amazon, CWC = Centre West Cerrado, NER = North East Cerrado, NEC = North East Coast, SE = South East, S = South.

Wanders and Van Lanen 2015; Wanders and Wada 2015). To reduce the uncertainty of future climate change, we calculated our results based on five models of climate change, and averaged our results over these scenarios. Therefore, our drought values may be considered conservative, vis-a-vis scenarios of stronger climate change.

We made use of a threshold method to identify drought events. This method does not take into account the fact that some regions may be more adapted to droughts than others (Wanders et al., 2015). In areas with variable soil moisture, native vegetation may be better adapted to survive periods of droughts than in wetter areas. Farmers may also adapt their agricultural practices to drought, through increased irrigation (which is captured by the model) or by changing crops (which is not captured by the model) (Maneta et al., 2009). Therefore, for two regions experiencing the same relative drought increase, the severity of the impacts may differ.

The large geographical range of the study, the assumptions in the input data, the PCR-GLOBWB model itself and the calculation of drought indicators all introduce uncertainty in the results presented here. Therefore the results in this study should be viewed as potential trends in hydrological impacts following increased ethanol demand in Brazil, rather than exact predictions of drought in the future. We identify regions of interest due to potential increase or decrease in drought, while further research should assess these regions in more detail. However, this study provides the first spatial assessment of hydrological impacts of increased ethanol demand in Brazil including the full geographical extent of potential direct and indirect land-use changes, based on a translation of a global shared socio-economic pathway scenario into a regional land-use change scenario and using a hydrological model that includes dependencies in the hydrological cycle. The projected strong increase in production of Brazilian ethanol may have multiple potential benefits; provision of renewable fuel, reduced greenhouse gas emissions, enhanced energy security and contribution to rural development. However, sugarcane expansion may also result in negative impacts such as increased drought, which depend on the location of new sugarcane growing area, the previous land-use type and indirect effects. Agricultural and hydrological drought can result in large social, economic and ecological impacts, in particular in the Southeast and Centre West Cerrado regions, where population density and agricultural production are high, and where unique ecosystems provide a wide range of ecosystem services. The information on areas at risk of drought due to increased ethanol demand can be used as input for land-use planning, to minimize negative impacts of sugarcane expansion. Future research is needed to quantify how projected drought may result in economic, social and ecological impacts, and how these impacts may be avoided.

5. Conclusion

This study provided a projection of changes in agricultural and hydrological drought as a result of projected increase in ethanol-driven sugarcane expansion in Brazil. Expansion of sugarcane between 2012 and 2030 projected to occur predominantly in the Southeast and the Centre Cerrado region, where it replaces grass- and shrubland and rainfed cropland. In the Centre West Cerrado, where sugarcane expands, seasonality in soil moisture and discharge is strong. Water use for sugarcane irrigation projected for 2030 is almost 50% higher in the ethanol scenario than in the reference situation. Sugarcane expansion between 2012 and 2030 is expected to result in increased and more intense agricultural droughts, particularly in the Centre West Cerrado region (7% increase in drought deficit). The differences between the ethanol and the reference scenario are small when averaged over entire regions, but are considerable at a local scale. This underlines the importance of a spatially explicit approach for the assessment of drought impacts of land-use change. Our results show that locally, ethanol-driven sugarcane expansion is expected to lead to increased problems of water scarcity, particularly in terms of agricultural drought. Land-use planning should take these risks into account.

Credit author statement

A.S. Duden: Conceptualization, Visualization, Project administration, Writing - Original Draft. P.A. Verweij: Conceptualization, Supervision, Project administration, Writing - Review & Editing, Y.V. Kraak: Formal analysis, Validation, Software. L.P.H van Beek: Formal analysis, Writing - Review & Editing, Software. N. Wanders: Formal analysis, Visualization, Writing - Review & Editing, Software, D.J. Karssenberg: Writing - Review & Editing, Methodology. E.H. Sutanudjaja: Formal analysis, Writing - Review & Editing, Validation, Software. F. van der Hilst: Conceptualization, Supervision, Project administration, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.111942.

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