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

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A B S T R A C T

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