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Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios

Laura Miguel Ayala ^{a,*}, Michiel van Eupen ^a, Guoping Zhang ^b, Marta Pérez-Soba ^a, Lucieta G. Martorano ^c, Leila S. Lisboa ^d, Norma E. Beltrão ^e

^a Alterra Wageningen University and Research Centre Alterra Wageningen University and Research, Wageningen Campus, Building 101, Droevendaalsesteeg 3a, 6708 PB Wageningen, The Netherlands

^b Water Footprint Network, International Water House, Bezuidenhoutseweg 2, 2594 AV, The Hague, The Netherlands

^c Embrapa Eastern Amazon, Trav. Dr. Enéas Pinheiro s/n° Caixa Postal, 48, CEP 66.095-100 Belém, Brazil

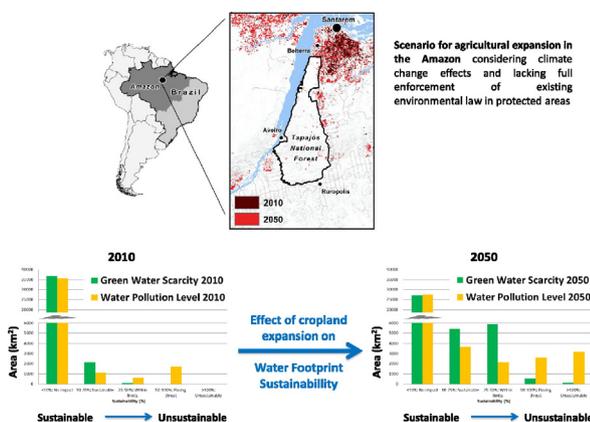
^d Esalq-São Paulo University, Av. Pádua Dias, 11 - Cx. Postal 9, Piracicaba CEP 13418-900, São Paulo, Brazil

^e University of Pará State, University of Para State – UEPA, Trav. Dr. Enéas Pinheiro 2626, CEP 66095-100 Belém, Brazil

HIGHLIGHTS

- Agricultural expansion entails potential environmental impacts in nearby river basins.
- Water Footprint Assessment analyses present & future watershed sustainability.
- Green Water Scarcity: useful sustainability indicator accounting protection status.
- Future soybean production impacts environment beyond sustainability limits.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural expansion and intensification are main drivers of land-use change in Brazil. Soybean is the major crop under expansion in the area. Soybean production involves large amounts of water and fertiliser that act as sources of contamination with potentially negative impacts on adjacent water bodies. These impacts might be intensified by projected climate change in tropical areas.

A Water Footprint Assessment (WFA) serves as a tool to assess environmental impacts of water and fertiliser use. The aim of this study was to understand potential impacts on environmental sustainability of agricultural intensification close to a protected forest area of the Amazon under climate change. We carried out a WFA to calculate the water footprint (WF) related to soybean production, *Glycine max*, to understand the sustainability of the WF in the Tapajós river basin, a region in the Brazilian Amazon with large expansion and intensification of soybean. Based on global datasets, environmental hotspots – potentially unsustainable WF areas – were identified and spatially plotted in both baseline scenario (2010) and projection into 2050 through the use of a land-use change scenario that includes climate change effects.

* Corresponding author.

E-mail address: laura.miguelayala@wur.nl (L. Miguel Ayala).

Deforestation
Land use change

Results show green and grey WF values in 2050 increased by 304% and 268%, respectively. More than one-third of the watersheds doubled their grey WF in 2050. Soybean production in 2010 lies within sustainability limits. However, current soybean expansion and intensification trends lead to large impacts in relation to water pollution and water use, affecting protected areas. Areas not impacted in terms of water pollution dropped by 20.6% in 2050 for the whole catchment, while unsustainability increased 8.1%. Management practices such as water consumption regulations to stimulate efficient water use, reduction of crop water use and evapotranspiration, and optimal fertiliser application control could be key factors in achieving sustainability within a river basin.

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1. Introduction

One of the most problematic issues affecting the natural environment is agricultural expansion and intensification. Increasing food feed and energy demands leads to more intensive farming and landscape transformation. The conversion of natural areas to new cropland is particularly marked in tropical regions (Neill et al., 2013; Hoekstra and Wiedmann, 2014).

In recent decades, the acceleration of agricultural expansion – but also land use intensification – has resulted in a significant negative impact to tropical rainforests, leading to deforestation, loss of biodiversity and ecosystem services, and changes to watershed hydrology and water balance (Lathuillière et al., 2014; Neill et al., 2013). Sampaio et al. (2007) emphasize the importance of Amazonian rainforests in the regulation of climate, conservation of biodiversity and maintenance of ecosystem services in the region. The removal of forest cover can lead to reduction of evapotranspiration, which is expected to cause a decrease in precipitation and an increase in surface temperature (Sampaio et al., 2007). In the Amazon rainforest region, agricultural encroachment, including soybean expansion, is the major reason for deforestation.

The expansion of soybean fields and the subsequent change in land use is increasing dramatically in countries such as Brazil since the second half of the 20th century. Brazil has become the second biggest producer of soybean in the world after the United States of America, with a harvest of 65.8 Mtons per year (Faostat, 2014). Government subsidies and cheaper land, among other reasons, facilitate the advance of soybean into the Brazilian Amazon (Fearnside, 2001). Soy expansion in the Santarem region (state of Pará, Brazil) has been increasing since the opening of Santarem port in the last decade, which boosted trade and, ultimately, the conversion of forests to soybean fields (Steward, 2004; Vera-Diaz et al., 2009). Since 2006, initiatives such as the Brazilian Soy Moratorium – a private sector agreement to not purchase soy grown on deforested lands in the Brazilian Amazon after July 2006 – and other environmental protection policies, as well as the drop of the market due to the recent global recession contributed to the reduction of deforestation rates after 2006 (Assunção et al., 2015; Nepstad et al., 2014). Regardless of the (in-)direct effect of policies on deforestation rates, neither the Soy Moratorium nor the recent world recession could stop soybean expansion (Gibbs et al., 2015). This pattern is also visible in the Santarem region.

A large amount of water and nutrients (e.g. phosphorus and nitrogen contained in fertilisers and in the soil) are required to maintain high level of soybean production. The increase in water and nutrient use for soybean production is known to be a potentially significant cause of water contamination (Lathuillière et al., 2014), which could have a negative impact on nearby water bodies. Liu et al. (2012) show that anthropogenic nutrient input into the major rivers of the world is increasing. Water and nutrient resources are also virtually flowing out the region, embedded in the soybean product, to other areas or countries through the export of soybean (Lathuillière et al., 2014). Therefore, the increase in water and nutrient use not only affects nearby water bodies, but it also has implications on environment from the global perspective.

Several methods can be applied to assess these environmental impacts from different perspectives. These methods are, among others,

Life Cycle Assessment (LCA), the Ecological Footprint (EF) method and the Water Footprint Assessment (WFA). LCA has been widely applied to evaluate the environmental impact of products by looking at the potential impacts throughout the entire life cycle of the products, while the EF method is used to assess the environmental sustainability of land use changes (Alvarenga et al., 2012; Da Silva et al., 2010; Ruviaro et al., 2012). The aims and application boundaries, thus the pros and cons of these methods with respect to their applications have been elaborated in a number of scholar discussions such as Boulay et al. (2013), Chenoweth et al. (2014), and Hoekstra (2016).

The Water Footprint Assessment (WFA) aims to study the sustainability of the water footprint of processes, products, organisations or geographic areas from environmental, economic and social dimensions that leads to the formulation of water footprint response strategies. The WFA is a four-phase methodological framework encompassing: setting goals and scope, water footprint accounting, water footprint sustainability assessment, and water footprint response formulation (Hoekstra et al., 2011). The water footprint measures human appropriation of freshwater resources that occurs not only directly but also indirectly, e.g., supply-chain water use for a product (Galli et al., 2012; Hoekstra et al., 2011). It takes into account both consumptive water use (quantity) and water pollution (quality). WFA studies can feed the discussion within different sectors or contexts that relate to water management strategies and water allocation policies and they can also form a starting-point for more in-depth assessments of environmental, social and economic impacts of water use (Zhang et al., 2013). Water footprint can be expressed spatially which allows the assessment to contextualise the impact in a specific region. The WFA offers potential to assess the environmental impact of water footprint using a variety of river basin oriented indicators such as blue water scarcity, green water scarcity and water pollution level (e.g. Mekonnen et al., 2015; Mekonnen and Hoekstra, 2015; Mekonnen and Hoekstra, 2016). Particularly, the green water scarcity (Schyns et al., 2015) is a unique measure for water resources management and environmental impact assessment relevant to the areas with rain-fed agriculture and nature conservation. Therefore, WFA proves to be a useful methodology to assess the impact of soybean production since it has a strong link between water, pollution, land use and climate changes (Bocchiola et al., 2013; Orłowsky et al., 2014; Zoumides et al., 2014).

The aim of this study was to understand the potential impacts on environmental sustainability of agricultural intensification close to a protected forest area of the Amazon under climate change. Soybean production (*Glycine max*) has intensified and expanded in recent decades in the Tapajós river basin, one of the main sub-basins of the Amazon. According to the data of Hansen et al. (2013), 12.8% of the pristine rainforest in the Tapajós river basin has been deforested since 2000. Agricultural intensification entails impacts on the environment which could, in the long term, compromise the sustainability of the basin. It especially raises concerns due to the risk of endangering the protected areas in the catchment. In order to understand the sustainability of the WF in the Tapajós river basin we carried out a Water Footprint Assessment (WFA) in the uppermost part of the basin near the city of Santarem (study area), using both locally- and globally-available data (Hoekstra et al., 2011). This is a novel approach to the application of the WFA to understand the potential impact of agricultural expansion

in the Amazon at the catchment level under climate change scenarios. Using the green water scarcity in this study to assess the impact on environmental sustainability is a pioneering work attempting to tackle the challenge of determining the productive green water flow in space and time. We identified the environmental hotspots, i.e., areas where the WF is potentially unsustainable. The WF and hotspots were spatially plotted across the river basin in order to assess the current impact of soybean expansion and create a baseline scenario. Additionally, we identified the areas of potential change in 2050 by using a land use change scenario that includes climate change effects in a future socio-economic context (Van Eupen et al., 2014).

2. Materials and methods

2.1. Study area

The study area is located in the northern part of the Tapajós river basin in the state of Pará, northern Brazil, and the river is one of the main tributaries of the Amazon River (Fig. 1). The study area covers approximately 42,352 km² (as measured by GIS analysis) which belongs to the Flona Tapajós (in Portuguese: “*Floresta Nacional de Tapajós*”; Tapajós National Forest) and its surroundings (Fig. 1). Annual precipitation in the study area ranges between 1750 mm to 2250 mm, with a mean annual precipitation of ~2000 mm, of which >75% falls during the wet season (December to May) (FAO, 2006; Smith, 1993; WorldClim-Global Climate Data, 2014). Daily average temperature ranges between 21 °C and 30 °C, with a mean annual temperature of 26 °C (FAO, 2006; Smith, 1993; WorldClim-Global Climate Data, 2014). The demand for more crop and livestock areas of this region in recent years has led to widespread deforestation mainly concentrated around the largest urban centres of Santarém, Belterra and Ruropolis

(IBAMA, 2004). In this area, soybean production has largely encroached into the deforested areas with production intensification in the last few decades (Lathuilière et al., 2014).

Flona Tapajós was designated as a protected area for sustainable use by decree in 1974 (Brazil, 1974) (Tanner et al., 1997). Sustainable-use areas allow for controlled resource extraction, land use change and, in many instances, human settlements (Hayashi et al., 2011; Veríssimo et al., 2011). Parts of the Flona are considered an international focus area for monitoring undisturbed primary forests (Gonçalves et al., 2013). Deforestation for agricultural use is the main cause of environmental alteration in the Flona Tapajós (IBAMA, 2004). The amount of deforestation in the study area is comparable with the amount of deforestation found in the entire Tapajós river basin (Hansen et al., 2013). Since 2000 the deforestation accounts for 10% of all forests in the study area. This deforestation is, however, unevenly distributed within the study area: the two protected areas (*Tapajós National Forest* and *Tapajós Arapiuns*) show a percentage of 1.4% deforestation while the rest of the study area reaches 14.0% (Hansen et al., 2013; INPE, 2015).

2.2. The Water Footprint Assessment

The Water Footprint Assessment (WFA) is the methodological framework (Hoekstra et al., 2011) under which a full range of water footprint studies are to be conducted in phases, including:

1. defining goals and scope: determine study objectives, scope, and boundaries,
2. accounting water footprint: quantify water footprint (of a process or product) and locate where it occurs,
3. assessing water footprint sustainability: analyse and evaluate the sustainability of the water footprint within a geographical context

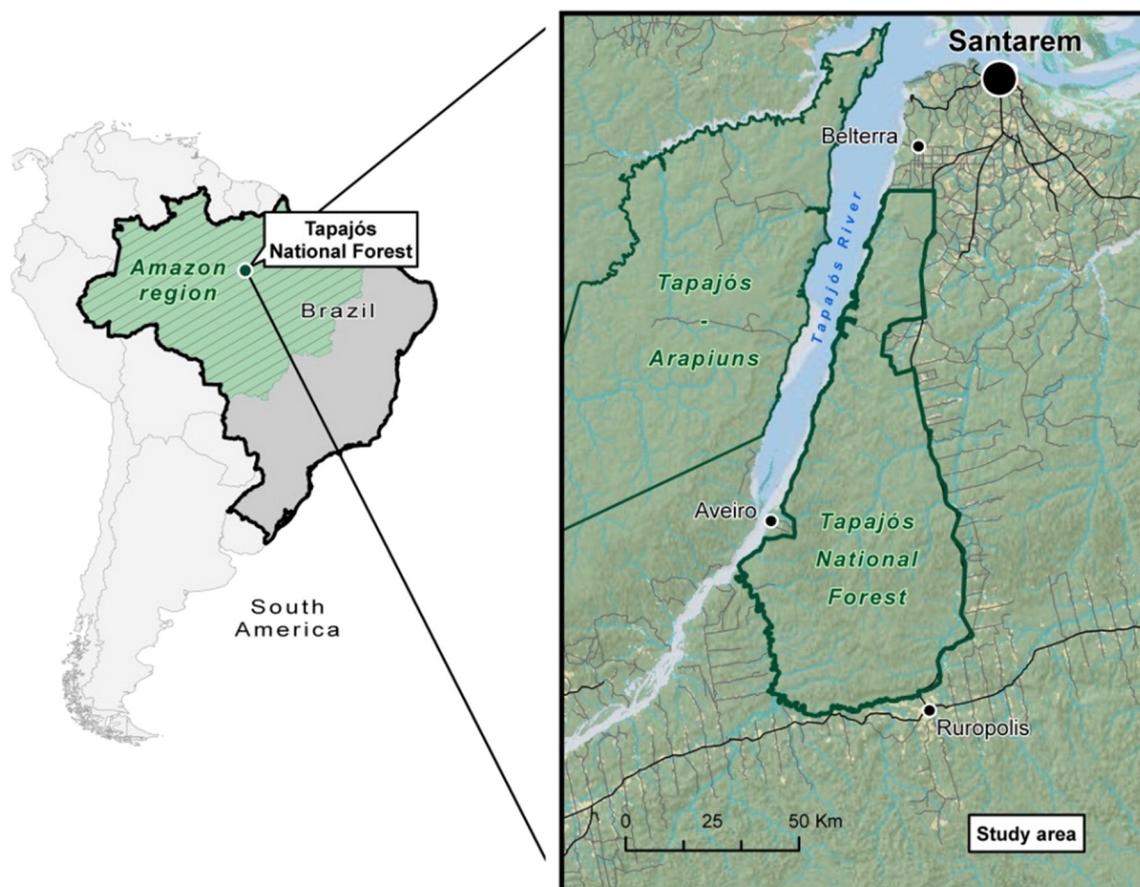


Fig. 1. Map of the study area in Tapajós river basin, Amazon region, Brazil.

- (e.g., a basin) from environmental, economic and social perspectives, and
- formulating water footprint response strategies: identify response strategies and measures to improve water footprint sustainability.

The scope of this study is the assessment of the WF within a catchment area of Tapajós river basin (Section 2.1), aiming to evaluate the impact of expected soybean expansion based on projected land use and climate changes for 2050. In this study, we focus on water footprint accounting and environmental sustainability assessment while economic and social sustainability assessment and the response formulation are left out of this study scope for a further research.

2.2.1. Water footprint accounting

The total water footprint of soybean production generally comprises three components: blue WF (consumptive use of surface water and groundwater), green WF (consumptive use of rainwater stored as soil moisture) and grey WF (pollution assimilation capacity consumed) (Hoekstra et al., 2011). In this study we did not consider blue WF since no irrigation has been applied in soybean cultivation in Tapajós river basin. The WF of soybean was calculated from planting to harvest, considering one growing season per year in the study area.

Data for the WF calculations were derived from the most recently available national and international databases and models (Table 1). Year 2010 was chosen as the reference year for comparison because it is the year with the most recent available land use database (TerraClass 2010) matching with the current climatic conditions (Coutinho et al., 2013). Year 2050 was chosen for the future scenario projections as it is considered a good intermediate timeframe for both climate projections (long term) and policy projections (short term), as described by Jones and Kok (2013). In order to generate land use maps for the 2010 baseline and 2050 projection, a conventional economic growth scenario was chosen and applied the CLUE land use change model (Verburg et al., 2002) (Section 2.3). Values of precipitation and temperature were obtained from WorldClim database (Table 1). For the reference year (2010) interpolations of observed data representative of 1950–2000 were used; climate data for the 2050 projection was obtained using the most recent global climate projections that appear in the Fifth Assessment IPCC report (Flato et al., 2013; WorldClim-Global Climate Data, 2014). The resolution of the used WorldClim data is approximately 1 km² (Table 1).

Local expert knowledge indicates that soybeans cannot be grown in the south of the Flona, rendering only the north of the catchment suitable for soybean cultivation. Further, areas with a slope >8% cannot be worked by heavy machinery and are also considered unsuitable for

Table 1
Input data, variables and data sources for Green & Grey WF calculations.

Variable	Unit	Method	Data source	Reference
Reference crop evapotranspiration (ET ₀)	mm	using monthly Global Potential Evapo-Transpiration data	CGIAR-CSI	CGIAR-CSI (2014); Trabucco and Zomer (2009)
Total crop evapotranspiration (ET _c)	mm	Calculated in this study (Eq. (3))		
Crop coefficient (K _c)	–	Adjusted from FAO (Table 1)	FAO Crop Water Information: Soybean	Allen et al. (1998); FAO (2014)
Digital elevation model	m	Resolution 3 arc sec (~92 m)	Shuttle Radar Topographic Mission	USGS (2014)
Precipitation	Mm (monthly) in 2010	WorldClim-Global Climate Data, time period 1950–2000	WorldClim-Global Climate Data	WorldClim-Global Data (2014)
	Mm (monthly) in 2050	WorldClim-Global Climate Data, 2050 scenario HadGEM2-ES, RCP85 (= SSP5)	WorldClim-Global Climate Data	WorldClim-Global Data (2014)
Effective precipitation (P _{eff})	mm/month	Effective rain USDA Soil Conservation Service Method. Results were validated with CROPWAT model & CLIMWAT 2.0 database for the city of Santarem	Calculated in this study	Dastane (1978); FAO (2006); FAO (2009); Smith (1992); Smith (1993)
Temperature	°C (monthly) in 2010	WorldClim-Global Climate Data (2014): 1950–2000 2010 minimum temperature; 2010 maximum temperature; 2010 mean temperature		WorldClim-Global Data (2014)
	°C (monthly) in 2050	WorldClim-Global Climate Data (2014), 30 arc sec ~ 1 km: 2050 minimum scen. HadGEM2-ES, rcp85 2050 maximum scen. HadGEM2-ES, rcp85		WorldClim-Global Data (2014)
Land use	2010	Combination of TerraClass 2010 & 2010 CLUE continental run		Coutinho et al. (2013) & Van Eupen et al. (2014)
	2050	CLUE continental scenario SSP5s = SSP5 = Conventional development (development first) with the absence of carbon-focused or other policies)		Van Eupen et al. (2014)
Soil		Harmonised World Soil (HWSO) in combination with Brazilian soil map Mapa de Solos do Brasil, Rio de Janeiro: 1:5,000,000	IBGE; FAO, IIASA, ISRIC, ISSCAS, JRC	FAO, IIASA, ISRIC, ISSCAS, JRC (2012); IBGE (2001)
Slope		SRTM data using the slope function in ArcGIS 10.2	Shuttle Radar Topographic Mission	USGS (2014)
Yield	t/ha	Adjusted from literature for baseline scenario (2010) and 2050 scenario.		IBGE (2014); Masuda and Goldsmith (2009); MGAP (2012)
Fertiliser application rate	kg P/ha		FAO Fertistat	FAO Fertistat (2014)
P leaching-runoff fraction	–			Hoekstra et al. (2011); Velthof et al. (2009)
Maximum phosphorus concentration (C _{max})	mg/l			CONAMA 357/2005 (2005)

soybean cultivation. Therefore, the southern areas of the basin, such as the valley of Ruropolis (Fig. 1) are not considered soybean cultivation zones, but rather for grazing and other agricultural activities and are indicated as rangeland in baseline and future scenarios (L. Martorano, personal communication, October 2014). All suitable cropland areas which appear in both baseline (2010) and future projection (2050) maps were parameterised as soybean, the most rapidly expanding crop (1% to ~35% of total planted area between 2002 and 2010, Fig. 2), and therefore causing the greatest impact on the sustainability of the area. Other crops are not taken into consideration in this study in order to be able to compare the impact of exclusively soybean production.

2.2.1.1. *Green WF*. The green WF was calculated as follows (Hoekstra et al., 2011):

$$WF_{green} = \frac{CWU_{green}}{Y} \text{ [m}^3\text{/ton]} \quad (1)$$

where CWU_{green} is crop green water use in mm and Y is the yield expressed in t/ha. CWU_{green} is calculated by accumulation of daily evapotranspiration (ET_{green}) during the growing period. Green water is the precipitation water stored in soil as soil water for crop growth. Green water evapotranspiration (ET_{green}) was taken as the minimum of effective precipitation (Pe_{eff}) and total crop evapotranspiration (ET_c), as per Hoekstra et al. (2011):

$$ET_{green} = \min(ET_c, Pe_{eff}) \text{ [mm/month]} \quad (2)$$

Effective precipitation, which is defined as the part of the rainfall which is stored in the root zone and can be used by the plants, was determined with the help of the CROPWAT tool (FAO, 2009; Smith, 1992) and the CLIMWAT 2.0 database (FAO, 2006; Smith, 1993) using the method of the Soil Conservation Service of the United States Department of Agriculture (USDA SCS) provided by FAO guidelines (Dastane, 1978). The total crop evapotranspiration is determined by

$$ET_c = ET_0 \times Kc \quad (3)$$

where ET_0 is reference crop evapotranspiration and Kc is crop coefficient. ET_c (Eq. 3) was calculated per cell (1 cell is derived from 3 arc-seconds coordinate system WG84_UTM22S 92.56433397 m squared \approx 0.85 ha) and grouped per watershed in order to identify WF hotspot areas. We considered the sub-watersheds inside the protected area to have a maximum size of approximately 1700 km² in order to summarise the output values. Reference crop evapotranspiration (ET_0) data were obtained from CGIAR-CSI (Trabucco and Zomer, 2009).

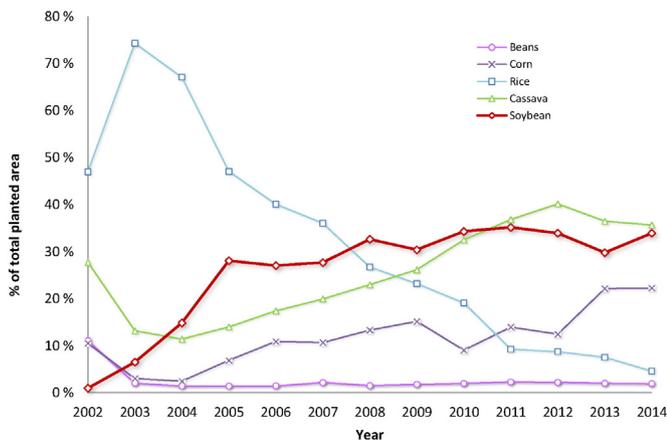


Fig. 2. Share of the main crops in the municipalities of Santarem and Belterra between 2002 and 2014 (IBGE, 2016).

The crop coefficient (Kc) incorporates crop characteristics and averaged effects of evaporation from the soil (Allen et al., 1998). According to the literature (Neill et al., 2013; Sampaio et al., 2007), ET is 25–30% higher in forest than in cropland in north-eastern Amazon. ET_c data were, therefore, adjusted in cropland areas to yearly 25% lower values, using different Kc factors per month. Kc values were monthly adjusted in a way that results in a yearly 25% lower ET_c (Table 2) following the soybean development stages curve provided by FAO (2014). From a conservative point of view, we assumed bare soil after growing period which implies that there is no second crop after harvesting.

ET_{green} values were summed per month for one growing period in 2010. We considered an average growing period of 3.5 months (105 days, from December to March) (El-Husny et al., 2003; El-Husny et al., 2006; L. Martorano, personal communication, October 2014). A factor 10 was used to convert ET_{green} (mm) into CWU (m³/ha).

In the baseline scenario, a value of 2.5 t/ha was assigned as average yield (IBGE, 2014; Masuda and Goldsmith, 2009; MGAP, 2012). In the 2050 scenario, according to the SSP5 scenario, the yield trend shows an increase to 3 t/ha as per Masuda and Goldsmith (2009) and MGAP (2012). Per the definition of the water footprint, i.e. appropriation of fresh water resources for human activities, if a natural forest is not used for timber production or other purposes for human use, evapotranspiration of rainwater is not part of the “green water footprint”. In this case, we only consider ‘yield’ as coming from cropland (soybean) as it is assumed the forest is not intended to be used for timber production. All cropland areas are considered soybean, therefore the following rule was applied: if yield = 0 (e.g., in case of no cropland area), then $WF = 0$. An increase of soybean production area would mean an increase in CWU and Y , and consequently WF final values will also vary. In this study, the water incorporated into the harvested crop has not been taken into account due to the fact that its addition only accounts for between 0.1 and 1% of the water footprint related to the evaporated water (Hoekstra et al., 2011).

2.2.1.2. *Grey WF*. The grey water footprint (GWF) is “an indicator of the fresh water volume needed to assimilate a pollutant load that reaches a water body” (Hoekstra et al., 2011). It is essentially an indicator to reflect the water pollution of a process. Pollution can be a result of emissions from either point sources or diffuse sources, or both. In the case of soybean cultivation, we consider that pollution results from diffuse sources due to the application of agrochemicals such as fertilisers. The GWF of diffuse pollution is calculated by

$$GWF = \frac{L}{C_{max} - C_{nat}} \text{ [m}^3\text{/year]} \quad (4)$$

$$L = \alpha \times Appl \text{ [kg/ha]} \quad (5)$$

We followed the approach of Franke et al. (2013) to determine parameters such as the runoff leaching coefficient (α) in the above equations. The pollutant load (L , in mass/time) is divided by the difference between the ambient water quality standard of the pollutant (the maximum acceptable concentration C_{max} , in mass/volume) and its natural background concentration in the receiving water body (C_{nat} , in mass/volume).

A certain percentage of chemical substances applied to the soil is lost to the surface or groundwater due to leaching or runoff. This fraction (α) varies per substance. As explained by Hoekstra et al. (2011), if the water body is able to dilute the pollutant with the highest

Table 2

Adjusted soybean crop coefficients (Kc) in Tapajós river basin based on the FAO database (FAO, 2014).

Month	Dec	Jan	Feb	March	Apr	Jun	July	Aug	Sep	Oct	Nov
Kc	0.65	1.15	1.00	0.75	0.50	0.60	0.60	0.60	0.60	0.60	0.60

concentration, it is assumed that other co-existing pollutants will be assimilated simultaneously. According to Fertisat data (FAO Fertisat, 2014), phosphorus is one of the most critical contaminants in Brazil. Due to its potentially hazardous environmental impact, we focused our GWF assessment on phosphorus. We considered a phosphorus application rate (*Appl*) of 66 kg P/ha on the soil (FAO Fertisat, 2014).

According to Franke et al. (2013), the average leaching-runoff fraction for phosphorus (α , dimensionless) is 0.03. This means that 3% of phosphorus content in the applied fertiliser would eventually reach the nearby water bodies. Heathwaite et al. (1998) reported that runoff from sloping soils was generally around the 10% of the N and P applied as fertiliser or manure. Therefore, we adjusted the leaching-runoff factor by accounting for runoff and slope, varying the factor of these accordingly within the range of 0.03–0.1 (Velthof et al., 2009).

Basin-specific values for the maximum and natural concentrations (*Cnat* and *Cmax*) for the Tapajós river basin were not found in literature. It is reported that particulate phosphorus accounts for some 90% of total phosphorus (particulate phosphorus and dissolved phosphorus) that is present in rivers (Lewis, 2008). However, particulate phosphorus values found in the Amazon system are generally very low (Allan and Castillo, 2007; Lewis, 2008). Therefore, due to the lack of basin-specific natural background concentration data, and in order to keep our GWF conservative, *Cnat* value was assumed to be zero.¹

The GWF [m^3/yr] is calculated with reference to the Brazilian ambient water quality standards in order to evaluate the ability of the receiving water body to assimilate the phosphorus load. According to the Brazilian standards and environmental legislation (CONAMA 357/2005, 2005), the maximum allowable total phosphorus concentration (*Cmax*) for lotic environments (such as rivers or streams) is 0.1 mg/L. A summary of data sources is presented in Table 1.

2.2.2. Sustainability assessment

The water footprint within a catchment needs to meet certain criteria in order to be considered sustainable. We assessed sustainability solely from an environmental point of view, which is expressed in terms of green water scarcity (*WSgreen*) and water pollution levels (*WPL*) through the identification of environmental hotspots. By definition, the water footprint in a river catchment is environmentally unsustainable when the environmental water needs are disrupted, or when local environmental assimilative capacity is exceeded (Hoekstra et al., 2011).

2.2.2.1. Environmental sustainability of green WF – green water scarcity.

There are a number of indicators representing green water availability and scarcity (Schyns et al., 2015). In this study we apply the green water scarcity defined in Hoekstra et al. (2011) in order to maintain the methodological consistency. It is defined as the ratio of the calculated green water footprint, *WFGreen*, which accounts for the WF coming from soybean production, to the green water availability in the catchment.

$$WS_{green} = \frac{WFGreen}{WAGreen} [-] \quad (6)$$

where *WAGreen* is the green water availability, which is determined by:

$$WAGreen = ET_{green} - ET_{env} - ET_{unprod} \quad [\text{m}^3/\text{year}] \quad (7)$$

¹ The records of a measuring point in Pedreira, a riparian municipality where the background concentration of phosphorus (*Cnat*) proved to exceed the Brazilian ambient water quality standards in 1996 (IBAMA, 2004). This indicates that small communities already experience some effects of P contamination. However, we consider Flona to be a natural environment and the scope of this study extends to the whole catchment (including the effect of other tributaries). Therefore, we considered *Cnat* to be zero.

where *ETgreen* (Eq. (2)) is the total evapotranspiration of rainwater from land, *ETenv* is the evapotranspiration from land reserved for natural vegetation and *ETunprod* is the evapotranspiration from land that is not productive or unsuitable for the crop.

When *WSgreen* is equal or > 100% it means that the total green water consumption is equal or larger than the total green water available in the catchment. This indicates that the catchment is a green water scarcity hotspot and the green water footprint in the catchment is unsustainable.

Green WF sustainability criteria were chosen conservatively in order to take the inaccuracy of the used datasets into account. These criteria are the following:

- *WSgreen* > 100%, the green WF is “unsustainable” (hotspot area);
- $50\% \leq WSGreen \leq 100\%$, the green WF “poses a threat” to the environment in the future;
- $25\% \leq WSGreen < 50\%$, the green WF lies “within sustainability limits”;
- $10\% \leq WSGreen < 25\%$, the green WF is considered “sustainable”;
- *WSgreen* < 10%, the green WF is considered to have no negative impact on the environment.

Fig. 3 shows the cell-specific settings that were taken into account in the calculations to determine *WFgreen* in a spatially-distributed manner, given the spatial variation of land use patterns in the study area. Fig. 3a shows the current situation (2010) and Fig. 3b refers to the projected scenario (2050). Yellow cells represent cultivated soybean, while green cells account for forest and other natural vegetation. Since we were working with a future scenario that lacks any policies to safeguard protected areas, we considered soybean areas that are located inside the Flona as being unprotected (i.e., illegally cultivated and with no law enforcement in place). Therefore, they are not included within *ETenv* but kept within *ETgreen*, defined in Fig. 3 as *Env Protected but not accounted for ETenv*. *ETunprod* includes built-up areas (where *ET* = 0) and areas that are unavailable for cultivation (i.e., areas with a slope > 8%). If a cell is unproductive and protected, it will be included in one of the categories only in order to avoid double counting.

2.2.2.2. Environmental sustainability of grey WF – water pollution level.

The sustainability of the grey WF is evaluated using the water pollution level (*WPL*) as an indicator. By definition, water pollution level (*WPL*) is the ratio of total grey WF within the catchment to the actual runoff of the catchment. It is a measure of the degree of contamination within a catchment (Hoekstra et al., 2011):

$$WPL = \frac{WFGrey}{Ract} [-] \quad (8)$$

Where *WFGrey* is the total grey WF within the catchment and *Ract* is the actual run-off from the catchment area. When *WPL* of the catchment is > 100%, the catchment is considered to be a grey WF hotspot, implying that the grey WF in the catchment is not sustainable.

It is commonly assumed that the annual quantity of runoff is a proportion of the total annual rainfall (FAO, 1991). An accurate hydrological (rainfall-runoff) analysis would take into account interception, infiltration, root-zone water balance and deep percolation, among others (Kuchment, 2004). Due to a lack of data, however, we considered *Ract* as a potential run-off (*Rpotential*). *Rpotential* equals the total amount of the precipitation multiplied by a runoff coefficient (*Cr runoff*) (Kuchment, 2004; Yu et al., 2015). *Rpotential* is calculated monthly per cell and summed per year, per (sub-)catchment area:

$$Rpotential = (TotalPrecipitation) * Crunoff \quad (9)$$

Under high deforestation rates, atmospheric feedbacks are expected to cause reduced regional precipitation leading to a decreased discharge. As these land use change processes and atmospheric feedbacks

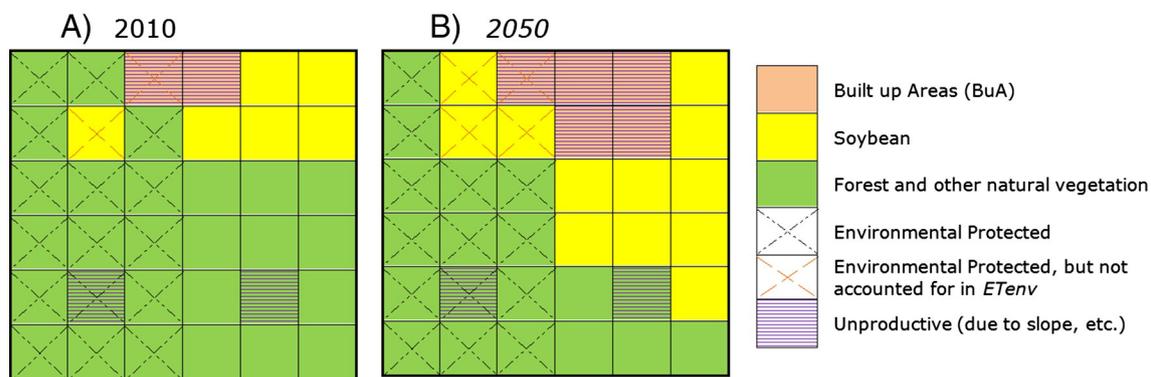


Fig. 3. Example map of the behaviour of the defined categories in the calculation of the green water availability (W_{Agreen}) for the two scenarios.

processes are counteracting each other on different spatial and temporal scales, significant, complex and unexpected changes in stream flow of Amazonian tributaries can be expected (Coe et al., 2009). Kuhl and Miller (1992) and Calde et al. (2002) found that the total runoff (R_{act}) lies within the range of 42% and 53% of the total annual rainfall in the Amazon area. Their approaches are based on the evaluation of the total Amazon basin where seepage or other losses from one area will be counterbalanced by the contributions in another area. As previously mentioned, due to lack of data availability to perform more complex runoff analyses for the study area, the use of a runoff coefficient approach (C_{runoff}) was considered adequate. The runoff coefficient is influenced by the type of soil and land use, among others (Kuchment, 2004; Yu et al., 2015). Since carrying out a precise estimation of the runoff fraction is not within the scope of this study, we assumed a C_{runoff} value of 0.5. This value was kept constant for both the 2010 and 2050 scenarios for ease of comparison.

In order to evaluate the level of sustainability of the grey WF in the catchment, we used the following grey WF sustainability criteria:

- $WPL > 100\%$, the grey WF is “unsustainable” (hotspot area);
- $50\% \leq WPL \leq 100\%$, the grey WF “poses a threat” to the environment in the future;
- $25\% \leq WPL < 50\%$, the grey WF lies “within sustainability limits”;
- $10\% \leq WPL < 25\%$, the grey WF is considered “sustainable”;
- $WPL < 10\%$, the grey WF is considered to have no negative impact on the environment.

2.3. Future soybean expansion scenario

2.3.1. Selected future socio-economic context in 2050

Future socio-economic contexts (SSPs) - described as the challenges faced by society with respect to climate change mitigation and adaptation (Jones and Kok, 2013) and in combination with policies and climate pathways (RCP) were selected as framework for the scenario context in 2050. From this broad range of possible futures the most conventional development oriented scenario was selected, reflecting a situation with a high potential impact on agricultural water use. The selected scenario focusses towards economic growth as the solution to social and economic problems and shows a lack of any policies to manage carbon stocks or additional safeguards of ecosystem services, resulting in a severe agricultural expansion in Brazil and subsequently, in the Tapajós region. The energy system is dominated by fossil fuels; human development goals are attained; there is a highly engineered infrastructure and highly managed ecosystems. The lack of specific policies for protecting biodiversity, deforestation and degradation continues or there is return to previously high deforestation rates due to the abandonment or failure to enforce existing policies. The long-term trend in deforestation will largely depend on the increase in livestock yields on existing managed land. Historical trends of deforestation of Conservation Units by INPE

show that 95% of Brazilian nationally protected areas is effectively protected (Verburg et al., 2014). An analysis of the detailed deforestation data given by INPE (2015) indicates that both the Tapajós-Arapiuns and the Tapajós National Forest showed historical signs of small scaled deforestation. Tapajós National Forest clearly shows a strong negative trend in deforestation since the moratorium with an average deforestation rate of around 1 km^2 per year. This average deforestation rate is well below the deforestation rates outside protected areas, which implies that a high level of law enforcement is being maintained inside both protected areas.

Protection status was used as one of the major location factors to model future land use change. Strictly protected areas in the Amazon consistently showed less deforestation in recent years compared with so-called “Sustainable Use Conservation Units”, regardless of the level of deforestation pressure. Between August 2009 and January 2011, the accumulated deforestation in protected areas was equivalent to 16.3% of the total deforestation occurring in the Amazon (Verissimo et al., 2011). Both major protected areas in the study region, Flona Tapajós and Arapiuns, are classified as “Sustainable Use Conservation Units”.

The CLUE-S land use allocation model (Verburg et al., 2002) was used for the spatial allocation of specific land use classes of the selected scenario in 2050. CLUE-S simulates competition among land uses for the available land use classes based on the demand at national level and the local options set by the biophysical and socio-economic environment.

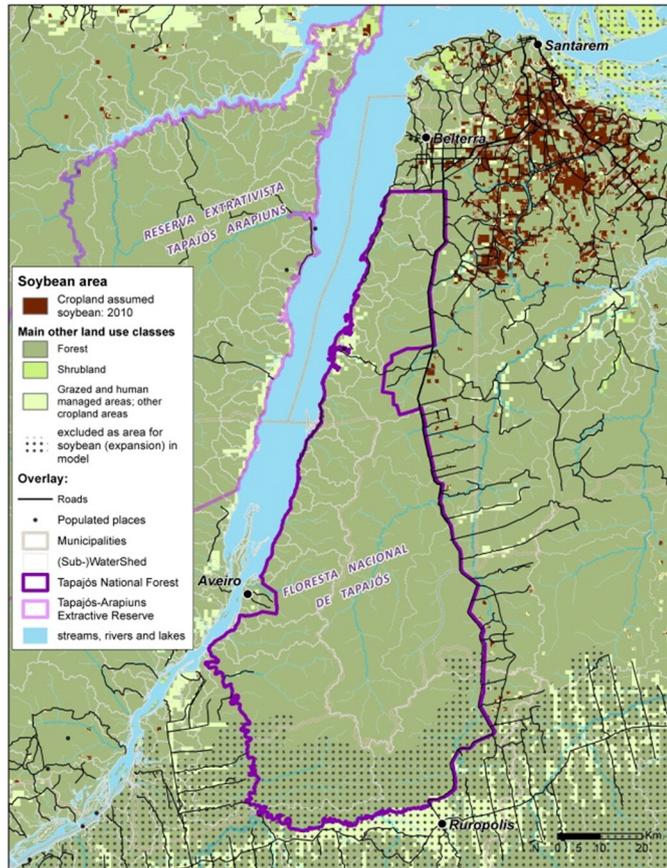
Yields of the most abundant crops were derived from FAOSTAT (2014) for the period 1961–2011 and IBGE (2014) for the municipalities in the study area for the period 2002–2014. Linear trends were fit to obtain the yields until 2050. The areas with the most abundant crops up to 2050 multiplied by their market shares provided us with the trend for the change in cropland area. To calculate demands for land use types, we used the following basic assumption:

$$\text{Area (ha)} = \frac{\text{Production (ton)}}{\text{Yield} \left(\frac{\text{ton}}{\text{ha}} \right)} \quad (10)$$

The main assumptions taken in making these calculations are as follows:

- There is a lack of policy to manage carbon stocks or additional safeguards of ecosystem services.
- The current environmental laws in place are valid: deforestation inside protected areas is not permitted, but the law is also not fully enforced. In practice, this will be reflected in a much more rapid deforestation rate outside protected areas, while areas under very high pressure for agricultural expansion inside protected areas will be deforested for soybean.
- As the exact spatial distribution of soybean in the area is not known, all cropland areas were considered soybean cultivation. Areas considered unsuitable (Fig. 4) were left out of the calculation.

Soybean area 2010



Expected expansion 2050

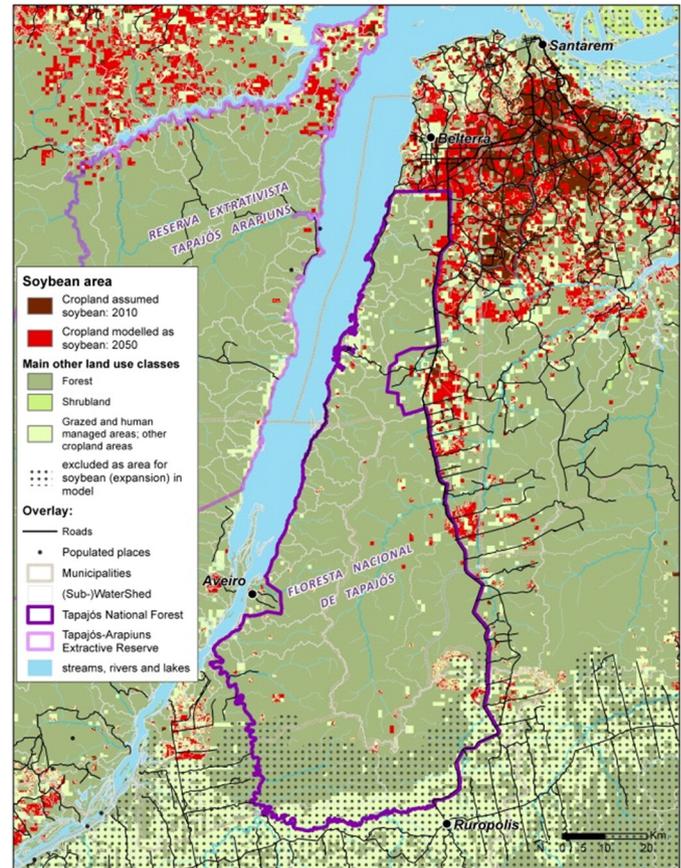


Fig. 4. Soybean expansion and main other land use changes, 2010–2050.

- 2050 scenario: yield equals 3 t/year.
- WorldClim-Global Climate Data for 2050 (HadGEM2-ES - RCP85, Table 1) was used to obtain associated rainfall data for the future projection scenario (2050). The climatic conditions vary considerably from 2010 to 2050: future temperature projection shows an increase between 3 and 4 °C showing the highest increase around the city of Santarém. On average there is ~18% less rain (350 mm less) over the year occurring mostly during the soybean growing period and located in the south of the study area.
- The same rules of calculation of green and grey water footprint of the baseline were applied in the 2050 scenario.
- The fertiliser rate was converted from kg P/ha to kg P/cell. We applied a conversion factor of ~0.85 to the fertiliser application rate (t/ha) in each cell since we used a raster cell size of approximately 0.85 ha.

Fig. 4 shows the land use classes, current soybean cultivation areas, and projected land use change and soybean expansion in the study area in 2050. The expansion is to a great extent confined to the north of the catchment, caused by the unsuitability of the south of the Flona for soybean cultivation (shaded area in Fig. 4). Some small pockets of soybean expansion can be found in both protected areas, but the main concentration extends in the north-east where better infrastructure and the larger municipalities of Belterra and Santarém are located.

Table 3 shows an overview of the land use change characteristics used as the basis for the WF calculations. The statistics are based on the expansion pattern of soybean visible in Fig. 4. The majority of soybean expansion takes place on existing pasture, primary and secondary forest areas outside the protected areas. The total modelled deforestation rate for the period 2010–2050 in the study area due to soybean

expansion is 5.7%; the deforestation rate of primary forest inside protected areas is not >2.1% by 2050. Both totals are very modest transition rates and considerably lower than the average historical rates (Hansen et al., 2013; INPE, 2015), which makes this future scenario plausible to be used in WF calculations.

3. Results

3.1. Water footprint accounting

Fig. 5 presents the map results of the green and grey water footprints for both the 2010 and 2050 scenarios. The results are summed per watershed with an averaged green WF per cell ranging between 1550 and 1700 m³/t, which is in line with the values found by Mekonnen and Hoekstra (2011).

WF values for both green and grey WF in the 2050 projection have increased considerably (304% and 268%, respectively) in comparison with both baseline WFs. More than one-third of the watersheds have duplicated their grey WF in comparison with the 2010 values. The maps show that higher values of WF appear in the north-eastern part of the basin which coincides with a higher concentration of roads, good accessibility and expected soybean expansion (Fig. 4). A similar increase in WF values could be expected in the south of the catchment. However, different rules apply in this area and no soybean expansion has been projected.

3.2. Environmental sustainability assessment

Table 4 shows GWS and WPL in 2010 and 2050 per region in the Tapajós river basin per environmental sustainability class. For both GWS

Table 3Overview of land use changes per land use class in 2010 and 2050 per area (km²) in the Tapajós river basin used for the WF accounting.

Land use change 2010–2050	Class	Land use 2010	Floresta Nacional Tapajós	Tapajósarapiuns	All other areas	Total study area
Existing land use not changed to soybean	(Semi-)natural vegetation	Primary forest	5046	5639	16,206	26,891
		Secondary forest	207	297	3587	4091
		Shrubland		19	509	528
	Subtotal (semi-)natural vegetation		5254 (95.3%)	5955 (93.5%)	20,301 (66.7%)	31,510 (74.5%)
	Human managed areas	Grazed shrubland	1		87	88
		Pasture	57	113	2219	2389
		Cropland	1	7	865	872
		Other	111	159	4768	5038
	Subtotal human managed areas		169 (3.1%)	279 (4.4%)	7940 (26.1%)	8388 (19.8%)
	Subtotal existing land use not changed to soybean			5423 (98.3%)	6234 (97.9%)	28,241 (7.2%)
Deforestation & intensification	Intensification to cropland, modelled as soybean	Secondary forest	15	38	690	744
		Shrubland		10	43	53
		Grazed shrubland			45	45
		Pasture	1	22	336	360
	Subtotal Intensification		16 (0.3%)	70 (1.1%)	1115 (3.7%)	1202 (2.8%)
	Deforested to cropland, modelled as Soybean	Primary Forest	75			
	Subtotal deforested to soybean		75 (1.4%)	62 (1.0%)	1085 (3.6%)	1223 (2.9%)
Subtotal deforestation & intensification to cropland modelled as soybean			91 (1.7%)	133 (2.1%)	2200 (7.2%)	2425 (5.7%)
Grand total			5514 (100%)	6367 (100%)	30,441 (100%)	42,322 (100%)

and WPL the majority of the classes demonstrate an increase in area towards the more unsustainable classes in 2050. Percentages of changes in the area per sustainability class are shown in the lower part of the table. The most remarkable increases are highlighted in bold. The Flona is kept within the limits of sustainability while the areas outside protection suffer an increase of 10.5% towards unsustainability. In the whole catchment, the areas without impacts have dropped 20.6% while unsustainability has increased 8.1%.

Fig. 6 shows the spatial results of GWS and WPL for 2010 and 2050. In the 2010 baseline, the majority of the catchment indicates sustainable GWS values ($GWS < 25\%$), which means that current soybean production does not compromise green water availability. The GWS results for 2050 show an increase in GWS values, especially inside the Flona protected area. This is due to the fact that the rules applied in the protected area are more strict as water is reserved for natural vegetation and therefore there is less water available for agriculture (Fig. 3). In the 2050 scenario, the sustainability of some of the northern areas of the catchment is compromised by the appearance of some areas that 'pose a threat' ($GWS > 50\%$) and several environmental hotspots ($GWS > 100\%$).

Overall current water pollution levels (baseline) can still be considered sustainable. However, the existing soybean areas in the north-eastern part of the basin show remarkably higher values and are already considered to be posing potential environmental risk in terms of sustainability. These high-risk areas, together with the new soybean expansion areas in the north-west, become unsustainable in the future scenario, indicating that there is insufficient natural capacity to assimilate the phosphorus load through the leaching of fertilisers. Fig. 6 shows that the majority of the impact occurs outside the Flona, where the greatest soybean expansion is expected. Most of the watersheds along the eastern part of the Flona, however, present higher pollution levels but these still remain within the sustainability limits ($WPL < 50\%$).

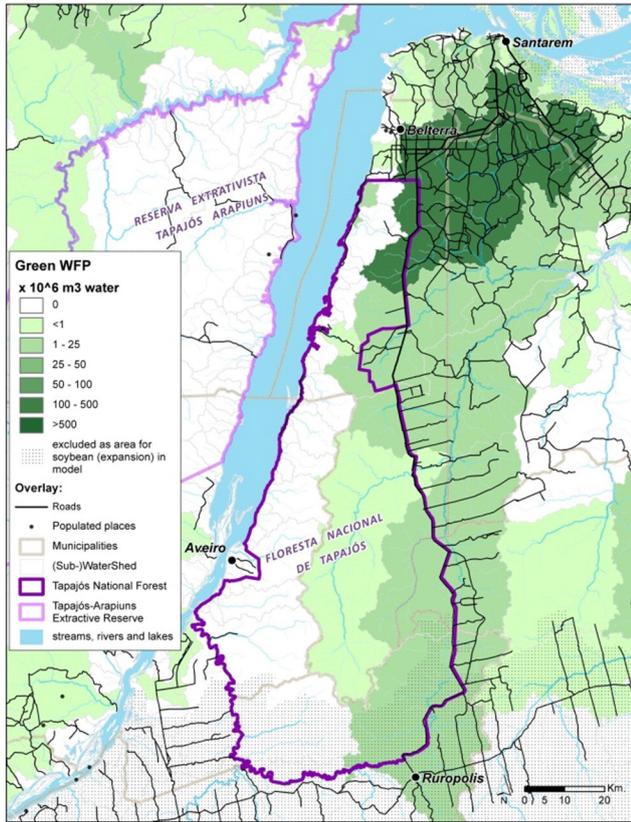
4. Discussion

The projected agricultural expansion is based on the outcome of a model (CLUE) that reflects a situation where deforestation rates are well below the historical average. The results are in line with a conceivable agricultural expansion and intensification in the Amazon region in a situation where policies do not work as planned. For example, the Soy Moratorium is no longer in effect, or the Forest Code is not properly implemented due to a fragile institutional framework (Verburg et al., 2014). Existing literature often focuses on the projection of land use change, including deforestation and agricultural expansion issues. There is little emphasis, however, on the links between land use change projection, water use and pollution, which is key information for sustainable water management and policy-making. Therefore, based on a simple approach we obtained a projection of soybean expansion in 2050, water footprint accounting values, water scarcity and water pollution levels based on fertiliser use (phosphorus concentration is used as a proxy), with which we assessed the sustainability of the study area.

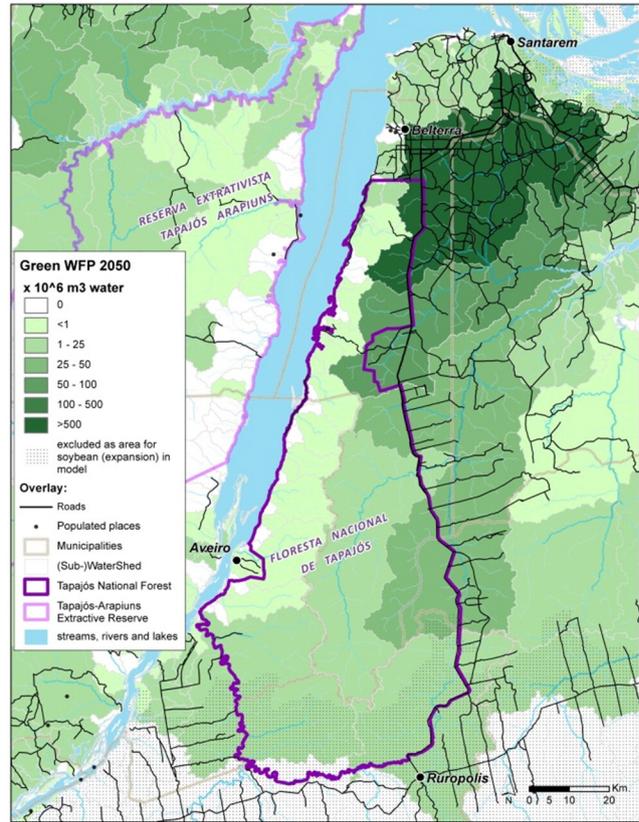
WF accounting results for the Tapajós river basin show an average increase in WF values for both green and grey WF in the 2050 projection in comparison with both baseline WFs. This increase is not equally dispersed across the area. Due to lower soybean expansion within the protected areas, the increase in WF values is remarkably higher in the areas outside the Flona. Both green WF and grey WF 2050 projections show higher values in the north-east of the basin (Fig. 5), which coincide with areas where currently the majority of agriculture and roads are concentrated and where transportation distances to the main river are minimal. WF results in the Flona area show a large increase considering the modest deforestation rates applied in the 2050 scenario (Table 3). This suggests that WF is a very sensitive indicator of (illegal) deforestation and agricultural expansion inside protected areas.

The Flona Tapajós is a protected area under Brazilian environmental legislation. In both 2050 projections, and in the grey WF 2050 projection

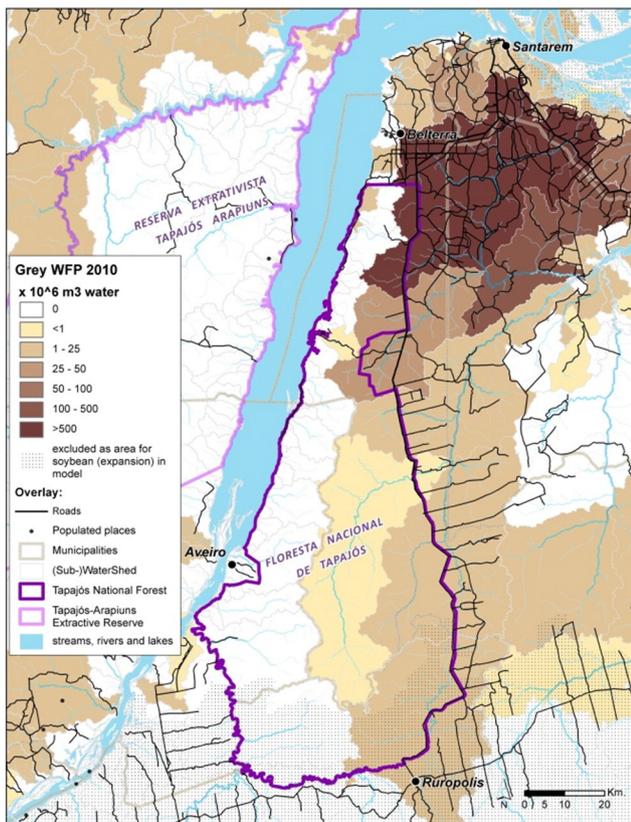
Green Water Footprint 2010



Green Water Footprint 2050



Grey Water Footprint 2010



Grey Water Footprint 2050

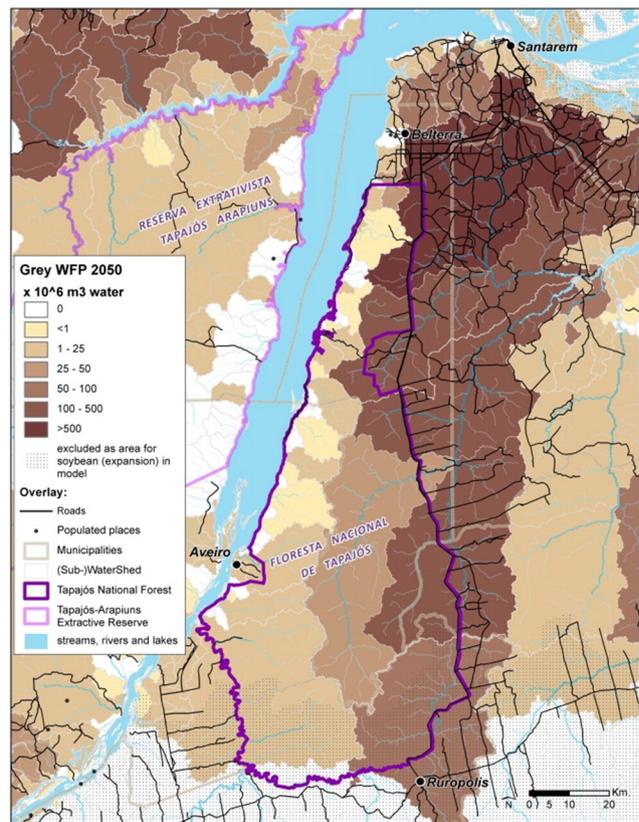


Fig. 5. Green and grey WFs for the baseline scenario (2010) and the projection (2050). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4

Green water scarcity and water pollution levels in 2010 and 2050 per region in the Tapajós river basin, expressed in both area (km²) and percentage of change per sustainability class.

Sustainability class (km ²)	Floresta Nacional de Tapajós				Tapajós Arapiuns				All other areas				Total study area			
	Green water scarcity		Water pollution levels		Green water scarcity		Water pollution levels		Green water scarcity		Water pollution levels		Green water scarcity		Water pollution levels	
	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050
<10%: No impact	5248	2614	5304	4167	6262	3354	6328	5730	28,311	23,579	26,863	19,696	39,856	29,292	38,584	29,766
10–25%: Sustainable	234	1525	26	727	0	666	3	125	2116	3613	1191	3150	2304	5867	1185	3973
25–50%: Within limits	32	1216	0	377	95	1881	34	206	3	3129	672	1739	140	6373	687	2315
50–100%: Posing threat	0	122	184	57	8	387	0	166	1	85	1709	2668	9	632	1856	2826
>100%: Unsustainable	0	36	0	185	2	79	3	139	11	35	6	3189	13	158	9	3441
Sustainability class (% of change)	2010–2050		2010–2050		2010–2050		2010–2050		2010–2050		2010–2050		2010–2050		2010–2050	
<10%: No impact	–47.8%		–20.6%		–45.7%		–9.4%		–15.5%		–23.5%		–25.0%		–20.8%	
10–25%: Sustainable	+23.4%		+12.7%		+10.5%		+1.9%		+4.9%		+6.4%		+8.4%		+6.6%	
25–50%: Within limits	+21.5%		+6.8%		+28.1%		+2.7%		+10.3%		+3.5%		+14.7%		+3.8%	
50–100%: Posing threat	+2.2%		–2.3%		+6.0%		+2.6%		+0.3%		+3.1%		+1.5%		+2.3%	
>100%: Unsustainable	+0.7%		+3.4%		+1.2%		+2.1%		+0.1%		+10.5%		+0.3%		+8.1%	

in particular, the edges of the protected area are to a certain extent affected by the expansion of the cropland area, which in terms of grey WF implies an increase in contamination. Measured levels of P-contamination within the tributaries of the Flona locally exceed the ambient water quality standards, showing that there are areas already under pressure. An increase in contamination from agricultural activities would hamper adherence to Brazilian water quality standards in the region.

WF environmental sustainability values lie predominantly below 25% in the baseline scenario which indicates that sustainability is safeguarded, but it will be easily compromised in the future if the current conditions are maintained (i.e., fertiliser application, projected soybean expansion). According to the green water scarcity (GWS) calculations, water within protected areas is reserved for natural vegetation, which leaves less water available for agriculture. Therefore, there is a higher impact of soybean expansion shown within the Flona in the future scenario in terms of GWS. It can be seen how even a small expansion of soybean agriculture in the current situation can cause a large impact in terms of water scarcity in the future. Soybean agriculture is not yet beyond the threshold of sustainability in the current situation, but this could easily change in the future. In this regard, the results demonstrate how the protection of certain environments is directly related to water use and availability. GWS proves to be a useful indicator that accounts for such protection and it could be employed in policy discussion.

Baseline results for water pollution levels show hotspot areas which are not to be considered problematic in the current situation (within sustainability limits). For the future projection, however, a significant increase appears in the north-eastern areas of the basin with values higher than 100% (beyond sustainability limits). This indicates that if the levels of pollution from soybean cultivation are kept at this pace, the basin may easily reach unsustainable status in terms of contamination in 2050. The use of a runoff coefficient when assessing potential streamflow might not explain the regional deviations in site- or catchment-specific factors (FAO, 1991). For an accurate runoff generation assessment, the use of runoff measurements and meteorological data series is required (Kuchment, 2004). The amount of runoff calculated may, therefore, be significantly over- or underestimated and consequently, WPL results must be seen as indicative.

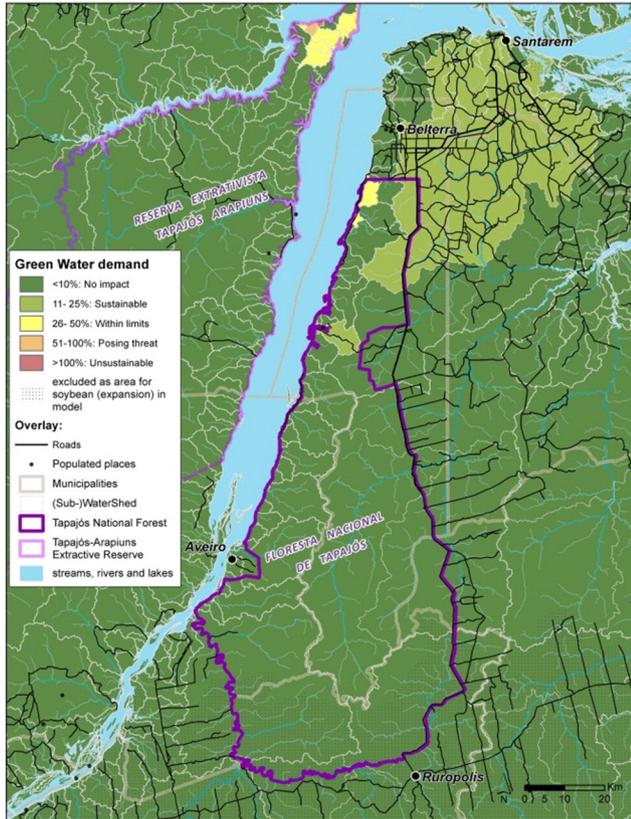
The sustainability results of this study are based on certain assumed yield values. Therefore, if the same amount of water was used to generate a higher yield, sustainability levels would be more easily reached in the future scenario. Due to the increase in global food demands, higher crop yields need to be achieved through a subsequent increase in fertiliser application and water use (Neill et al., 2013). Crop production management plays an important role in the sustainability of the

catchment. Some studies show that the application of no-tillage systems lead to higher crop yields, higher saving of minerals and less soil degradation (Carvalho, 2012; Martorano et al., 2012; Smaling et al., 2008) which could potentially reduce WF values through the reduction of evapotranspiration and increase of crop production efficiency. The projected unsustainable grey WF shows the importance and need for further implementation of more water efficient practices in agricultural management such as no-tillage systems. No-tillage systems are currently in use in the Santarem region and they are showing promising results in terms of evapotranspiration decrease in combination with a comparable crop yield (Martorano et al., 2012). Specific local data on the effect of management practices and crop varieties, when available, can be easily included in the WFA to determine the magnitude of its effects on water use (K_c values, Eq. (3)). Further analysis on the effect of management practices on water footprint is beyond the scope of this study.

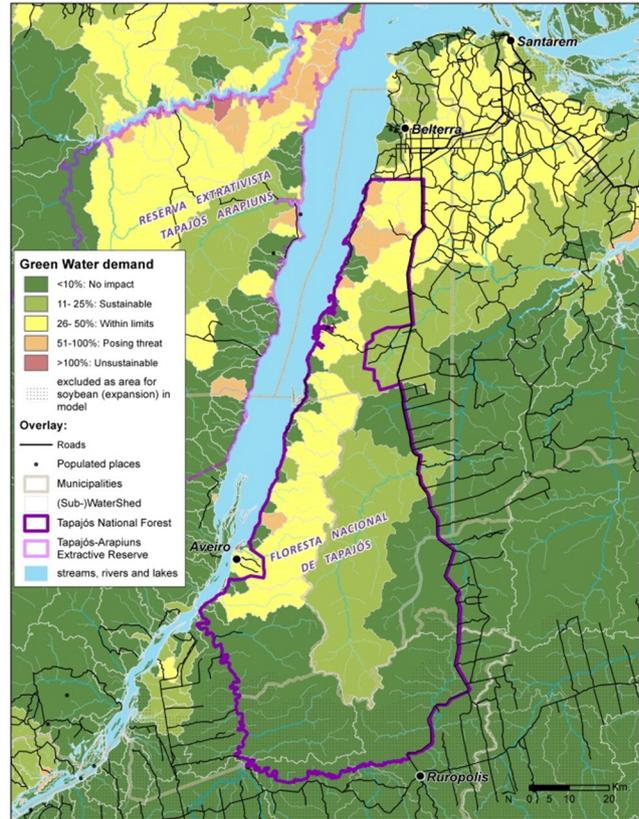
WF calculations require certain assumptions and estimations, which might lead to under- or overestimation of the water footprints to some degree. The grey WF, green WF, GWS and WPL can largely differ depending on a number of factors such as scenarios assumed, timeline and study area, among others (Liu et al., 2012). One important limitation encountered was that all areas considered suitable for soybean and agricultural expansion in the baseline (Fig. 4), and therefore also for the future projection, were assumed to be for soybean production. However, there is room for crop diversification in the future, with e.g., a crop showing lower water consumption. In order to be conservative in our results, no second crop was assumed after harvesting which can have an underestimating effect after the growing period. For the grey WF calculations, basin-specific values for C_{nat} and C_{max} are difficult to find in the literature but have nevertheless an important influence on the calculation of the final WF result. Therefore, it is considered that grey WF values could be underestimated since C_{nat} value was assumed to be zero due to the lack of basin-specific natural background concentration data. Water pollution levels might also be underestimated to some extent due to a possible overestimation in the runoff potential calculation. Using a specific runoff model or runoff measurements could help to improve the accuracy of the grey WF outcome.

Accuracy of WFA results highly depends on the availability of local data (Galli et al., 2012). Precipitation patterns, for example, exhibit large spatial and temporal variations of up to 10–20% of the total annual precipitation measured at conventional stations (Fitzjarrald et al., 2008). We used the freely-available WorldClim datasets in our study due to the constraints of local data availability. Calculations were based on monthly values to ensure higher accuracy and sustainability limits were chosen conservatively to take into account the inaccuracy

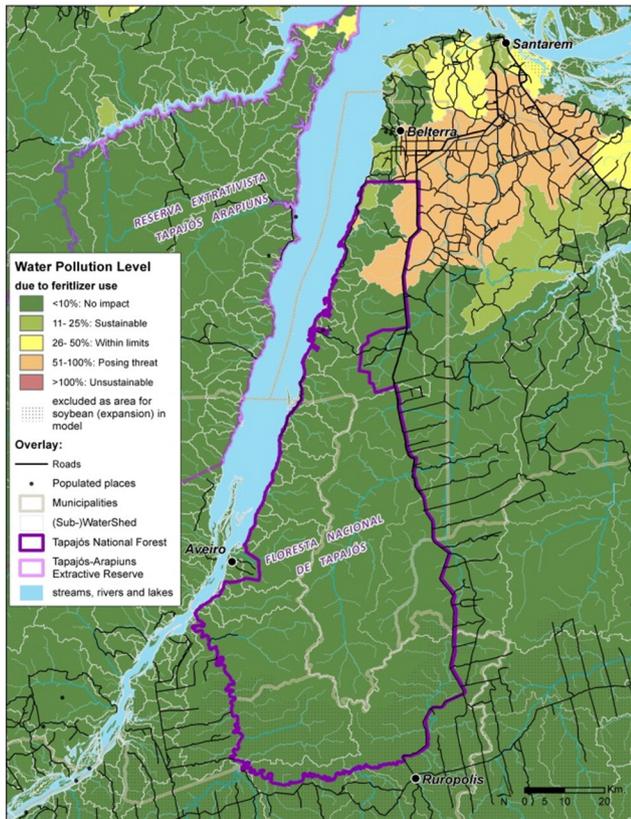
Green Water Scarcity 2010



Green Water Scarcity 2050



Water Pollution Levels 2010



Water Pollution Levels 2050

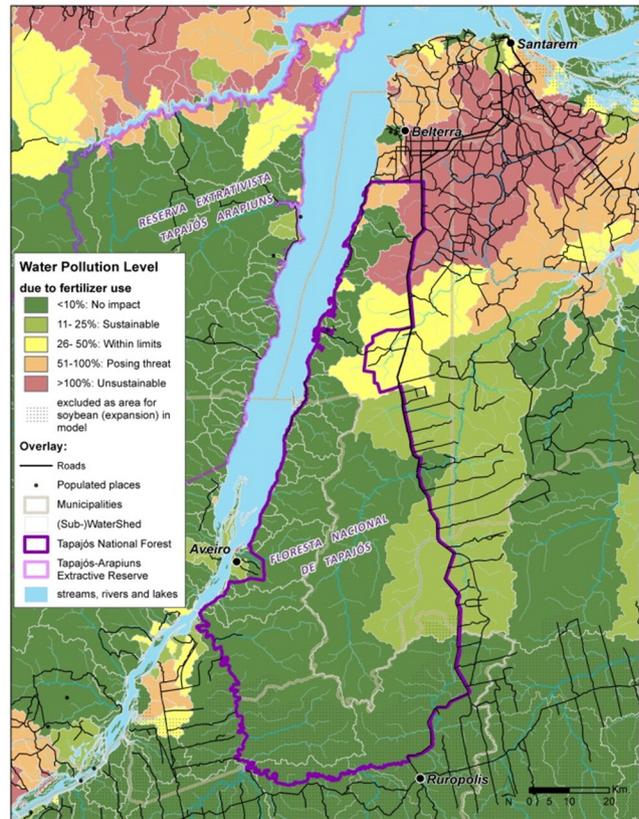


Fig. 6. Green water scarcity and water pollution levels for the baseline scenario (2010) and projection (2050). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the used datasets. The use of freely-available datasets allows the application of WFA to regions all over the world, although a complete set of coherent local data, if available, might lead to more accurate results. For future WFA studies, for instance, satellite-derived spatial precipitation data (Fitzjarrald et al., 2008) could be a possible improvement over the accuracy of the used WorldClim data. The validation of results is a complex task, as there is no way to empirically measure indicators such as green water scarcity in a catchment, nor is there existing literature on the WFA for the Tapajós river basin. The impact of climate change in the Amazon is uncertain (Killeen and Solórzano, 2008). Deforestation rates in the Brazilian Amazon have declined considerably in the last years, which show that land-use trajectories can experience severe changes in the short term (Leydimere et al., 2013). Despite the bias that the use of modelling entails and the hypothetical nature of the results modelling exercises, like the ones presented in this study, model projections are useful in identifying potential areas of change due to climate change (Killeen and Solórzano, 2008; Leydimere et al., 2013). Comparative studies in Mato Grosso—a region south of Pará State with significant soybean expansion during the last decade—have produced total WF results that are consistent, both in the direction and magnitude, with the ones assessed in this study (i.e., Lathuilière et al., 2014; Mekonnen and Hoekstra, 2011).

The geographical water footprint assessment can be helpful when applied regionally since it gives a good insight into the current uses of water and their potential impact in the future despite the limitations experienced in this case study. Identification of the most affected areas (unsustainable hotspots) with the WFA approach in the Amazon region can be a useful tool in terms of water management at regional and national scales. Green water scarcity conveys a valuable message in terms of sustainability that can be used by governments and other stakeholders as a tool to raise awareness about the fact that green water resources are limited and therefore, managing green water resources is important for both agriculture and nature in many regions (e.g. Falkenmark, 1995; Hanasaki et al., 2010; Hoekstra and Mekonnen, 2012; Rockström, 2001; Rijsberman, 2006; Savenije, 2000). Study and application of the green water scarcity is rare and new, particularly the green water scarcity defined in Hoekstra et al. (2011). This is due to the fact that it is challenging to overcome the difficulties in determination of productive and unproductive green water evapotranspiration, and environmental green water requirements in space and time. This work applied the green water scarcity as a crucial indicator to measure the sustainability level in the study area. It is a pioneering study in its kind, which provides a practical approach to dealing with those challenges in practice.

By giving an insight into the future environmental impact of the current crop production systems, the WFA, with the facts and figures related to water consumption and pollution by both human and environmental use of the blue and green water resources, can feed discussions in policy-making processes and help to focus on unsustainable agricultural practices and adaptive measures to climate change, including development of early warning systems. Future agricultural expansion could be maintained within sustainability terms with the help of law enforcement and good management practices that comply with water quality standards and aim towards a “more crop per drop” approach within the sustainability limits of the region. Policies need to be carefully designed and implemented to safeguard protected areas and to maintain sustainability levels.

This study serves a first exploration on how the potential impacts on environmental sustainability of agricultural expansion and intensification can be expressed spatially over time, using a combination of approaches (land use and climate change scenarios, WF analysis). In order to gain further insight of the impact at a catchment scale, future studies need to include local data and analyse additional climate change scenarios. A more precise approach to estimate runoff under such scenarios will help refining the results provided by GWS and WPL indicators. Including the effect of different management practices on water

footprint will be of added value for determining changes on the sustainability of the catchment.

5. Conclusion

This study presents the potential effects of soybean expansion in the Tapajós river basin in terms of water use (water footprint) and highlights the most challenging areas in environmental sustainability terms (hotspots) in the future scenario. Our findings indicate that the intensity of the current soybean production systems are prone to have a noteworthy impact beyond protection limits in the future, especially in relation to water pollution (grey water footprint and water pollution levels) and water use (green water scarcity). Management practices can play an important role to achieve sustainability with the help of, e.g., water consumption regulations to stimulate water use efficiency, such as reduction of crop water use and evapotranspiration, and optimal fertiliser application control. The use of freely available global datasets in the calculations produced comparable results to other WF studies in the Amazon area, which offers a wide range of possibilities for regions with lack of data at a local level. The assessment of GWS and WPL in this study brings an innovative component to the assessment of sustainability. GWS proves to be a useful sustainability indicator and a good method for communicating the message in terms of sustainability since it includes protected areas in the rules of calculations. Results show that what is considered to be minor changes in land use in the current situation (soybean expansion) may imply significant impacts in terms of water pollution and water use in the future. The assumptions used in the calculations are considered reasonable and we believe that the WFA is a useful tool for policy-making since it provides early-warning information that can be effectively implemented in planning. In order to gain further insights on the potential environmental impacts on agricultural expansion at catchment level, application of local data should be considered, in combination with other climate change and management scenarios.

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