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Land occupation and transformation impacts of soybean production in Southern Amazonia, Brazil

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ABSTRACT

Since 2000, soybean production has gained increasing importance in Brazil, particularly in Southern Amazonia and the state of Mato Grosso, the largest producer in the country. This expansion has taken place through cropland extensification into natural ecosystems in the Amazon (tropical forest) and Cerrado (savanna) biomes with land transformation and occupation activity well documented by remote sensing. Guidelines from the UNEP/SETAC Life Cycle Initiative now allow for impact assessment of land transformation and occupation within a Life Cycle Assessment (LCA) to estimate potential impacts to biodiversity and ecosystem services. In this study, we apply these guidelines to soybean produced in 2010 in order to complement more traditional soybean LCAs with mid- and end-point impact assessment on biodiversity, erosion potential, water purification, groundwater recharge, biotic production and climate regulation potential in each of the Amazon and Cerrado biomes. In addition to providing regionalized characterization factors of land transformation and occupation in both Mato Grosso biomes, we estimate that one tonne of soybean produced in 2010 in the Amazon had greater impacts than when produced in the Cerrado. For the Amazon, total land transformation and occupation damage was estimated at \$ 532 ton^{-1} and \$ 260 ton^{-1} respectively, with estimates of \$ 231 ton^{-1} and \$ 153 ton^{-1} for the Cerrado. The largest contributors to these damage estimates came from the change in mechanical filtration properties of the soil followed by the land's climate regulation and biotic production potentials. The impact allocation to pasture as a transitional landscape in the establishment of cropland onto natural ecosystems diminished the soybean contribution through allocation of pasture to the beef production system, further adding to the land sparing argument for future cropland expansion in the region.

1. Introduction

Brazil is currently the second largest producer of soybean on the international stage (USDA-FAS, 2016) with production more than doubling between 2000 (33 Mtons) and 2014 (88 Mtons) (IBGE, 2016). Soybean production is concentrated in the country's Central Western states, led by Mato Grosso producing 26 Mtons of soybean on 8.6 Mha of land in 2014 (IBGE, 2016). Soybean in Mato Grosso is almost exclusively rain-fed. The crop is planted at the beginning of the rainy season (October–November) and harvested after about 120 days (Lathuillière et al., 2012). Once soybean is harvested (February–March), secondary crops are often planted to take advantage of the end of the rainy season. This "double cropping" system became a more common practice in the 2000s, with areas under double cropping increasing six-fold between 2001 and 2011. Soybean-maize double cropping accounts for 92% of rotations (Spera et al., 2014).

The increase in soybean production coincided with an evolution of land, water and fertilizer use in the region, but also a shift in the main export destination in the 2000s from Europe to China (Lathuillière et al., 2014). Mato Grosso is home to an agricultural frontier which has slowly been advancing north, from savanna

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landscapes in the Cerrado biome towards and into the Amazon's tropical forest (Macedo et al., 2012; Barona et al., 2010). Land transformation of the Amazon and Cerrado natural vegetation to cropland has typically occurred through a pasture land use transition (Barona et al., 2010). Greenhouse gas emissions related to this land use change totaled 4372 Tg CO_2-eq between 1990 and 2005, representing a significant portion of Brazil's total emissions (22% in 2010 according to MCTI (2013)), and placing Mato Grosso as a main emissions hotspot on the South American continent (de Sy et al., 2015).

State-wide land transformation for pasture and soybean through deforestation was reduced by 70% between the first and second half of the 2000s (Nepstad et al., 2014) with a significant reduction in deforestation allocated to soybean (455 m^2 y^{-1} per tonne of soybean in 2001–2005 to 97 m^2 y^{-1} per tonne of soybean in 2006–2010) but a 30% increase in land, water and fertilizer use (Lathuillière et al., 2014). This shift resulted from complex interactions of production decisions in light of international demand for soybean and market dynamics, but also government policies, and interventions in the soybean supply chain since 2004 (Nepstad et al., 2014). In addition to law enforcement initiatives and credit limitations to municipalities with the highest deforestation rates, a "Soybean Moratorium" and a "Cattle Agreement" were put in place as an initiative to exclude from the supply chain, producers who had deforested land respectively after July 2006 and October 2009 (Nepstad et al., 2014).

The Soybean Moratorium presents an interesting example from the standpoint of producers and consumers aiming to reduce environmental impacts of soybean production across the supply chain (Gibbs et al., 2015), and was recently renewed indefinitely (Adario, 2016). Other incentives such as The Roundtable on Responsible Soybean (launched in 2006) have sought to advance product certification to create a new market for soybean with lower social and environmental burdens (Nepstad et al., 2014). These initiatives along with private sector policies from companies or associations of producers require decision making tools that can quantify environmental impacts of production in order to identify environmental impact hotspots in production practices. Life cycle assessment (LCA) is a commonly used tool for such an assessment, which has been typically used for the environmental optimization of product systems (Hellweg and Milà i Canals, 2014). The quantification of environmental impacts of agricultural products using LCA has been of interest in recent years, despite challenges of including land use, water use and soil in the methodology (Caffrey and Veal, 2013). Brazil is also known to be lacking important data and information for national and sub-national life cycle inventory (LCI) and LCAs, including for soybean production (Ruviaro et al., 2012). Studies which have applied LCA to soybean produced in Brazil's Central Western region, including the state of Mato Grosso, have mostly focused on cradle-to-farm gate analyses of greenhouse gases emitted during production with a focus on production practices (Raucci et al., 2015), land use change and cultivation systems (Castanheira and Freire, 2013) or comparisons between production practices and soybean transport options (da Silva et al., 2010). More recently, a LCA study for Mato Grosso soybean produced in 2010 using information collected from 110 farms identified land use as an important contributor to impacts in the production process but with results mainly focused on global warming potential (Miranda, 2016). These impacts affect the carbon and water cycles, but also biodiversity with important challenges for improving the sustainability of Brazilian biodiesel (Castanehira et al., 2014). The importance of land use in soybean production and the availability of high resolution information on expansion call for further analysis of impacts resulting from land use change to further understand environmental burdens in the soybean supply chain.

Developments in life cycle impact assessment (LCIA) have made possible the quantification of land transformation and occupation impacts on biodiversity and ecosystem services, now recommended by the United Nations Environment Programme Society of Environmental Toxicology And Chemistry (UNEP/SETAC) Life Cycle Initiative (Koellner et al., 2013). Specifically, these impacts relate to the loss of species biodiversity (de Baan et al., 2013) and soil ecosystem services described by Erosion Resistance Potential (ERP), Mechanical and Physiochemical Water Purification Potential (WPP-MF, WPP-PCF), Groundwater Recharge Potential (GWRP) (Saad et al., 2013), Biotic Production Potential (BPP) (Brandão and Milà i Canals, 2013) and Climate Regulation Potential (CRP) (Müller-Wenk and Brandão, 2010). This set of mid-point impacts have already been implemented in the LCA of margarine (Milà i Canals et al., 2013) or bio-based polymer production (Cao et al., 2015). Given recent land transformation in Mato Grosso for soybean production (Gibbs et al., 2015; Silvério et al., 2015; Macedo et al., 2012) and apparent associated impacts (Miranda, 2016) there is an opportunity to quantify other mid- and end-point impacts of production for the region.

The objectives of this study are to (1) test the robustness of the UNEP/SETAC Life Cycle Initiative guidelines (hencefourth the UNEP/SETAC guidelines) for LCIA of land transformation and occupation in a region having experienced intense land use and land cover changes, and (2) identify a land use focused production hotspot using regionalized biophysical data in order to compare soybean produced in the Amazon and the Cerrado biomes. This study complements previous soybean LCA studies but with a focus on land transformation and occupation impacts to biodiversity and ecosystem services in Mato Grosso. Such a complementary LCA not only provides more information on mid- and end-point impacts, but also provides additional information about future production decisions to reduce the environmental burdens of soybean production within already existing initiatives to reduce deforestation in the region.

2. Materials and methods

2.1. System boundaries and functional unit

The geographical boundary of the study is constrained to the state of Mato Grosso, Brazil (Fig. 1). Mato Grosso is home to three distinct biomes: the Amazon in the north containing tropical and transition deciduous and semi-deciduous forests, the Cerrado in the central part of the state which is composed of a mixture of savanna landscapes (shrubland, grassland, dry forest), and the Pantanal wetland in the south which is not considered in this study as soybean cultivation is not permitted in this biome. The expansion of soybean first took place in the Cerrado biome in the central and southern part of the state (near Cuiabá) with an agricultural frontier moving north towards the city of Sinop (Fig. 1) (Barona et al., 2010; Simon and Garagorry, 2005). Land use change dynamics have been studied in great detail using remote sensing products such as the MODerate resolution Imaging Spectroradiometer (Silvério et al., 2015; Spera et al., 2014; Macedo et al., 2012) and Landsat satellite imagery (Gibbs et al., 2015; Müller et al., 2015). These data products have been used in the earth sciences with focus on the effects of land transformation on greenhouse gas emissions (Galford et al., 2011) including future emissions considering changes in legislation affecting forest cover (Soares-Filho et al., 2014), and the effects of land use and cover change on the hydrological cycle (Lathuillière et al., 2016b).

The system boundary is soybean produced in 2010 in both Amazon and Cerrado biomes. While maize double cropping is common in Mato Grosso (Spera et al., 2014), all impacts in this

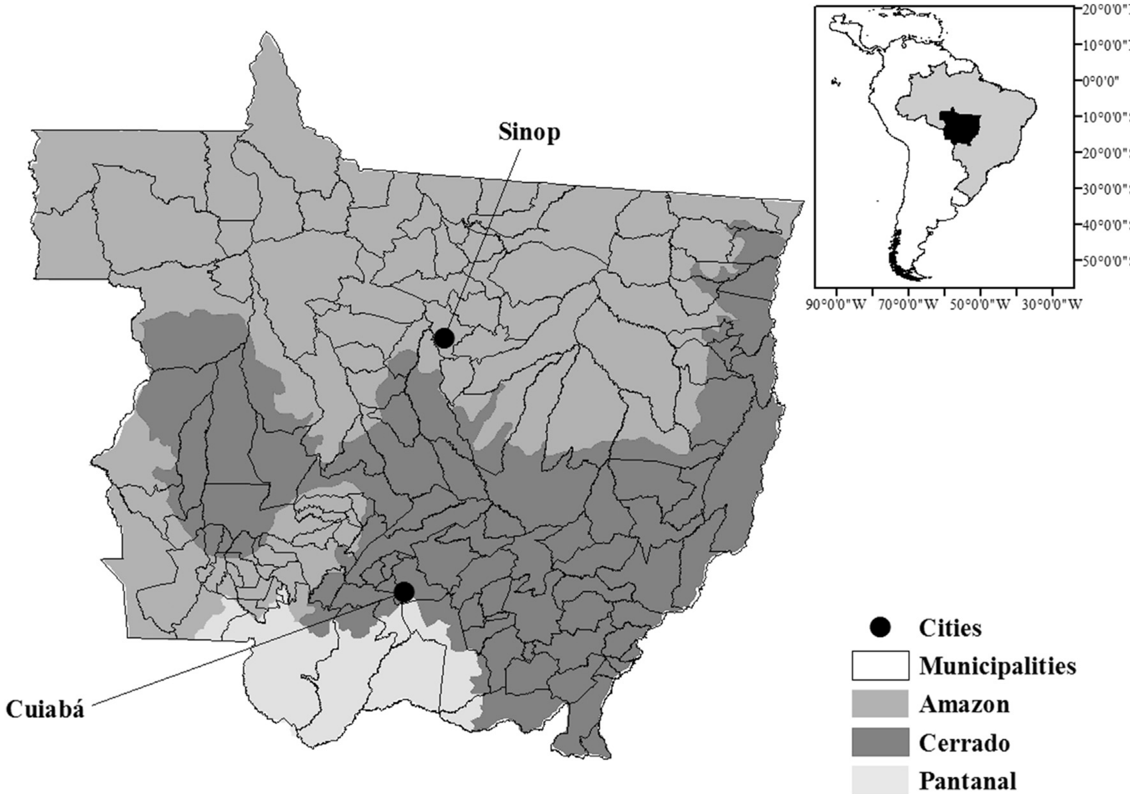

Fig. 1. The Brazilian state of Mato Grosso and its biomes.

study are allocated to soybean as it is considered the main driver of deforestation in the region following pasture (Gibbs et al., 2015; Macedo et al., 2012; Barona et al., 2010). We consider transformation impacts allocated over the first 20 years following land transformation. In other words, the annual impact of land transformation represents 1/20th of the total impact, after which impacts are considered null. While this choice of allocation is recommended in the UNEP/SETAC guidelines (Koellner et al., 2013), it remains arbitrary. The functional unit is one tonne of soybean produced in 2010 with reference flow based on the inverse yield calculated in each biome: 0.3251 ha y ton^{-1} (Amazon) and 0.3291 ha y ton^{-1} (Cerrado) for land occupation in 2010 (IBGE, 2016).

2.2. Land transformation and occupation mid-point impact assessment

Land transformation and occupation impacts were assessed following UNEP/SETAC guidelines on land use impact assessment for biodiversity (de Baan et al., 2013) and ecosystem services (Koellner et al., 2013) using biophysical data from both the Amazon and Cerrado biomes to calculate regionalized characterization factors. Impacts to Biodiversity Potential (BDP, PDF m^2 y) are expressed as the amount of species lost with land transformation (de Baan et al., 2013) and were determined based on the amount of species estimated from previous studies (Solórzano et al., 2012; Assunção et al., 2011; Morandi, 2010; Franczak, 2009) (see Supplemental Material). While UNEP/SETAC guidelines of 2016 recommend the use of the method by Chaudhary et al. (2015) to assess biodiversity impacts, this method focusses on the impacts to global species and global species loss, rather than impacts to local biodiversity available from the method of de Baan et al. (2013) and more relevant here. Land transformation and occupation impacts to soil specific ecosystem services (ERP, WPP-MFP, and GWRP) were assessed following Equations (1) and (2) (Koellner et al., 2013) according to ecosystem quality curves described in the Supplemental Material (Fig. S1)

$$I_{trans} = CF_{trans}\,A \quad (1)$$

$$I_{occ} = CF_{occ}\,A\,t_{occ} \quad (2)$$

where I_{trans} and I_{occ} are respectively the land transformation and occupation impacts (for mid- or end-point impacts), A (ha) is the area transformed or occupied, t_{occ} (y) is the occupation time, CF_{trans} and CF_{occ} are the characterization factors (for mid- or end-point impacts) defined separately for land transformation and land occupation and shown in equations (3) and (4).

$$CF_{trans} = \frac{1}{2}(Q_{NV} - Q_{LU})t_{regen} \quad (3)$$

$$CF_{occ} = (Q_{NV} - Q_{LU}) \quad (4)$$

where Q is the ecosystem quality of natural vegetation (Q_{NV}) or new land use (Q_{LU}), t_{regen} is the regeneration time needed for the landscape to relax to NV (assumed linear) and was selected as 159 years for Amazon NV and 117 years for Cerrado NV following Curran et al. (2014). In the special case of NV to pasture to cropland expansion (Fig. S1, panel B in the Supplemental Material), we assume that all pasture converted to cropland had already been established for 20 years or more. This assumption is reasonable due to the greater area of pasture available in Mato Grosso (20–23 Mha in the 2000s according to Lathuillière et al. (2012)), but also reflects limited knowledge of the age of the pasture transformed. Pasture transformation impacts were subtracted from cropland transformation impacts so as to allocate part of the transformation responsibility to the pasture land use. From Equations (1)–(4) above, positive values of I_{occ} and I_{trans} represent impacts in which a loss of biodiversity and ecosystem services take place, while negative values are interpreted as benefits.

We consider mid-point impacts to ERP (ton), WPP-MF (m^3), GWRP (m^3), BPP (ton C) and CRP (ton C). Values of ERP were obtained by assessing the change in soil erosion resistance arising from agricultural land practices using a sealing factor from machinery (Beck et al., 2010). Impacts on WPP-MF were estimated based on the change in soil filtration capacity due to agricultural land practices which also relies on a sealing factor. GWRP was obtained by assessing the difference in groundwater recharge based on land use evapotranspiration and runoff resulting from land transformation and occupation (Saad et al., 2013). Values of BPP determine the change in soil organic carbon following land transformation and occupation (Brandão and Milà i Canals, 2013), while CRP refers to the amount of carbon lost from above and belowground biomass during land transformation taking into account the ability of the new agricultural land use to sequester part of this carbon over time (Müller-Wenk and Brandão, 2010).

Detailed derivations of CF_{trans} and CF_{occ} for each mid-point impact are described in the Supplemental Material including methods for BPP and CRP which do not follow Equation (1) through (4). Soil and meteorological parameters were derived for each biome using spatial averages of soil parameters (see section 2.4), precipitation and evapotranspiration were obtained for Amazon and Cerrado biomes from various field and remote sensing sources previously published (Table 1).

2.3. Land transformation and occupation end-point impacts

We estimate the land transformation and occupation end-point impact for ecosystem services (ERP, WPP-MF, GWRP, BPP and CRP) following the valuation method of Cao et al. (2015). This method determines the costs associated with each mid-point impact category from which an end-point impact is calculated following Equation (5):

$$CF_{end} = ECF(CF_{mid})\ XF_i\ AC \tag{5}$$

where $ECF(CF_i)$ ($/physical unit) is the economic conversion factor of each mid-point impact, CF_{mid} is the characterization factor determined for each mid-point impact of land occupation (CF_{occ}) or transformation (CF_{trans}), XF_i is the exposure factor whose units depend on the impact category considered, and AC (dimensionless) is the adaptation capacity as defined by socio-economic data (Cao et al., 2015). Both XFi and AC are between 0 and 100%, with values of 0 meaning no ecosystem exposure and no adaptation and values of 100% suggesting full ecosystem exposure and adaptation (Cao et al., 2015). We estimate a value of CF_{end} for each ecosystem services impact category and then derive the land transformation and occupation end-point impacts from Equations (1) and (2). Any positive mid-point impact is represented by cost, while apparent benefits appear as a negative end-point score. Further details on calculations of CF_{end} are available in the Supplemental Material.

2.4. Spatial data analysis

Characterization factors of mid-point impacts rely on detailed soil information obtained from Shannguan et al. (2014) as 1 km^2 raster data. Soil data include soil skeleton and humus content, soil organic carbon and cation exchange capacity directly available at 0–28.3 cm depth and manipulated using statistical software R version 3.03 (R Core Team, 2014) *raster* package (Hijmans, 2014). Soil texture class was derived for each 1 km^2 pixel using sand, silt and clay data from Shannguan et al. (2014) and classified using the German Bodenkundliche Kartieranleitung texture classification available through the R *soiltexture* package (Moeys, 2014) and required for establishing the various mid-point impacts on soil conditions as per Beck et al. (2010) (see Supplemental Material). Information on terrain was obtained from Jarvis et al. (2008) to derive slope for GWRP. Precipitation information and annual soybean-maize-fallow evapotranspiration were estimated from remote sensing and crop water modeling (see Supplemental Material) (Table 1).

2.5. Sensitivity analysis

We repeat calculations of mid-point impacts using variations in the input data that have the greatest uncertainty and variability in the state of Mato Grosso. Data on aboveground biomass for both Amazon and Cerrado biomes, as well as differences in precipitation, evapotranspiration (without maize as the double crop) and runoff coefficient can affect mid-point impacts for both carbon and water balances (CRP and GWRP). We perform a sensitivity analysis by changing these physical parameters as shown in detail in the Supplemental Material.

3. Results

3.1. Land occupation impacts of soybean production in 2010

A total of 18.8 Mtons of soybean were harvested in Mato Grosso in 2010 on 6.23 Mha of land located in the Amazon (31%) and the Cerrado biomes (69%) (IBGE, 2016). Land occupation impacts of one tonne of soybean grown in 2010 were almost equal for the Amazon

Table 1
Environmental and soil parameters for Amazon and Cerrado biomes in Mato Grosso, Brazil, used for the calculation of characterization factors of land transformation and occupation. Soil values represent averages from the 0–28.5 cm depth.

Parameter	Amazon	Cerrado	Units	Reference
t_{regen}	159	117	years	Curran et al., 2014
Precipitation	2096	1369	mm y^{-1}	Rodrigues et al., 2014
Evapotranspiration	1099	817	mm y^{-1}	see Supplemental Material
Slope	5	10	degrees	Jarvis et al., 2008
Soil type	Weakly clayey sand	Medium clayey sand		Shannguan et al., 2014
Average natural soil erosion (ANSE)	1.55	1.45	ton ha^{-1} y^{-1}	Shannguan et al., 2014
Filtration capacity	10.5	7.20	cm day^{-1}	Shannguan et al., 2014
Filtration distance to groundwater	0.8–1.5		m	Beck et al., 2010
Soil organic carbon	63.0	50.7	ton ha^{-1}	Shannguan et al., 2014
Aboveground biomass	198.0	53.0	ton C ha^{-1}	Castanehira et al., 2014

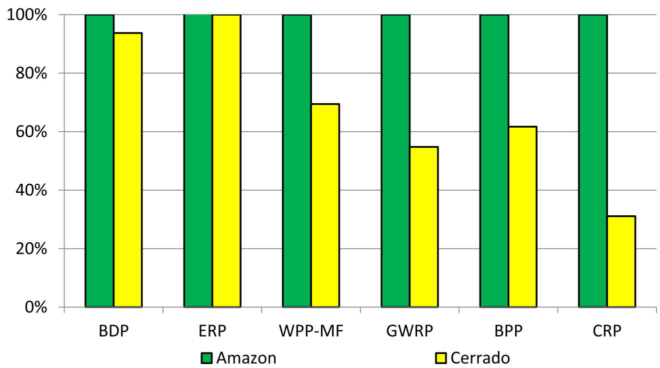

Fig. 2. Relative mid-point land occupation impacts for one tonne of soybean produced in 2010 in the Amazon and Cerrado biomes of Mato Grosso, Brazil. Impacts are listed as biodiversity potential (BDP, PDF m^2 y), Erosion Resistance Potential (ERP, ton), Mechanical Water Purification Potential (WPP-MF, m^3), Groundwater Recharge Potential (GWRP, m^3), Biotic Production Potential (BPP, ton C), and Climate Regulation Potential (CRP, ton C).

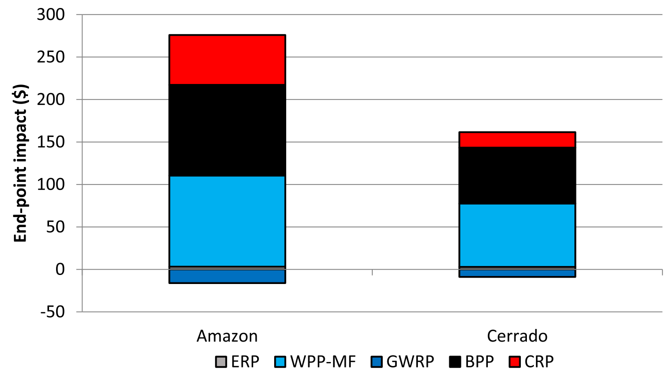

Fig. 3. End-point land occupation impacts ($) on ecosystem services for one tonne of soybean produced in 2010 in the Amazon and Cerrado biomes of Mato Grosso, Brazil: Erosion Resistance Potential (ERP), Mechanical Water Purification Potential (WPP-MF), Groundwater Recharge Potential (GWRP), Biotic Production Potential (BPP), Climate Regulation Potential (CRP).

and Cerrado biomes as the production location (Fig. 2) for BDP ($2.93\ 10^3$ PDF m^2 y and $2.75\ 10^3$ PDF m^2 y respectively) and ERP (2.8 ton and 2.6 ton respectively). All other impacts were greater for soybean produced in the Amazon biome when compared to the Cerrado, with the impacts from soybean production in the Cerrado equivalent to 55–76% of Amazon biome impacts of production with smaller differences for WPP-MF ($6.23\ 10^3\ m^3$ and $4.33\ 10^3\ m^3$), and greater differences for GRWP ($-438\ m^3$ and -240 m^3), BPP (9.5 ton C and 5.8 ton C) and CRP (0.44 ton C and 0.14 ton C). These results parallel values of CF_{occ} which were greater in the case of BDP, WPP-MF, and CRP and more negative for ERP and GWRP when comparing the Amazon to the Cerrado (Table 2). Comparison with global literature values (de Baan et al., 2013; Saad et al., 2013; Brandão and Milà i Canals, 2013; Müller-Wenk and Brandão, 2010) shows that our CF_{occ} were similar for BDP, CRP and BPP, but lower for ERP and GWRP (the latter by two orders of magnitude, and a negative number) (Table 2).

End-point impacts of land occupation of one tonne of soybean were greater in the Amazon biome ($ 260) with impacts in the Cerrado representing 59% ($ 153) of total impacts in the Amazon (Fig. 3). Damage categories were generally larger in the Amazon than in the Cerrado biome with the exception of ERP ($ 3.1 and $ 3.0, respectively). Damage to WPP-MF was $ 107 and $ 75 for the Amazon and Cerrado biomes, while GWRP reached $ −16 and $ −9, respectively. Finally, damage to BPP and CRP were $ 107 and $ 66, and $ 59 and $ 18, for the Amazon and Cerrado biomes (Fig. 3). Values of damage CF_{occ} were generally lower than those reported by Cao et al. (2015) (Table 4), with BPP previously reported as 0 (see Supplemental Material).

3.2. Land transformation impacts of soybean produced in 2010

Similar to land occupation, land transformation impacts from NV of one tonne of soybean in the Amazon were typically greater than in the Cerrado (Fig. 4), particularly with BDP ($1.17\ 10^4$ PDF m^2 y and $8.04\ 10^3$ PDF m^2 y, respectively), ERP (11.0 ton and 7.7 ton), WPP-MF ($2.48\ 10^4\ m^3$ and $1.27\ 10^4\ m^3$ respectively), GWRP ($-1740\ m^3$ and -701 m^3), BPP (2.2 ton C and 1.3 ton C), and CRP (1.0 ton C and 0.09 ton C). Allocation of impacts to pasture when considering a NV-pasture-soybean transition diminished impacts to 60–90% compared to NV for ERP, and 10–17% compared to NV impacts for BDP and GWRP impact categories considering both biomes. Values of BPP were larger when considering a NV-pasture-soybean transition in the Amazon biome (2.6 ton C), while this same transition in the Cerrado was 1.3 ton C which was as high as a NV-soybean transition in the Cerrado. While the NV-pasture-soybean showed no impact in the WPP-MF impact category, values of CRP actually changed to a negative impact (−0.13 ton C)

Table 2
Mid-point characterization factors of land occupation (CF_{occ}) of soybean from natural vegetation (NV) for Biodiversity Potential (BDP), Erosion Resistance Potential (ERP), Mechanical Water Purification Potential (WPP-MF), Groundwater Recharge Potential (GWRP), Biotic Production Potential (BPP) and Climate Regulation Potential (CRP) in the Amazon and Cerrado biomes of Mato Grosso, Brazil. Values obtained in this study are compared to literature values.

Biome	Amazon		Cerrado	
	this study	literature	this study	literature
Land occupation from to	NV soybean	forest[a] permanent and annual crops	NV soybean	savanna[b] permanent and annual crops
BDP[c] (PDF)	0.90	0.54	0.83	0.65
ERP[d] (ton $ha^{-1}\ y^{-1}$)	8.53	16.42	7.98	15.3
WPP-MF[d] ($m^3\ ha^{-1}\ y^{-1}$)	$1.92\ 10^4$	1.73	$1.31\ 10^4$	3.46
GWRP[d] (mm y^{-1})	−189	1.63	−127	−2.98
BPP[e] (ton C $ha^{-1}\ y^{-1}$)	29.1	28.0	17.7	22.0
CRP[f] (ton C $ha^{-1}\ y^{-1}$)	1.36	0.43	0.42	0.37

[a] Tropical and subtropical (moist) broadleaf forest.
[b] Tropical and subtropical grasslands, savannas and shrublands.
[c] Transformation according to Brazilian average from de Baan et al. (2013).
[d] Saad et al. (2013).
[e] Brandão and Milà i Canals (2013).
[f] Müller-Wenk and Brandão (2010).

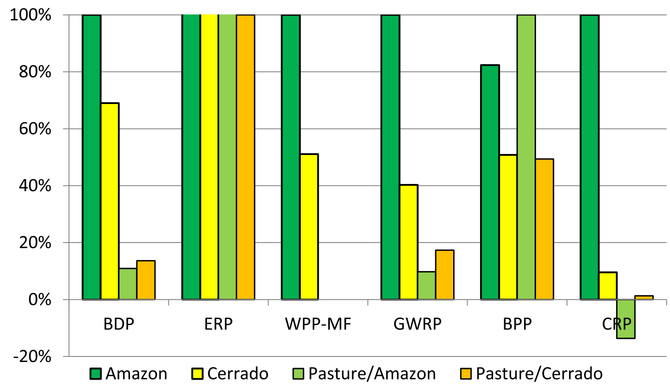

Fig. 4. Relative mid-point land transformation impacts for one tonne of soybean produced in 2010 in the Amazon and Cerrado biomes of Mato Grosso, Brazil, considering direct transformation of natural vegetation to soybean (Amazon and Cerrado), and a pasture transition (Pasture/Amazon, Pasture/Cerrado). Impacts are listed as biodiversity potential (BDP, PDF m^2 y), Erosion Resistance Potential (ERP, ton), Mechanical Water Purification Potential (WPP-MF, m^3), Groundwater Recharge Potential (GWRP, m^3), Biotic Production Potential (BPP, ton C), Climate Regulation Potential (CRP, ton C).

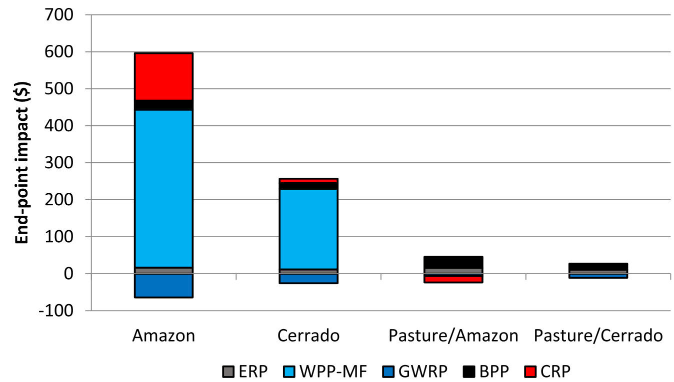

Fig. 5. End-point land transformation impacts ($) for one tonne of soybean produced in 2010 in the Amazon and Cerrado biomes of Mato Grosso, Brazil, considering direct transformation of natural vegetation to soybean (Amazon and Cerrado), and a pasture transition (Pasture/Amazon, Pasture/Cerrado): Erosion Resistance Potential (ERP), Mechanical Water Purification Potential (WPP-MF), Groundwater Recharge Potential (GWRP), Biotic Production Potential (BPP), Climate Regulation Potential (CRP).

when considering a NV-pasture-soybean transition in the Amazon biome.

Values of CF_{trans} for the NV to pasture transformation followed a similar trend as CF_{occ}, but with greater differences observed between the Amazon and the Cerrado for some mid-point impacts: GWRP with −9659 and −2428 mm y^{-1}, BPP with −28.7 ton C ha^{-1} and 2.33 ton C ha^{-1}, and CRP with 67 ton C ha^{-1} and 4.8 ton C ha^{-1}. Values of CF_{trans} for WPP-MF were identical when considering a NV to soybean and a NV to pasture transformation: 1.52 10^6 m^3 ha^{-1} and 7.69 10^5 m^3 ha^{-1} in the Amazon and Cerrado, respectively. When compared to literature values (de Baan et al., 2013; Saad et al., 2013; Brandão and Milà i Canals, 2013; Müller-Wenk and Brandão, 2010), our values of CF_{trans} were consistently lower for GWRP, and generally greater for ERP, BPP and CRP when considering the NV-to-cropland transformation (Table 3). The largest differences were found in the values of GWRP (Saad et al., 2013) when considering the transformation of NV into soybean in both biomes. Similar trends in the values of CF_{trans} were observed when considering the NV-to-pasture transformation (Table 3): values of GWRP were lower than literature values reported by Saad et al. (2013) with greater ERP, BDP and CRP. Unlike the literature values, we report a value of CF_{trans} for WPP-MF and BPP which were considered as zero by Saad et al. (2013) and Brandão and Milà i Canals (2013).

Land transformation damage of one tonne of soybean produced in 2010 in the Amazon ($ 532) was greater than in the Cerrado ($ 231) (Fig. 5) with important differences in damage categories between both biomes. When comparing a NV-soybean transition in both biomes, ERP damage was respectively $ 16.7 and $ 11.7, WPP-MF was $ 427 and $ 218, GWRP was $ −64 and $ −26, BPP was $ 25 and $ 15 and CRP was $ 128 and $ 12. The allocation of impacts to pasture in the NV-pasture-soybean transitions reduced damage in the WPP-MF (100%) and CRP (>86%), but increased GWRP (57–90%) in both Amazon and Cerrado biomes. Damage scores for ERP dropped marginally (6% in both biomes) when comparing the NV-pasture-soybean to the NV-soybean transition. Allocation to pasture actually led to a negative CRP damage of $ −17 in the Amazon while BPP damage increase from $ 25 to $ 30 in the same biome. Absolute values of end-point CF_{trans} were greater than those reported by Cao et al. (2015) for WPP-MF, and CRP (Amazon biome only) and lower for GWRP (Table 4). Values for ERP varied with the biome but were within the range of the literature values, while

Table 3
Mid-point characterization factors of land transformation (CF_{trans}) of soybean from natural vegetation (NV) for Biodiversity Potential (BDP), Erosion Resistance Potential (ERP), Mechanical Filtration Water Purification Potential (WPP-MF), Groundwater Recharge Potential (GWRP), Biotic Production Potential (BPP) and Climate Regulation Potential (CRP) in the Amazon and Cerrado biomes of Mato Grosso, Brazil. Values obtained in this study are compared to literature values.

Biome	Amazon				Cerrado			
	this study	Literature value	this study	Literature value	this study	Literature value	this study	Literature value
Land transformation from to	NV soybean	forest[a] permanent and annual crops	NV pasture	forest[a] grassland[b]	NV soybean	savanna[c] permanent and annual crops	NV pasture	savanna[c] grassland[b]
BDP[d] (PDF y)	71.7	42.9	63.9	35.8	48.8	38.1	39.2	7.0
ERP[e] (ton ha^{-1})	678	448.7	61.6	2.1	467	434.7	42.4	3.2
WPP-MF[e] (m^3 ha^{-1})	1.52 10^6	1.72 10^6	1.52 10^6	0	7.69 10^5	3.59 10^6	7.69 10^5	0
GWRP[e] (mm y^{-1})	−15049	44.4	−9659	1038	−7457	−84.7	−2428	−1179
BPP[f] (ton C ha^{-1})	134	−281	−28.7	0	81.6	−216	2.3	0
CRP[g] (ton C ha^{-1})	59	13.3	67	10.5	5.6	18	4.8	0

[a] Tropical and subtropical (moist) broadleaf forest.
[b] Grassland: pasture/meadows.
[c] Tropical and subtropical grasslands, savannas and shrubland.
[d] Transformation according to Brazilian average from de Baan et al. (2013), using t_{regen} from Curran et al. (2014).
[e] Saad et al. (2013).
[f] Brandão and Milà i Canals (2013).
[g] Müller-Wenk and Brandão (2010).

Table 4
End-point characterization factors of land occupation (CF_{occ}, \$ ha^{-1} y^{-1}) and transformation (CF_{trans}, \$ ha^{-1}) of soybean from natural vegetation (NV) for Biodiversity Potential (BDP), Erosion Resistance Potential (ERP), Mechanical Water Purification Potential (WPP-MF), Groundwater Recharge Potential (GWRP), Biotic Production Potential (BPP) and Climate Regulation Potential (CRP) in the Amazon and Cerrado biomes of Mato Grosso, Brazil.

Biome	Amazon			Cerrado			Brazil	
	CF_{occ}	CF_{trans}		CF_{occ}	CF_{trans}		CF_{trans}	
	this study	this study		this study	this study		Cao et al. (2015)	
From to	NV soybean	NV soybean	NV pasture	NV soybean	NV soybean	NV pasture	permanent and annual crops	pasture
ERP	9.60	1030	59.5	8.98	709	41.0	1384	257
WPP-MF	330	2.63 10^4	2.63 10^4	226	1.32 10^4	1.32 10^4	11,535	11,535
GWRP	−50	−3945	−3560	−27	−1570	−895	1382	1382
BPP[a]	329	1511	−324	200	921	26.3	0	0
CRP	180	7873	8946	55.5	743	641	3221	7786

CF_{trans} for BPP had previously been reported as zero (Cao et al., 2015) (see Supplemental Material).

3.3. Sensitivity analysis

Values for CF_{occ} and CF_{trans} were found to be more sensitive for GWRP and CRP given the large uncertainties in input variables for the water and carbon balances. The two scenarios considered for the sensitivity analysis (see Tables S12 and S13 in the Supplemental Material) show possible increases in GWRP from +84 to 112% in the Amazon and +81–112% for the Cerrado biome. In the case of CRP, uncertainty in aboveground biomass showed changes in the Amazon by +1% to +36% (CF_{occ}) and −9% to +86% (CF_{trans}), while the Cerrado showed greater differences from −43% to −88% for both CF_{occ} and CF_{trans}.

4. Discussion

4.1. Hotspots of land use for soybean production in Mato Grosso

The application of UNEP/SETAC guidelines for land occupation and transformation (Koellner et al., 2013) provide further insight into the impacts of the soybean production system that could not be demonstrated otherwise in a more traditional LCA (Miranda, 2016). The differences in yield, soil type, aboveground biomass, and regeneration times between biomes suggest a greater potential impact for soybean produced in the Amazon when compared to the Cerrado. During the 2000s, deforestation directly attributed to soybean production was estimated at 455 m^2 y^{-1} per tonne of soybean in 2001–2005 and 97 m^2 y^{-1} per tonne of soybean in 2006–2010 (Lathuillière et al., 2014) with even greater deforestation for soybean expected in the Cerrado biome due to mandatory forest cover for each biome following the Brazilian forest code (Gibbs et al., 2015). Until 2012, the law required different fractions of natural forest cover on properties based on the biome, from 20% for Cerrado areas in Western Mato Grosso, 50% for Cerrado/Amazon transition areas, and 80% for areas within the Amazon biome (Brannstrom et al., 2008; Fearnside and Barbosa, 2004). The NV-pasture-soybean transition reduced impacts due to the allocation of impacts to the pasture land use by subtraction and therefore should not be interpreted necessarily as an absolute benefit to the soybean production system. Rather, the allocation of impacts to the pasture land use acts as a benefit for relative impacts allocated to the soybean land use which change with respect to the allocation of impacts following the land transformation activity. An increase from the proposed 20-year timeframe (Koellner et al., 2013) to 30 or 40 years would further decrease the impacts allocated to soybean following the NV to pasture transition. This result could also be interpreted as a land sparing effect that could follow from the use of pasture over NV in both biomes, while these impacts should be allocated to the beef production system. Current law enforcement, national and international incentives to reduce deforestation can promote future conversion of pasture into soybean, which has been observed already in 2006–2010 when Amazon deforestation dropped considerably (Nepstad et al., 2014; Macedo et al., 2012). We therefore expect future soybean production to occur with the smaller impacts identified here, particularly in the event of intensification of the beef production system thereby freeing up pasture for cropland.

In addition to losses in biodiversity expected from the conversion of NV, important changes to the water (GWRP, WPP-MF) and carbon cycles (BPP, CRP) which rely on local precipitation and evapotranspiration as well as carbon stocks, can be expected. Similar to precipitation, there are biome differences in evapotranspiration due to the local vegetation in Mato Grosso: the Amazon biome returns 1099 mm y^{-1} of water vapour to the atmosphere (Lathuillière et al., 2012), while the Cerrado returns 939 mm y^{-1} (Oliveira et al., 2014). These differences suggest changes to the water yield resulting from land transformation that appears as a benefit in both mid- and end-point GWRP (and explain the large differences with the literature values for the characterization factors), expressed by an increase in groundwater recharge. Changes to the water yield have been observed with simulations performed in northeastern Mato Grosso: tropical forest (Amazon) and savanna (Cerrado) dominated watersheds showed similar runoff of 324 mm y^{-1}, compared to 694 mm y^{-1} for soybean and pasture dominated watersheds (Dias et al., 2015). Dias et al. (2015) further showed that a tropical forest to soybean and savanna to soybean transformation would lead to positive changes in groundwater of 31 mm y^{-1} and 19 mm y^{-1}, which is less than what we estimated in our mid-point CF_{occ} for GWRP. This difference can be due to the depth of the water table assumed to be 0.8–1.5 m in our study but which is known to be as deep as 20 m in parts of Mato Grosso (Pokhrel et al., 2014) and perhaps not well represented with the runoff coefficient proposed in Beck et al. (2010). Beck et al. (2010) propose a runoff coefficient of 1 with a water table greater than 1.5 m meaning that all precipitation not returning to the atmosphere ends up in the water table. This consideration would increase further the GWRP benefit calculated here. Similarly, a reduction of the runoff coefficient from 2 to 1 based on declination obtained from SRTM information for Mato Grosso (Jarvis et al., 2008) increased groundwater recharge, regardless of precipitation and ET input variables.

Nevertheless, the apparent benefit to groundwater recharge represented by the negative values of GWRP can be deceptive and should be put into context of the regional water balance. Land transformation can increase groundwater recharge and runoff locally due to reduced evapotranspiration on the land, but this reduction also has consequences on the atmospheric water balance and regional precipitation. Based on the size of the region considered, Lathuillière et al. (2016a) estimated that the land occupation impacts of one tonne of soybean in the Amazon biome of Mato Grosso could potentially reduce precipitation by up to 704 m^3 (2798 m^3 for land transformation) resulting in impacts to terrestrial ecosystems up to 202 PDF m^2 y (803 PDF m^2 y for land transformation). These impacts balance the apparent benefits expressed by GWRP alone.

A tropical forest to pasture transition (Amazon) assuming long-term cultivation can lead to 69.2 ton C ha^{-1} of soil organic content as determined in this study (50.2 ton C ha^{-1} for savanna and savanna woodland in the Cerrado), while the direct transition of NV to soybean will reduce the soil organic carbon content to the 33–35 ton C ha^{-1} range in both biomes. When the native vegetation is transformed to cropland, a change in soil carbon distribution also occurs, with evidence of depletion on the top layer and an increase in the deeper layers (Miranda et al., 2016). Some long-term soil studies on Cerrado to soybean transformation showed an increase in total soil carbon, especially when a deeper profile is considered (Miranda et al., 2016; Sá et al., 2013).

4.2. Regionalization of characterization factor

The values of CF_{occ} and CF_{trans} are part of an effort to regionalize land transformation and occupation impacts based on detailed information on land use, soil type and environmental conditions in each biome. Current global values of CF_{occ} and CF_{trans} have been aggregated either globally, nationally, or even by biome (Koellner et al., 2013), with only limited details on the type of agricultural land being transformed (Cao et al., 2015; Koellner et al., 2013). Moreover, our regionalized values were obtained using a mix of datasets which rely on recent information from the earth sciences, including soil surveys and databases (Shannguan et al., 2014), crop water modeling (Lathuillière et al., 2012), and remote sensing for evapotranspiration (Mu et al., 2011). This information was complemented by academic literature reporting direct results from field observations. As such, we expected differences between our values of CF_{occ} and CF_{trans} with the literature values as regionalized data allow for better estimates of mid-point impacts such as BDP, GWRP or CRP, despite still large uncertainties even at the regional level as shown by the sensitivity analysis. For instance, annual precipitation and evapotranspiration are both required variables to determine groundwater recharge in the case of GWRP, and can change greatly among landscapes and biomes. Different crops, soil and water management as well as year-to-year precipitation variability can affect the amount of landscape evapotranspiration. The Amazon biome stores more aboveground carbon with estimates in the 198–275 ton C ha^{-1} range (Castanheira and Freire, 2013; Saatchi et al., 2007; Santos et al., 2003) compared to Cerrado landscapes with 10–53 ton C ha^{-1} (Castanheira and Freire, 2013; Barbosa and Feamside, 2005; De Castro and Kauffman, 1998; Kauffman et al., 1994). Similarly, field observations and simulations of the effects of land transformation on soil organic carbon in the region (Maia et al., 2010) can provide more detailed information on the effects of land transformation on the soil and can act as a source of validation of the previously derived characterization factors (Brandão and Milà i Canals, 2013).

Some of the values calculated for the land transformation characterization factors of the end-point impacts to ecosystem services have been much greater than \$ 1000 ha^{-1}. Although they have been in the range of previously reported values, their interpretation become difficult if associated with a social cost of water filtration (WPP-MF and GWPR) or climate change (CRP). These values stem from the choices made for modeling the costs of services that would be equivalent to each ecosystem function lost during transformation rather than the real cost incurred for the service within the context of this research. However, despite these large numbers, the end-point impacts to ecosystem services were able to highlight hotspots related to the water and carbon cycles which are of known concern in Brazil. More importantly, government laws and incentives are available to act upon such impacts such as general goals to reduce deforestation by 80% in the Amazon biome and 40% in the Cerrado (Galford et al., 2013) as well as incentives to increase soil organic carbon through the Low Carbon Agriculture Program (Nepstad et al., 2014). Such incentives, in addition to no-till agriculture would affect the values of CRP, BPP and WPP-MF estimated in this study.

4.3. Importance of assumptions on land transformation and occupation impact assessment

Results of the described impact assessment models are limited by the quality of input variables. Our calculations did not include important changes in the landscape that are known to occur in the region, such as the consideration of pasture as NV and indirect land use change. The Cerrado is made of a mix of landscapes such as dry deciduous forest, scrub forest and woodlands, and also includes natural pastures. Our analysis did not consider the possible historical conversion of natural pasture to soybean. Such a consideration would likely reduce the impacts per tonne of soybean given the smaller differences in ecosystem quality between pasture and cropland (e.g. evapotranspiration, soil organic carbon, erosion, etc.). The replacement of pasture in the central and southern region of Mato Grosso (Cerrado) has led to further expansion of pasture in northern Mato Grosso (Amazon biome) in the early 2000s (Barona et al., 2010). Such indirect land use change has not been considered here due to lack of detailed spatial information. Such consideration would likely increase the impact of soybean production by possibly canceling the impacts allocated to pasture in the NV-pasture-soybean transformation sequence.

The greatest differences with the literature values were found in impact categories where either classification has been performed differently or where greater heterogeneity exists within the biophysical parameters. For instance, the differences observed in CF_{trans} for ERP can be a result of a difference in soil classification at the global level between our study and Saad et al. (2013). While we used classification based on sand, silt and clay content according to Shannguan et al. (2014) available at 1 km^2 resolution, we chose the mean average natural soil erosion values despite large differences within the biome. Moreover, the biome average slopes of 5° (Cerrado) and 10° (Amazon) represent average biome slope conditions that are likely not representative of the declination of cropland. Our values of ERP are therefore likely an overestimate of potential erosion which can be refined at the landscape level based on local soil and slope conditions. Similarly, the average Mato Grosso water table depth was assumed to be within 0.8–1.5 m despite known differences across the state which would offer more heterogeneity in the values of GWRP. These differences suggest that further consideration in regionalization and high resolution spatial information can provide more information that would not be accessible at the biome or country scale.

Finally, the proposed methods and results depend greatly on available information for the region. The values reported for BDP relied on plant species richness information, which can also be lacking. Recent results suggest an Amazonia species richness of 969–1093 species 20,000 km^{-2} (Lathuillière et al., 2016a; Ferry-Slik et al., 2015) which are lower than an expected 16,000 species according to ter Steege et al. (2013).

4.4. Effects of model choices on land transformation and occupation impact assessment

Results also depend on the choices made in the model in addition to the inputs described above, namely the choice of reference NV, the regeneration time, and attribution of biome ecosystem quality. Given the deforestation dynamics documented in the region (Gibbs et al., 2015; Macedo et al., 2012; Barona et al., 2010) we chose the NV as the reference vegetation to which the landscape will return post-occupation. Therefore, we have assumed that the landscape's ecosystem quality post-soybean production will naturally return to the same ecosystem quality of the tropical forest or savanna landscapes, an assumption which can vary with the cultural perspective and temporal preference for decision making (Cao et al., 2016). Additionally, the regeneration times provided here were 159 years and 117 years based on tropical forest and savanna ecosystem regeneration times listed by Curran et al. (2014). All else remaining the same, transformation impacts increase with regeneration time and therefore, in addition to potential changes in impact from inventory results based on productivity of crops in different biomes, we expect differences based on time. While these regeneration times were similar in the case of tropical forest and savanna, biome differences are expected in some cases (Saad et al., 2013) despite considerable overlap in some characterization factors in current biomes for the same crop under consideration (Cao, 2016). These similarities provide further insight into the allocation of impacts to pasture which may lead to a negative or no land transformation impact of tropical forest in this study (for CRP and WPP-MF in particular) since the difference in ecosystem quality is small when transitioning from a pasture to a cropland landscape. This consideration calls for higher resolution ecosystem quality information to further separate the biome (or hectare) differences in the land transformation and occupation impact assessment (Cao, 2016).

5. Conclusions

This study provided further insight into the impacts of land transformation and occupation resulting from the production of soybean in Mato Grosso in 2010. The Amazon showed a greater potential impact to biodiversity and ecosystem services for soybean production when compared to the Cerrado according to available biodiversity and biophysical data. Land transformation and occupation impacts to biodiversity were 1.17 10^4 PDF m^2 y ton^{-1} soybean and 2.93 10^3 PDF m^2 y ton^{-1} soybean, respectively for the Amazon, and 8.04 10^3 PDF m^2 y ton^{-1} and 2.75 10^3 PDF m^2 y ton^{-1} for the Cerrado. Total impacts to ecosystems services from land transformation and occupation amounted to \$ 532 ton^{-1} and \$ 260 ton^{-1}, respectively for one tonne of soybean produced in the Amazon, and \$ 231 ton^{-1} and \$ 153 ton^{-1} for the Cerrado. As such, the Amazon biome has been under international scrutiny while the Cerrado has historically experienced more transformation (Brannstrom et al., 2008). Within the context of continued regional increase in production expected for 2020 (MAPA, 2013), expansion into current pasture has the advantage to halt further loss in biodiversity while significantly reducing possible effects on ecosystem services, assuming there is no resulting indirect land use change for pasture.

Results of this study complement regional LCA studies by considering its biodiversity and ecosystem services hotspots alongside human toxicity and terrestrial and freshwater ecotoxicity hotspots (Miranda, 2016). Moreover, the ecosystem services damage highlighted the importance of the soil mechanical filtration and climate sequestration processes as the greatest contributors in the end-point impact assessment. Such a consideration is not intuitive and calls for further consideration of soil processes in addition to biodiversity and greenhouse gas emissions from deforestation in the region.

The regionalization of characterization factors requires detailed knowledge of the biophysical processes taking place in the soybean production which is largely available in Mato Grosso due to the region's international importance in the soybean supply chain and its geographical position in three of Brazil's biomes. However, regionalization also means greater uncertainty in characterization factors due to greater spatial heterogeneity in biophysical parameters such as soil, water and atmosphere relationships, factors which should be taken into account when using LCA to inform decision making, especially when combined to ecosystem services valuation.

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Abbreviations

BDP	Biodiversity potential
BPP	Biotic production potential
CF_{occ}	Characterization factor of land occupation impact
CF_{trans}	Characterization factor of land transformation impact
CRP	Climate regulation potential
ERP	Erosion resistance potential
GWRP	Groundwater recharge potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NV	Natural vegetation
PDF	Potentially disappeared fraction of species
UNEP/SETAC	United Nations Environment Programme Society of Environmental Toxicology And Chemistry
WPP-MF	Mechanical Water Purification Potential
WPP-PCF	Physiochemical Water Purification Potential

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.02.120.

References

Adario, P., 2016. 10 years Ago, the Amazon Was Being Bulldozed for Soy. Then Everything Changed. Blog Post. Greenpeace International available at: http://www.greenpeace.org/international/en/news/Blogs/makingwaves/soy-farming-devastating-amazon-soya-moratorium-renewed/blog/56418/, 10 May 2016.

Assunção, V.A., Guglieri-Caporal, A., Sartori, Â.L.B., 2011. Florística do estrato herbáceo de um remanescente de cerradão em Campo Grande, Mato Grosso do Sul, Brasil. Hoehnea 281–288.

Barbosa, R., Feamside, P., 2005. Above-ground biomass and the fate of carbon after burning in the savannas of Roraima, Brazilian Amazonia. For. Ecol. Manag. 1–3, 295–316.

Barona, E., Ramankutty, N., Hyman, G., Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 2, 024002.

Beck, T., Bos, U., Wittstock, B., Baitz, M., Fischer, M., Sedlbauer, K., 2010. LANCA© Land Use Indicator Value Calculation in Life Cycle Assessment. http://www.ibp-gabi.de/files/lanca_website.pdf.

Brandão, M., Milà i Canals, L., 2013. Global characterisation factors to assess land use impacts on biotic production. Int. J. Life Cycle Assess. 6, 1243–1252.
Brannstrom, C., Jepson, W., Filippi, A.M., Redo, D., Xu, Z., Ganesh, S., 2008. Land change in the Brazilian savanna Cerrado, 1986-2002: comparative analysis and implications for land-use policy. Land Use Policy 25 (4), 579–595.
Caffrey, K.R., Veal, M.W., 2013. Conducting an agricultural life cycle assessment: challenges and perspectives. Sci. World J. 472431.
Cao, X.V.A., 2016. Développements méthodologiques pour l'utilisation des terres en évaluation des impacts du cycle de vie : application aux polymères agrosourcés. Dissertation. Polypublie, Polytechnique Montréal, Montreal, Canada. https://publications.polymtl.ca/2106/.
Cao, V., Margni, M., Favis, B.D., Deschenes, L., 2015. Aggregated indicator to assess land use impacts in life cycle assessment (LCA) based on the economic value of ecosystem services. J. Clean. Prod. 94, 56–66.
Cao, V., Margni, M., Favis, B.D., Deschênes, L., 2016. Choice of land reference situtation in life cycle impact assessment. Int. J. Life Cycle Assess. http://dx.doi.org/10.1007/s11367-016-1242-2 (in press).
Castanehira, E.G., Grisoli, R., Freire, F., Pecora, V., Coelho, S.T., 2014. Environmental sustainability of biodiesel in Brazil. Energy Policy 65, 680–691.
Castanheira, E.G., Freire, F., 2013. Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems. J. Clean. Prod. 54, 49–60.
Chaudhary, A., Verones, F., de Baan, L., Hellweg, S., 2015. Quantifying land use impacts on biodiversity: combining species-area models and vulnerability indicators. Environ. Sci. Technol. 49, 9987–9995.
Curran, M., Hellweg, S., Beck, J., 2014. Is there any empirical support for biodiversity offset policy? Ecol. Appl. 24 (4), 617–632.
da Silva, V.P., van der Werf, H.M.G., Spies, A., Soares, S.R., 2010. Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. J. Environ. Manag. 9, 1831–1839.
de Baan, L., Alkemade, R., Koellner, T., 2013. Land use impacts on biodiversity in LCA: a global approach. Int. J. Life Cycle Assess. 6, 1216–1230.
De Castro, E., Kauffman, J., 1998. Ecosystem structure in the Brazilian Cerrado: a vegetation gradient of aboveground biomass, root mass and consumption by fire. J. Trop. Ecol. 263–283.
de Sy, V., Herold, M., Achard, F., Beuchle, R., Clevers, J.G.P.W., Lindquist, E., Verchot, L., 2015. Land use patterns and related carbon losses following deforestation in South America. Environ. Res. Lett. 10, 124004.
Dias, L.C.P., Macedo, M.N., Costa, M.H., Coe, M.T., Neill, C., 2015. Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. J. Hydrol. Reg. Stud. 108–122.
Fearnside, P.M., Barbosa, K.I., 2004. Accelerating deforestation in Brazilian Amazonia: towards answering open questions. Environ. Conserv. 31 (1), 7–10.
Ferry-Slik, J.W.F., et al., 2015. An estimate of the number of tropical tree species. Proc. Natl. Acad. Sci. U. S. A. 24, 7472–7477.
Franczak, D.D., 2009. Mudança na Comunidade Lenhosa de um Cerradão e um Cerrado Stricto Sensu no Parque do Bacaba. Nova Xavantina – MT.
Galford, G.L., Melillo, J.M., Kicklighter, D.W., Mustard, J.F., Cronin, T.W., Cerri, C.E.P., Cerri, C.C., 2011. Historical carbon emissions and uptake from the agricultural frontier of the Brazilian Amazon. Ecol. Appl. 3, 750–763.
Galford, G.L., Soares-Filho, B., Cerri, C.E.P., 2013. Prospects for land-use sustainability on the agricultural frontier of the Brazilian Amazon. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 368, 20120171.
Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's soy moratorium. Science 6220, 377–378.
Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 6188, 1109–1113.
Hijmans, R.J., 2014. Raster: Geographic Data Analysis and Modeling, R Package Version 2.2-31.
IBGE, 2016. Banco de dados agregados. http://www.sidra.ibge.gov.br/.
Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled Seamless SRTM Data V4. International Centre for Tropical Agriculture (CIAT). http://srtm.csi.cgiar.org.
Kauffman, J.B., Cummings, D., Ward, D., 1994. Relationships of fire, biomass and nutrient dynamics along a vegetation gradient in the Brazilian Cerrado. J. Ecol. 3, 519–531.
Koellner, T., de Baan, L., Beck, T., Brandao, M., Civit, B., Margni, M., Mila i Canals, L., Saad, R., de Souza, D.M., Mueller-Wenk, R., 2013. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle Assess. 6, 1188–1202.
Lathuillière, M.J., Johnson, M.S., Donner, S.D., 2012. Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. Environ. Res. Lett. 2, 024024.
Lathuillière, M.J., Miranda, E.J., Couto, E.G., Johnson, M.S., 2014. Land transformation and occupation impacts of farming practices for the production of soybean in Mato Grosso, Brazil, using life cycle impact assessment. In: Presentation GC21B-0528, San Francisco, CA, USA: AGU Fall Meeting 2014.
Lathuillière, M.J., Bulle, C., Johnson, M.S., 2016a. Land use in LCA: including regionally altered precipitation to quantify ecosystem damage. Environ. Sci. Technol. 50 (21), 11769–11778. http://dx.doi.org/10.1021/acs.est.6b02311.
Lathuillière, M.J., Coe, M.T., Johnson, M.S., 2016b. A review of green- and blue-water resources and their trade-offs for future agricultural production in the Amazon Basin: what could irrigated agriculture bring to Amazonia? Hydrol. Earth Syst. Sci. 20 (6), 2179–2194. http://dx.doi.org/10.5194/hess-20-2179-2016.
Macedo, M.N., DeFries, R.S., Morton, D.C., Stickler, C.M., Galford, G.L., Shimabukuro, Y.E., 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc. Natl. Acad. Sci. U. S. A. 4, 1341–1346.
Maia, S.M.F., Ogle, S.M., Cerri, C.E.P., Cerri, C.C., 2010. Soil organic carbon stock change due to land use activity along the agricultural frontier of the southwestern Amazon, Brazil, between 1970 and 2002. Glob. Change Biol. 10, 2775–2788.
MAPA, 2013. Projeções do agronegocio: Brasil 2012/2013 a 2022/2023 Projeções de longo prazo. Ministério da Agricultura, Pecuária e Abastecimento, Brasilia, DF.
MCTI, 2013. Estimativas annuais de emissões de gases de efeito estufa no Brasil. Ministério da Ciência, Tecnologia e Inovação, Brasília, DF. http://www.mct.gov.br/upd_blob/0228/228468.pdf.
Milà i Canals, L., Rigarlsford, G., Sim, S., 2013. Land use impact assessment of margarine. Int. J. Life Cycle Assess. 6, 1265–1277.
Miranda, E., 2016. Avaliação do ciclo de vida da soja mato-grossense. Universidade Federal de Mato Grosso, Cuiaba, Mato Grosso, Brazil.
Miranda, E., Carmo, J., Couto, E., Camargo, P., 2016. Long-term changes in soil carbon stocks in the Brazilian Cerrado under commercial soybean farm. Land Degrad. Dev. 27 (6), 1586–1594.
Moeys, J., 2014. Package 'soiltexture'. http://cran.r-project.org/web/packages/soiltexture/soiltexture.pdf.
Morandi, P.S., 2010. Riqueza e co-ocorrência de herbáceas em três fitosionomias de cerrado. Universidade do Estado de Mato Grosso, Nova Xavantina-MT. Nova Xavantina, Mato Grosso, Brazil.
Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 1781–1800.
Müller, H., Rufin, P., Griffiths, P., Barros Siqueira, A.J., Hostert, P., 2015. Mining dense Landsat time series for separating cropland and pasture in a heterogeneous Brazilian savanna landscape. Remote Sens. Environ. 490–499.
Müller-Wenk, R., Brandão, M., 2010. Climatic impact of land use in LCA-carbon transfers between vegetation/soil and air. Int. J. Life Cycle Assess. 2, 172–182.
Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., da Motta, R.S., Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O., Hess, L., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 6188, 1118–1123.
Oliveira, P.T.S., Nearing, M.A., Moran, M.S., Goodrich, D.C., Wendland, E., Gupta, H.V., 2014. Trends in water balance components across the Brazilian Cerrado. Water Resour. Res. 9, 7100–7114.
Pokhrel, Y.N., Fan, Y., Miguez-Macho, G., 2014. Potential hydrologic changes in the Amazon by the end of the 21st century and the groundwater buffer. Environ. Res. Lett. 8, 084004.
R Core Team, 2014. R: a Language and Environment for Statistical Computing. Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.
Raucci, G.S., Moreira, C.S., Alves, P.A., Mello, F.F.C., Frazao, L.d.A., Cerri, C.E.P., Cerri, C.C., 2015. Greenhouse gas assessment of Brazilian soybean production: a case study of Mato Grosso state. J. Clean. Prod. 418–425.
Rodrigues, T.R., Vourlitis, G.L., Lobo, F.d.A., de Oliveira, R.G., Nogueira, J.d.S., 2014. Seasonal variation in energy balance and canopy conductance for a tropical savanna ecosystem of south central Mato Grosso. Braz. J. Geophys. Res. Biogeosci. 1, 1–13.
Ruviaro, C.F., Gianezini, M., Brandao, F.S., Winck, C.A., Dewes, H., 2012. Life cycle assessment in Brazilian agriculture facing worldwide trends. J. Clean. Prod. 9–24.
Sá, J.C.M., Séguy, L., Tivet, F., Lal, R., Bouzinac, S., Borszowskei, P.R., Briedis, C., dos Santos, J.B., da Cruz Hartman, D., Bertoloni, C.G., Rosa, J., Friedrich, T., 2013. Carbon depletion by plowing and its restoration by no-till cropping systems in oxisols of subtropical and tropical agro-ecoregions in Brazil. Land Degrad. Dev. 26, 531–543.
Saad, R., Koellner, T., Margni, M., 2013. Land use impacts on freshwater regulation, erosion regulation, and water purification: a spatial approach for a global scale level. Int. J. Life Cycle Assess. 6, 1253–1264.
Saatchi, S.S., Houghton, R.A., Alvala, R.C.D.S., Soares, J.V., Yu, Y., 2007. Distribution of aboveground live biomass in the Amazon basin. Glob. Change Biol. 4, 816–837.
Santos, J., Freitas, C., Araujo, L., Dutra, L., Mura, J., Gama, F., Soler, L., Sant'Anna, S., 2003. Airborne P-band SAR applied to the aboveground biomass studies in the Brazilian tropical rainforest. Remote Sens. Environ. 4, 482–493.
Shannguan, W., Dai, Y., Duan, Q., Liu, B., Yuan, H., 2014. A global soil data set for earth system modeling. J. Adv. Model. Earth Syst. 1, 249–263.
Silvério, D., Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M., Coe, M.T., 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. Environ. Res. Lett. 10, 104015.
Simon, M.F., Garagorry, F.L., 2005. The expansion of agriculture in the Brazilian Amazon. Environ. Conserv. 3, 203–212.
Soares-Filho, B., Rajao, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., Alencar, A., 2014. Cracking Brazil's forest code. Science 6182, 363–364.
Solórzano, A., Pinto, J.R.R., Felfili, J.M., Hay, J.D.V., 2012. Perfil florístico e estrutural do componente lenhoso em seis áreas de cerradão ao longo do bioma Cerrado. Acta Bot. Bras. 6, 328–341.
Spera, S.A., Cohn, A.S., VanWey, L.K., Mustard, J.F., Rudorff, B.F., Risso, J., Adami, M., 2014. Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environ. Res. Lett. 6, 064010.
ter Steege, H., et al., 2013. Hyperdominance in the Amazonian tree flora. Science 6156, 325-+.
USDA-FAS, 2016. World Agricultural Production available. http://apps.fas.usda.gov/psdonline/circulars/production.pdf.